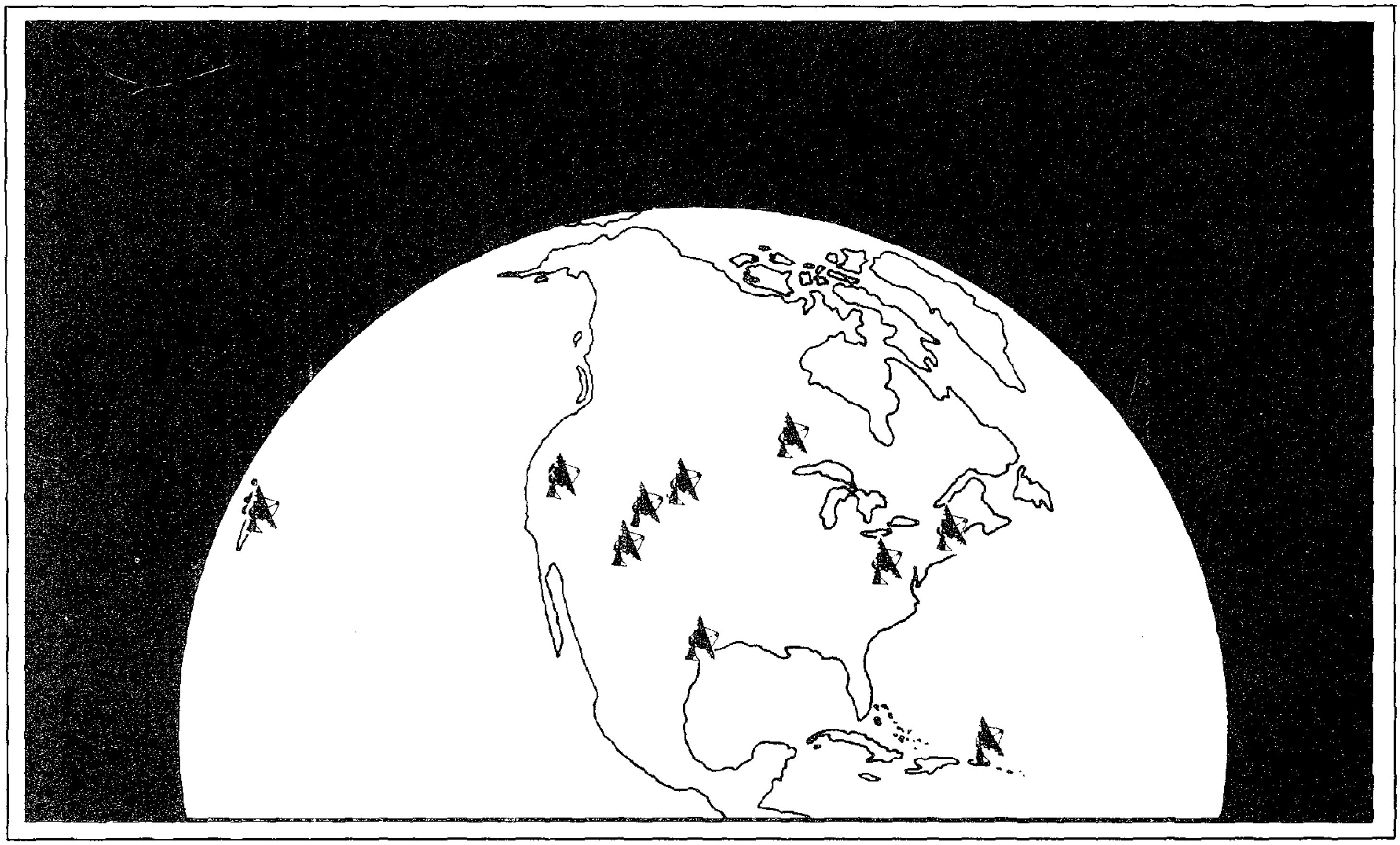
Multidisciplinary Use of the Very Long Baseline Array



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The National Research Council organized a workshop to gather together experts in very long baseline interferometry, astronomy, space navigation, general relativity and the earth sciences. The purpose of the workshop was to provide a forum for consideration of the various possible multi-disciplinary uses of the very long baseline array.

Geophysical investigations received major attention. Geodesic uses of the very long baseline array were identified as were uses for fundamental astronomy investigations. Numerous specialized uses were identified.

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CONTENTS

1

INTRODUCTION AND SUMMARY

BACKGROUND

The recently released report of the National Research Council's Astronomy Survey Committee recommends construction of an array of 10 radio telescopes situated over the continental United States, Hawaii, and Alaska. The Very Long Baseline Array (VLBA), as it is known in the astronomy community, would have as its principal scientific objective the observation with very high angular resolution of distant radio-emitting celestial objects such as quasars. In addition to providing an extremely accurate fix on the position of the objects, such high angular resolution would make possible the observation of the fine detail of their internal structure and dynamics.

Such high resolution can be accomplished by synchronizing 10 widely spaced antennas, the radio frequency signals of which are synchronized with extremely precise timing signals provided by atomic clocks. The signals are then combined with the aid of computer processing to yield a radio emission image with a resolution of 0.3 milliarc sec at a wavelength of 6 cm. The detail of the images so produced will far exceed that from any other instrument, making possible the resolution of new features of objects that are the subject of intense astronomical research, including quasars, galactic nuclei, interstellar molecular clouds, the center of our galaxy, and various energetic galactic objects such as X-ray binaries and flare stars.

The VLBA can also be applied to other important problems. In addition to assisting the navigation of interplanetary spacecraft and making possible tests of the general theory of relativity, the VLBA would provide very precise determinations of the distances between the stations. The current accuracy of such techniques is about 3 cm.

A recent Committee on Space Research (COSPAR) Bulletin (No. 92) details some of the important applications to earth science:

> By making repeated measurements over a period of years using . . . [such] techniques, crustal motions as small as 1 cm per year can be determined. Current knowledge of the relative motions of the tectonic plates is based on paleomagnetic data and other information, and is averaged over the past several million years of geologic time. These averaged rates are

estimated to be between 1 and 20 cm/year. Using laser ranging and Very Long Baseline Interferometry, these movements can be directly measured for the first time, and tectonic models can be revised to reflect contemporary plate motion.

In California, Alaska, and other regions of high earthquake activity, the driving forces of place tectonics cause a buildup of crustal strain near plate boundaries. When the resulting stress exceeds the strength of the underlying materials, the stress is released in the form of earthquakes or slow creep. A major objective of the Crustal Dynamics Project is to measure and analyse regional deformation and strain accumulation along major plate boundaries such as the San Andreas Fault in California, which separates the North American Plate from the Pacific Plate. This will help us to understand the basic mechanisms leading to earthquakes.

Radio interferometry is currently contributing to determination of universal time, polar wobble, and variation of the earth's spin. The VLBA would increase the precision and accuracy of such determinations. A very precise time series of data on polar wobble could give some additional clues to the internal structure of the earth. The VLBA might be able to provide data that would enhance the accuracy of the Global Positioning System (GPS). Enhancements in the accuracy and precision of sea-height determinations, which reveal gravitic variations over the surface of the earth, might give further clues to the earth's internal structure.

A recent report jointly issued by the NRC's Committee on Geodesy and Committee on Seismology (1981), Geodetic Monitoring of Tectonic Deformation--Toward a Strategy, reviews the potential of space techniques for application to geodesy. The report envisions the use of various space techniques "for measuring large-scale distortions within plates, as well as for determining the present rate of interplate motions. In addition, they can provide a framework surrounding seismic zones to which measurements by ground techniques can be tied."

There are also ways discussed in this report to make geodetic measurements with the aid of the GPS that the Department of Defense is establishing for the purpose of providing a consolidated global navigation system. The system, which will ultimately include 18 satellites in 12-h circular orbits, is expected to be in operation by 1987. There are several approaches to providing geodetic information by means of the GPS. One method makes use of measurements of the phases of the signals, with knowledge of the original modulation signal. A second method only requires general knowledge of the structure of the modulation code. The third method is similar to astronomical radio interferometry, but uses the GPS signals as the "noise" sources. This last method of using long-baseline radion interferometry with noise signals transmitted from a satellite was demonstrated over a decade ago at MIT. The high amplitude of the signal is a simplifying factor.

The report concludes that space techniques are the only approach available for checking the large-scale stability of major tectonic plates and measuring their present rates of motion.

WORKSHOP ON MULTIDISCIPLINARY USES OF THE VERY LONG BASELINE ARRAY

The NRC organized a 2-day workshop to gather together experts in very long baseline interferometry, astronomy, space navigation, general relativity, and the earth sciences--including geodesy and geophysics experts. The purpose of the workshop was to provide a forum for consideraion of the various possible multidisciplinary uses of the VLBA and to provide advice on its potential contributions to the applied science programs of the mission agencies participating in the workshop. The agenda and a list of invitees are contained in Appendixes A and B, respectively. Presentations were made by representatives of the National Radio Astronomy Observatory, the Smithsonian Astrophysical Observatory, the Joint Institute for Laboratory Astrophysics, the National Geodetic Survey, the Naval Research Laboratory, the National Aeronautics and Space Administration, the Jet Propulsion Laboratory, Haystack, and the U.S. Naval Observatory. A highlight of the program, which took place on April 8 and 9, 1983, was a discussion session led by George Keyworth, director of the Office of Science and Technology Policy. This session is summarized in Chapter 3.

Support for the workshop was provided by the Defense Mapping Agency, the National Geodetic Survey, the National Science Foundation, the National Aeronautics and Space Administration, and the Defense Advanced Research Projects Agency.

The organizing committee met at the conclusion of the workshop and agreed on the following summary.

WORKSHOP SUMMARY

The VLBA was originally conceived as an astrophysical facility. It has become clear, as planning proceeds, that there are many other areas of scientific activity that can profitably use the facility. Some of these uses will take the form of short experiments, proposed through normal channels; others of a more programmatic nature may well require advance planning so that the objectives can be properly met. There are classes of investigation that can be carried out by making use of data, particularly calibration data, without requiring special observations, although consultation about calibration strategy may be desirable.

Geophysical investigations received major attention at the workshop. Determinations of large-scale plate motions or deformation will surely be an important component of VLBA activity. Even where there will exist dedicated very long baseline interferometer (VLBI) networks such as those for polar motion and earth rotation studies, the VLBA will have the ability to provide accurate, independent measurements that can provide control values for UT1 and polar motion. By choosing

VLBA station locations properly and by combining the observations from U.S. programs with VLBI observations from foreign stations and VLBAs now being planned and built, highly interesting measurements of plate motions will result. The VLBA will probably be the instrument of choice for the development of source catalogs for the geophysical programs and for the determination of structural changes in the fundamental source that would otherwise degrade the quality of the dedicated geophysical network observations. It is very likely that the VLBA stations can be used as base stations for GPS geodetic systems.

Geodetic uses of the VLBA can also be identified. Combining VLBA and foreign stations would give a network that could lead to a definition of the conventional terrestrial reference system that would be far more accurate than any currently in existence or contemplated.

The VLBA will be used for fundamental astrometry in several different ways. The quasar reference system should be a better approximation to an inertial reference system than any other. The use of interplanetary spacecraft to determine a solar system reference system related to the quasar system allows comparison among different coordinate systems. These many capabilities make the VLBA an astrometric instrument par excellence. Stability of instrumentation and observation and reduction procedures will be essential. The VLBA can give independent measurements of the precession and nutation constants, determine the conventional terrestrial reference system, and measure the relationship between the quasar-based and earth-based frames.

A number of other uses were identified. These uses include the following:

1. The synthesis of an improved maser clock for the United States through coordination of the maser time standards located at each station of the VLBA. The worldwide network tied to the VLBA can provide universal clock synchronization of high accuracy between continents.

2. Spacecraft navigation by differential VLBI will be enhanced by the availability of the VLBA, which can provide increased sensitivity, simultaneous orthogonal baselines, and shorter baselines than present operational systems, all of which can be useful under certain circumstances.

3. Precision satellite orbit determinations can be made that will be useful both for studies of the higher multipole moments of the earth's gravitational field and for geodetic purposes. Here, the specialized measuring instruments need only to be stations that define the inertial frame relative to which the satellite motions are measured.

4. The existence of a ground-based VLBA system enhances the possibilities of using space-based interferometric antennas in an orbiting VLBI system to extend radio resolution corresponding to baselines with dimensions much larger than the earth.

The workshop identified and discussed a number of topics that must be considered if multidisciplinary use of the VLBA is to be optimized.

1. Geophysics input to the project is essential. Present plans call for augmentation of the Scientific Steering Group to include broader multidisciplinary participation. In the course of the workshop, a general invitation was issued to potential users to communicate concerns to the director of the National Radio Astronomy Observatory (NRAO) or to the project scientists.

2. Array configurations were discussed. Geodetic concerns should be considered in decisions about antenna placement. Such needs can often be met easily without compromising astrophysical mapping. The workshop concluded that the Hawaii and Puerto Rico stations are especially appropriate locations.

3. Dealing with proposals and scheduling requires proper lead time and planning. Proposals for multidisciplinary uses of the VLBA should be refereed by normal procedures. Referees should be selected from the appropriate disciplines. The need to contemplate subarray use and interleaving of observations will lead to complexity in the planning process.

4. Calibration procedures should address both array requirements and program requirements. Preparations for mutual use of calibration data by different program interests should be undertaken as soon as possible. Such preparations should include the examination of the best calibration procedures to optimize joint uses.

5. The workshop identified several auxiliary instrumentation needs. Water vapor radiometers, GPS receivers, gravimeters, meteorological sensors, geodetic monuments, and laser pads are examples. These instruments may well be operated by different agencies, but workshop participants foresaw no problems in such arrangements.

6. MARK III recording system compatibility was an issue that was examined closely. The workshop concluded that this matter is adequately treated in present plans. As systems develop, there should be proper notice and consultation well in advance of implementation of changes.

7. Performance specifications should be arrived at by mutual consultation. Examples include horizon-to-horizon coverage, high slew rate, frequency compatibility with dedicated geodetic arrays, and high time resolution ability. There should be provision for extra frequencies and flexible low-frequency capability. Multiband capability will be valuable for observations of general relativistic phenomena. Good quality control is an essential ingredient of this program. The existing Science Working Group appears to be an effective mechanism for discussing these issues.

8. The VLBA project and VLBI planning activities in other countries appear to be proceeding with good coordination. The 14-station MARK III capability of the currently planned processor properly recognizes the importance of this relationship. It should be noted that several international activities exist to support coordination. Among these activities are the International Radio Interferometric Surveying Advisory Committee (IRIS), chaired by W. Carter of the NGS; a subcommittee of the joint International Union of Geodesy and Geophysics (IUGG)/COSPAR Committee on International Coordination of Space Techniques for Geodesy and Geodynamics, chaired by I. Mueller of Ohio

State University; and the International Astronomical Union Commission 40 Working Group to encourage cooperation between geodesists and astrophysicists, chaired by K. Johnston of the Naval Research Laboratory.

9. Archiving of data should be thought about well in advance of implementation of the VLBA. This consideration is particularly important to facilitate use of data for astrometry and geodesy.

2

PURPOSE OF THE WORKSHOP

Bernard F. Burke
Workshop Chairman

A main purpose of this workshop is to remind participants of the various considerations that have gone into the planning of the Very Long Baseline Array (VLBA) and to stimulate questions that will affect planning of the VLBA as it is constituted at present. Our objective in adopting a workshop rather than a symposium format was to encourage maximum interaction. As background, I would like to mention an issue that arose in the early 1970s between the solar astronomers and the Very Large Array (VLA) project. Although there was a solar astronomer on the advisory committee, the importance of finding out the averaging time for the VLA had not been appreciated by the solar astronomy community. There was an assumption that the VLA would come into being and that they would be able to use it. Then at one meeting came the sudden realization that the natural averaging time for the VLA was 10 s, which, with some adjustments, might be reduced to 3 s. But what the astronomers wanted and needed was 0.1 s. At that stage the project was too far advanced to accommodate 0.1-s averaging. It would have been a far more effective instrument if that particular set of specifications had reflected the needs of the solar astronomers. And, had this point been raised at an earlier stage, I am sure that it could have been accommodated.

As we return to the purposes of this workshop, let me emphasize that users of the VLBA will not have the feeling of being presented with an instrument that will not do the job they want it to do. Therefore we should concentrate here on making the needs of the various communities known, stimulating thinking about ways that the VLBA might be used, and considering means of providing input to the project. That input should be made soon, for the project is gaining momentum and decisions are being made now.

The Very Long Baseline community is a diverse one. The contributions of the National Science Foundation, NASA, and the National Geodetic Survey are recognized. The evolution of the array is a symbiotic process, and its use will cut across many disciplines.

SPECIAL PRESENTATION

George Keyworth
Director, Office of Science and Technology Policy
Science Adviser to the President

Almost 22 months ago, in the first speech I gave when I came to this job, I discussed the necessity for discrimination based upon excellence in how we allocated resources for science. At that time, I had by no means adapted to Washington and I was still thinking, if you wish, in a white coat. I thought that discrimination was as simple as could be--that is what every single one of us does as a working scientist with our own research career. Yet I discovered that it was not so straightforward.

In the course of the last 2 years, in trying to implement a policy of supporting the best and the most productive science, we have made a lot of progress. I owe all of you a debt, because the Very Long Baseline Array (VLBA) is certainly an example of how we _should_ do things.

Many different communities--some of them rather visible right now, such as, of course, high-energy physics for the last 2 years, and materials science right now--have a very difficult time distinguishing between scientific priorities and, let me call it, priorities associated with institutional stability.

I have less politely called it good science and WPA, but I think you all know what I mean. But I have been particularly impressed with what happened with the Field report (_Astronomy and Astrophysics for the 1980's_, National Academy Press, 1982)--how it was done and how it was represented to me by the members. It was a first-class piece of work. I have also been very impressed with what has been done more recently within the planetary science community under Noel Hinners, which is a comparable piece of trying to make order out of chaos.

You cannot imagine how much easier it is for us to exercise the discrimination that this whole scientific community, at least one by one, wants to see, when things like this occur.

The VLBA is a straightforward example. It was picked as the number one priority in the Field report for very straightforward and comprehensible reasons. When we came into office and were trying to look at the overall health of astronomy (something that has been long an interest of mine, and it is almost an obsession of Doug Pewitt's), our life was made very easy because we had so much careful thought to draw on.

I look forward, as long as I am here, to encouraging progress in the VLBA as much as possible. What you are doing today is very interesting, because we are seeing this linkage between what before had been nonoverlapping disciplines more and more. This trend is extremely exciting, just as it is exciting to see experimental physicists working in neurophysiology. Certainly, fields like geodesy and astronomy are not by any means that different, but worrying about stellar theory at the same time someone is worrying about crustal dynamics is very intellectually stimulating. You all have a very exciting task in front of you, and I will encourage you in every way I possibly can. I know that Ed Knapp, director of the National Science Foundation, is also very enthusiastic about this. It is one of those programs that everyone supports. You are quite fortunate.

At this point, I would very much welcome the opportunity to answer questions about where we are going in science, what we see for astronomy, or any other aspect that you would like to know about.

DISCUSSION

BURKE: Let me start off with a straightforward question. In the case of very long baseline interferometry (VLBI), what was the quality that struck you as making it appropriate for a new thrust?

KEYWORTH: Well, the straightforward answer is that it encompasses a number of questions in astronomy. But let me be a little bit more explicit about what went through our heads at the time. In reading the whole Field report, there are a lot of different interpretations you can have, and I guess this played heavily on my prejudices, but I have become deeply concerned over the last 10 years that astronomy and astrophysics have been compromised by the enormous amount of emphasis placed primarily upon the development of technology in the space program.

I can simplify it and say that tiles have paid for experiments, but the fact is we built an exciting capability. We built some very exciting missions that were extremely expensive, and at the same time we failed to adequately support the disciplinary base that it is all really there for, at least from a scientist's perspective.

We were very much interested in looking at areas that were rich science, and we all take that for granted. These areas could support a research program that would foster a lot of new Ph.D. theses and would encompass not one or five experiments, not one or five observations, but a new extension in a disciplinary science.

I guess that relates to a lot more than just VLBA. I hope you all realize that we are now emphasizing science that is rich but also science that will produce a lot of new talent. We have perhaps not emphasized the necessity for new creative talent as much as we could have since the late and middle 1960s. We need to sustain an effort for a long period of time.

New facilities as well as support in general have got to be there. Back in the 1960s everybody was out hustling some new project. For every one that the government could afford to support, there were proposals for 20 that couldn't be funded. Half of these were crazy, and the other half were competent in varying degrees.

Now, believe it or not, there are practically no proposals for major new facilities. I am worried that that may be due to a lack of vision, imagination, and risk-taking.

FRIEDMAN: Jay, you have been a great supporter of the space telescope, and recently we have all been distressed by the problems that have occurred in that program. They have apparently reached massive proportions. Do you have any sense of what the political impact on the scientific programs will be of that overrun and delay?

KEYWORTH: First of all, I am an optimist, and I have a very short attention span for details and accounting matters. Doug Pewitt likes to compliment it by calling it wholesale rather than retail. My feeling is that the scientific community in general, and the field in particular, cannot be helped by a cost overrun of what may be a couple of hundred million dollars.

On the other hand, let me emphasize that I think the space telescope is so incredibly important that we must forge ahead as rapidly as we possibly can. Good science and a lot of excitement will come out of it. I even believe there may be a new public perception of this aspect of the space program.

Several years ago a number of reporters tried to popularize black holes. I never quite understood how anybody could popularize a black hole, but they did a beautiful job of it. I remember that the owner of The Washington Post, Katharine Graham, told me one time that one of the most successful weekly supplements to newspapers that was ever published was one that The New York Times did with a depiction of a black hole on the cover. Think of what excitement we can give to the American people if we are imaginative and pay some attention to trying to explain what we as scientists take for granted.

Now, let's go back to the question of risk, which I don't want to completely diminish. I think the cost overrun is unfortunate; we doubtless could have done the job somewhat better. But this is not a mission that can possibly be threatened by a 25 or 30 percent cost overrun.

But it would be deplorable if $200 million would be required that could have been used to support an entire new mission. We have got to do our very best to make sure that that overrun does not result in cutting the funds that are supporting theorists in academic institutions, or in stretching out the schedule for the gamma ray observatory, or anything else.

We have got to do our job better next time, but I am not shedding a lot of tears.

ROBERTS: My name is Morton Roberts. I am director of NRAO, the group that put in the proposal for VLBA. First, I would like to say we are very appreciative of the support we are getting from the administration and the appearance of VLBA in the 1984 budget.

A political question: The project is not yet authorized, and there are pitfalls within the Congress. What can we do to avoid these pitfalls, and what might be involved in getting authorization for this project starting, say, in 1985?

KEYWORTH: Well, maybe partly because I live constantly on the edge of the pit, I don't really see these pitfalls very clearly.

To put it another way, of all the major new scientific initiatives that we have, this is not one that I am really very worried about. You had an orderly procedure that set up priorities and that has been supported by virtually the entire scientific community.

That is going to be pretty hard to assail. The National Science Foundation is more and more developing a clear set of its own priorities, and Congress is entirely receptive to those. Of all the experiences I have had (mostly negative) of going from the laboratory to the bureaucracy, one of the most positive was in late January and early February, when I went up somewhat before and somewhat after the release of the 1984 budget and talked to all the key figures in Congress--committee chairmen, appropriations chairmen, and so on--and discussed the administration's philosophy.

It may seem straightforward to you, but for us to go up with increases between 15 and 22 percent across a major area of civilian R&D at the same time that Democrats and Republicans alike were screaming about a $185 billion deficit took quite a bit of explaining.

This could never have happened without the President's absolute and total encouragement. It is more than endorsement, and it happened because of him; it would not have happened any other way.

To go to the Congress and see within 2 weeks that bipartisan support for an emphasis in basic research, focusing primarily upon talent, was just absolutely universal--it was superb. I cannot conceive of something like the VLBA being threatened, because it so completely fits in to exactly what the administration's thrust is right now, and exactly what Congress is beginning to see is the one aspect of federal civilian R&D that has incontrovertibly paid dividends in the past. It is going to be more needed in the future than it has probably ever been in the past.

So, what I am basically saying is, it meets all requirements. I have no doubt that there are probably staffers on such-and-such an appropriations committee or such-and-such an authorization committee who don't support the VLBA. But I am only hypothesizing; I don't know of any, and you may. But it almost invariably occurs. I would just say I think VLBA is good enough to override that. Occasionally right wins.

COHEN: I am Marshall Cohen from Caltech. I was very gratified to hear you say that you supported the development of graduate students. Increasing--maybe not increasing and just keeping them as they are--is important. I have a vested interest, of course, in graduate student programs, as all of us at universities do, and I was very pleased to hear your support for such programs.

Going with that, of course, is general support of the experimental and other facilities that are needed in universities. I don't mean to say that the VLBA isn't one of those; in fact, the VLBA is. But one needs to keep in mind that all the other facilities that are needed in order to make these very large and wonderful national facilities go.

KEYWORTH: We must accept the inevitability of what in my field we have always called the advent of user science. I think it is unfortunate. Students are probably better trained in the long run if they can do their work with their peers in their academic environment. But the present trend is inevitable as science gets bigger and more expensive.

Keeping the balance is something we haven't done too well in the last 10 years, and I am deeply worried about it. I assure you that, for example, in NASA, Jim Beggs and I have discussed this a lot. Jim is very concerned, and you will see evidence of that in the 1984 budget.

It is a strange thing to go out and spend hundreds of millions of dollars on a facility or a planetary mission or whatever, and then go and hack away $5 or $10 million of support for students and their instructors who are involved in the very research that is being carried on in that mission. Of course it is penny-wise and pound foolish.

We have supported basic research, and justified basic research to the Congress and to the American people, on the argument that if you want a transistor, you must support research in the quantum theory of solids--the argument that science will eventually become technology.

We all know it is true. And we know that the payoff has been enormous, and we know it will continue to be so in the future. But there is a different climate in this town today than there has been in the last few decades. People now are very worried about the very near term. It is the huge unemployment rate, it is the threat of severe international competition that we face today.

Suddenly, the long-term arguments, at least in this area, unless they are very new, are not paying off as well. But, on the other hand, emphasis on what we have all taken for granted as the other half of the product of basic research support--students--is something that everyone is now deeply concerned about.

We must continually make it clear to the Congress, to program managers, and to everybody in organizations, that if this talent is lost we will lose our ability to pursue the research altogether. That is going to be a thread through the support of basic research in many administrations to come. It is by no means something that we have sponsored as a party platform issue. It is an urgent need for the nation.

BURKE: As Marshall was speaking I did a quick census of the participants of the workshop, and roughly one-quarter of the people here were graduate students who helped to build the VLB technique.

Most of them got their start during the 1960s. There has been a thin trickle of graduate students, and there are two or three young ones here who came as part of the outrun of that, but the great thrust was due to that support that came in the 1960s. I suppose we hope that there will be a new generation spawned by these new actions.

KEYWORTH: Well, I also am a product of that decade. I received my Ph.D. in 1968. That certainly brings to mind a central concern that we have. For example, let's take the National Science Foundation. Next year they will receive an 18 percent increase, and in many of the disciplinary areas--pure mathematics, material sciences, astronomy, for example--those increases are nearly 25 percent.

What good is that if it is for one year? How is it going to help you acquire more students, and how is it going to help you sustain them? And how is it going to make students feel that astronomy or whatever is an exciting profession? It won't. What we are really addressing is not a 1-, 2-, or 3-year remedial spike. What we are trying to do is to grapple for the right slope, and the slope cannot be based on a fraction of the gross national product or on any other such structural artifact. It has got to be based on need.

I have become more and more impressed in the last 2 years with how industrial management, corporate management, has been responding to the competitive threat by becoming much more visionary. Most visionaries today are worried about one thing first and foremost--where the skilled talent is going to come from: Ph.D.s, engineers, research scientists, and technicians. It doesn't matter what the unemployment rate is now. Growth means more and more emphasis upon technically trained people.

I think the support will be there. We are going to have to state it rationally, objectively, with some semblance of unity. We are going to have to look at justifying a sustained rate of growth to repair what we unwisely destroyed in the 1970s. Remember, it wasn't all done to us. We did it too. We scientists are the ones who decided, for example, that we were going to implement our cut by forgoing updating of instrumentation to avoid firing anybody. We made some short-term decisions that helped aggravate the problem in the long run.

But we have got a remedial job, and we have got a bigger challenge ahead of us. I don't know if this is optimism alone, but I think there is going to be a sustained rate of growth across a very large number of areas of science for a long period of time.

BURKE: Well, that is a marvelous message.

SHAPIRO: Given what is clearly a critical shortage of scientists and engineers and so forth, and also given the assumption that children are almost universally fascinated by astronomy and the new discoveries that are made almost daily in that field, do you think there is merit in attempting to reintroduce into the primary and secondary school educational curricula astronomy as a means to attract students to science and as a means to train them in mathematics and science?

Astronomy was in the curriculum in the nineteenth century in the United States, and it was turned out in about 1910 and never came back in.

KEYWORTH: You are addressing the question of precollege education, how we can entice more children into science and how we can attune them to the pleasures that we all have experienced in the profession of science.

We are going to have to do it a lot better than we are doing it right now. I speak not only from my present position, but because I have a 12-year-old and a 14-year-old, and I live in one of the highest income counties in America with a very well-funded school system. I will say that I a little disgusted with the quality of the education here.

It could be much better, and it should be much better, and we all know what the problem is. How would you like to be a secondary school teacher? How would you like to support a family on $17,000 or $18,000 and have all the other problems that are built into our teaching system?

The curricula have not kept up with the times. There are technologies that can help teach teachers to be more efficient. They have not been effectively implemented. Curricula have not been updated to reflect the fact that there have been enormous scientific takeoffs in many different areas.

Astronomy is one of the most exciting areas of science, and astronomy should serve as a major emphasis for both of the things you addressed, both education and enticement. There is nothing wrong with enticement; it is not conning. You are always trying to intrigue and excite a child's mind.

There are many other areas too. When I was 15 years old, I thought biology was about the dullest subject known to man, almost as dull as organic chemistry. I think neurophysiology is about the most exciting subject I know of today.

We have got to do the teaching job much better. In the academic world and in the university world we have got to help the entire precollege teaching process better. There are many people, but far too few, in the university environment who are seriously addressing this issue, who are willing to spend their own time to help develop means and curricula and help train teachers.

It is much easier for us to address how we can stimulate the field of astronomy. You support a space telescope and you support a VLBA, and you realize that is by far the easiest part of our job. Wrestling with precollege education is one of the most difficult and frustrating and patience-requiring actions required from the country today.

It all comes down to making parents think that educating their children is even more important than assuring that their retirement fund is adequate. It is the most important investment that there is for the future.

ROMAN: You have emphasized the importance of training graduate students, but obviously children don't grow into graduate students unless they have had a reasonable scientific background at the junior high level, if not before.

What is the administration doing to improve the teaching of science at the elementary and junior high level?

KEYWORTH: What we are trying to do is to make absolutely certain that the levers that we use are carefully chosen and appropriate levers. I really emphasize that, because it is so easy for us and for the Congress to say, well, there is clearly a lot of public concern in this--what we will do is throw half-a-billion dollars into the pot and we will put it on tree stumps. We will call these block grant programs, and the states can all come and take their share off the tree stumps.

But that is a coward's way of doing this. It is what you do when you don't know what to do and you are responding to political pressures.

What we have been doing for the last 2 years is trying to work with a very broad community of people to try to understand where we can put a lever. Let me give you an example of what I call a big lever that costs nothing, for all practical purposes.

There will be a program in the National Science Foundation next year where in each state in the union we will pick--the state will pick--a top math and science teacher whom they consider exemplary. Those individuals will come to Washington, they will meet, if it is not raining, in the Rose Garden with the President.

They will feel his genuine respect for their hero status, and he will present them with what to us would be a trivial check. But if you were a secondary school teacher and you suddenly were given $5000 with which to buy computers or anything else that you chose for your classroom, I think you would find it a very effective lever.

That program will cost a few million dollars, but I think it will be very effective. We also have a program to try to improve the quality of science and math teachers by supporting them actively and aggressively in organized course work, and I emphasize this, because it is somewhat different than paying them to go off to a colloquium.

We wish to subsidize them, or sponsor them, whatever, for a year, or a summer, or several summers. One important thing is that it is a joint federal government/industry supported program. It is not that we are trying to get industry to pick up the bills; it is because we believe that industrial support, involvement, is essential to doing these programs right and to their long-term stability. Industry is overwhelmingly in support on this.

Those are a couple of programs. There are several others we are implementing, and we are spending a lot of time thinking about it. We are trying to find out exactly where the levers are. Right now we are trying to answer for ourselves questions like how can a computer be used more effectively in the classroom than simply to improve a child's eye-hand coordination, and to satisfy the parents' requirement to have something that is better than the kid's playing Pac-Man.

The computer is a very powerful tool, and it gives us a very powerful potential capability. We also see coming down the road, for example, a time when it might very well be possible for a student to do his homework with the aid of graphics, but we have got to prepare for this.

The question of curriculum development arises not just because science has changed but also because the means have changed. It is something we worry about. It is a big problem. We want to do it thoughtfully, and we don't want to initiate programs that are politically motivated; we want programs that have such leverage and are so effective that they will grow under the pressure of their effectiveness.

ROGERS: It seems like we have got a little bit off the subject of the VLBA, but I would like to ask another question about education. I was not educated in this country as a high school student. I was in a class of about 40 students, and the quality of the teachers was excellent. I wonder what you think of the idea of much better pay for teachers, perhaps at the expense of increasing the size of the classes?

KEYWORTH: Well, if those were the alternatives I would thoroughly encourage it, quality versus quantity. However, why do we have to do that? Why should we pay a teacher a third of what a member of the Teamsters Union gets? We have got our priorities completely reversed. The nation can afford, it can afford easily, to support its teachers at a competitive level and to provide them with an absolute level of compensation that does not place them in the poverty bracket. I think it is absolutely disgraceful, and there is no excuse--we are not a poor nation. We are not forced to take the step that you specified. If we have to, then, yes, I would strongly recommend that; it is possible to teach 40 students effectively. But I think it is disgraceful to have to seriously discuss it. Look at the American gross national product compared to the GNPs of many other developing nations today, and look at their relative quality of life and their attention to students.

Let me give you an example of the sort of unfortunate philosophy into which we have fallen. It is only one example, and it suffers all the problems of an anecdotal demonstration, but several months ago we were in the process of carefully evaluating the student loan program. We had discovered that it is very expensive, and that it is possible for somebody in a near-infinite income bracket, under the proper circumstances, to get a federally subsidized loan. You can use those dollars more effectively, and we were doing that.

Shortly afterwards, somebody I know here in town--he may never speak to me again, but I have never mentioned him by name--came to me and he said that his son was going to have to drop out of Harvard because of the lowering of the threshold of qualifiability for the student loan program. But I remembered talking to him a couple of months before about the competitiveness of our automobile industry, at which point he had proudly told me that he had bought a new Mercedes 300TD, a $40,000 automobile. I said, "I do not mean to meddle in your personal affairs, but I know you have only two children and you are going to let your kid drop out of his third year at Harvard? And yet you don't mind spending $40,000 on an automobile?" He said, "Look, Jay, you are back in the dark ages. This is a period in our country when the people have decided we do not need to make sacrifices for education." I am not saying that attitude is common, but I consider that if it abounds there must be a lot of other trouble somewhere.

We have to do a lot to educate our parents on the nation's critical dependence upon the quality of our education. You are going to get those salaries up by getting people to agree that education is one of the highest, if not the highest, priority in their community investment. The federal government can't do it. We spend something on the order of $150 billion a year on precollege education. The federal government has never played anything but a very small role in that area, but we certainly can provide leadership and leverage, and we are trying to do that.

You know the President has been vociferous since the State of the Union Address--the last few weeks have been heavily defense-oriented--but in that intervening period the President was vociferous on the subject of tomorrow's talent and education, and he will continue to be so.

BURKE: Thank you, Jay. We really wish that you could be staying for the real science, which we are going to turn to now, but we greatly appreciate your taking the time to come down and share the larger picture with us.

I. The Proposed Very Long Baseline Array

4

THE VLBA: SCIENTIFIC, TECHNICAL, AND PLANNING OVERVIEW

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BACKGROUND

The independent oscillator-tape recording interferometer (very long baseline interferometer or VLBI) was initially developed to investigate the compact features found in radio galaxies and quasars (Bare et al. 1967, Broten et al. 1967). The technique was soon applied to the study of galactic hydroxyl (OH) maser sources (Moran et al. 1967), and it was quickly realized that VLBI was a powerful tool that could be used to study a wide variety of problems in galactic and extragalactic astronomy, including fundamental astrometry, terrestrial geodesy, and geophysics, as well as problems in fundamental physics (e.g., Gold 1967, Shapiro 1967, Cohen et al. 1968, Burke 1969).

It soon became apparent that a multielement radio telescope array with dimensions comparable to the size of the earth would be needed to study the complex structure found in compact radio sources (Swenson and Kellermann 1975). In 1974 a design group was appointed by the National Radio Astronomy Observatory (NRAO) director to investigate the feasibility of constructing a dedicated Very Long Baseline Array (VLBA) to complement and extend the Very Large Array (VLA) then being built on the plains of San Augustin in New Mexico. By 1977 it was clear that technology developed for the VLA and VLBI experiments was sufficient to construct a radio array of truly global dimensions, and the NRAO issued the results of this first design study, An Intercontinental Radio Telescope.

At that time, two practical problems remained, which would restrict the performance of the proposed array. First, prohibitive amounts of magnetic tape were required to obtain the very large bandwidths (50 to 100 MHz) to achieve a sensitivity comparable with directly linked radio arrays. Second, phase fluctuations in the independent oscillators or in the troposphere above each antenna caused large phase uncertainties in the data, which led to ambiguities and errors in the synthesized radio maps.

In 1980, a meeting was held at California Institute of Technology to further specify the system design and set performance specifications. In October 1980, Caltech issued the results of its design study, A Transcontinental Radio Telescope, and in February 1981

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the NRAO issued its second report, Design Study for the Very Long Baseline Array.

In October 1980, a group of some 70 scientists and engineers met for a 3-day intensive workshop in Green Bank to discuss the Caltech and NRAO studies, and to recommend choices between alternate plans where appropriate. Although the studies were meant in principle to be independent, many individuals, particularly from NRAO, Caltech, and MIT, actively participated in both studies, which differed primarily in the approach to management and operation of the VLBA.

At this time, two solutions to the problem of broadband tape recordings appeared feasible. One approach used a number of video cassette recorders (VCR) in parallel to obtain the necessary large bandwidth, at very low capital and construction costs made possible through the use of highly developed consumer technology. An alternative solution was based on writing very narrow tracks on commercial instrumentation recorders and moving the recording head slightly between tape passes to achieve a tenfold, twentyfold, or greater improvement in tape consumption.

Meanwhile, "self-calibration" or hybrid mapping schemes, which were developed in the UK and at MIT, Caltech, and the VLA, solved the problem of restoring the interferometer phase from apparently "phaseless" data. The extension of the full power of aperture synthesis techniques to global dimension became a realistic and well-understood goal, and in 1982 the Astronomy Survey Committee ("Field Committee") recommended the construction of a VLBA radio telescope as the highest priority for major new ground-based astronomical facilities.

In May 1982 the NRAO submitted to the National Science Foundation a proposal for the design, construction, and operation of the VLBA. This proposal, which was based on the earlier design studies, was the result of a 10-year effort to which more than 60 scientists and engineers throughout the country had contributed. In February 1983, memorandums of understanding were signed with Caltech and MIT to set the basis for continued collaboration of these groups in the design and development of the VLBA. Detailed engineering design and prototyping of individual subsystems are expected to continue through 1984, and construction of the VLBA is expected to begin in 1985. Partial operation will begin in 1987 when the first antennas are completed, and full operation will start in 1988.

PERFORMANCE SPECIFICATION AND SYSTEM DESIGN

The VLBA will contain 10 antenna elements spaced throughout the United States from Hawaii to Puerto Rico. The local oscillators at all stations will be synchronized by hydrogen maser frequency standards, and the intermediate frequency signal will be recorded on magnetic tape for later playback in a central processing facility. The two antennas nearest to the VLA will be connected in real time to the VLA Control Center via real-time microwave data links. All of the elements will be controlled and monitored in real time by a single array operator via leased telephone lines, and each antenna will normally be unattended except when it is necessary to change magnetic tapes.

The basic system specifications for the VLBA are outlined in Table 4-1. The wide geographic coverage of the array and maximum operating wavelength gives the best possible resolution from the surface of the earth consistent with current antenna and receiver technology as well as consideration of a reliable and cost-effective operation. The number of antenna elements allows about 80 percent of the amplitude and phase information to be obtained from self-calibration procedures and is sufficient to give good image quality (dynamic range) over a wide range of declination.

Antenna Elements

Twenty-five-meter diameter antennas were chosen, as antennas of this size with the desired accuracy can be readily fabricated with conventional techniques. Each element is designed for reliable low-maintenance operation with a shaped paraboloid reflecting surface to give a high efficiency. At frequencies above 1 GHz, operation will be from the Cassegrain focus, and an asymmetric secondary reflector will be rotated to illuminate the eight feed horns located at the Cassegrain focus. Prime focus feeds will be used at the two lowest frequencies. Dual-frequency operation can be provided with dichroic reflectors and is initially planned for the S/X wavelength bands commonly used for the NASA and NGS geodetic programs.

Radiometer Systems

Receivers for the two lowest frequencies will use relatively simple feed systems and ambient temperature GASFET amplifiers. In the six intermediate wavelength bands, GASFET amplifiers cooled to 20K will be used to give the best possible sensitivity consistent with reliable operation and economic construction. Maser amplifiers will be used at the two shortest wavelengths to give state-of-the-art sensitivity. Rapid change of the observing wavelength will be possible from the

TABLE 4-1 Design Specifications

Number of elements	10
Size of elements	25 m
Overall size	8000 km
Wavelength coverage (10 bands)	0.7 to 90 cm
Resolution	0.2 to 24 milliarc sec
Sensitivity	0.1 mJy
Polarization	Linear and circular
Spectral resolution	0.2 Hz to 50 kHz

Operations Center, allowing flexibility in observing programs as well as minimizing the impact of receiver failures or poor weather conditions.

The sensitivity and resolution in each of the 10 planned wavelength bands are shown in Table 4-2. The values given for noise fluctuations represent the noise in each picture element provided that there is a reference feature typically 10 times stronger visible on all baselines that is sufficiently strong to phase the array in a typical coherence time of 10 min. Such reference features are most conveniently used if they are within the primary beam of the antenna pattern; but phase referencing to nearby sources can also be used, and water vapor radiometers will be installed at each element to minimize the effect of variations of atmospheric water vapor content.

Intermediate Frequency and Recording System

The intermediate frequency system is being designed to accommodate up to 32 frequency channels each with a bandwidth selectable between 125 kHz and 16 MHz. The recording system will operate in a 2-bit or 4-bit mode at a normal rate of 100 Mbps (50-MHz bandwidth), and for limited periods at rates up to 200 Mbps (100-MHz bandwidth) or more for high-sensitivity continuum observations, or at lower rates as appropriate for narrow-band spectral line observations. The system is expected to be transparent to the specific recording medium, to allow for improvement in this rapidly developing area with a minimum of system retrofits, and to keep, where appropriate, compatibility with older VLBI recording systems that are in present use.

TABLE 4-2 VLBA: Sensitivity and Resolution

Frequency (GHz)	Receiver	System Temperature (degrees Kelvin)	Root Mean Square Noise (mJy for an 8-h integration)	Resolution (milliarc sec)
0.32	FET	65	0.16	24
0.61	FET	55	0.1	13
1.4/1.7	FET	29	0.035	5
2.3	FET	31	0.035	3.5
5	FET	37	0.04	1.6
8.4	FET	40	0.05	0.9
10.7	FET	45	0.05	0.7
15	FET	65	0.06	0.5
22	MASER	45	0.06	0.35
43	MASER	75	0.16	0.2

The recording system at each station will normally use either a bank of video cassette recorders, each writing at a 12.5-Mbps data rate, or several Mark III-type instrumentation recorders modified to permit 20 or more passes on each tape. Unattended operation of each station for at least 24 h is planned.

Processor System

The correlator system will be able to handle the input from at least 14 antenna elements in the normal continuum mode, including full polarization processing. In the spectroscopic mode, up to 2048 frequency channels will be available from frequency resolution down to 62 Hz.

FUTURE EXPANSION

Like all arrays, the VLBA can be expanded to improve the sensitivity, resolution, and dynamic range. The addition of three additional elements at appropriate sites in New Mexico will fill in the intermediate size scales between the VLA and VLBA, while the addition of a single element in South America will greatly improve the resolution in the north-south direction. The future placement of a large antenna in earth orbit will greatly extend the power of the VLBA.

On more immediate time scales, the use of other large radio telescopes such as the VLA, Arecibo, and Bonn 100 meter will be used together with the VLA, as will the dedicated VLBI antennas being constructed in Italy and planned in Canada.

OPERATION

Normally, each antenna element will run entirely under control from an Operations Center. A few technician/operators will be available at each site, however, for inspection, routine maintenance, and the simpler unscheduled repairs of malfunctioning equipment. The local staff will also be responsible for updating operating systems at the local control computer, for changing and shipping the data tapes to the Operations Center, for security and precautionary oversight, for emergency intervention, and for routine start-up and shutdown procedures.

The Operations Center will provide for major maintenance and repair requiring personnel with special skills, special equipment, or major replacement parts. However, since the plan is to replace complete modules in the case of failure, many such replacements can be easily performed by the local site personnel. Defective modules will be returned to the Operations Center for repair. This procedure, while requiring a somewhat larger than normal inventory of spare parts, will reduce travel and personnel costs.

The VLBA will be operated under a preplanned program under the control of a central computer, which will simultaneously monitor the performance of the antennas and receivers as well as the meteorological conditions at each site. An array control operator will be present at all times at the Operations Center to intervene when necessary and to carry out various housekeeping tasks. From time to time, brief samples of the received signal at each antenna will be sent to the Operations Center via the telephone lines and correlated in nearly real time to check that all components of the VLBA are functioning properly and to monitor meteorological effects on the data.

The VLBA will be operated by the NRAO as a national facility available to all qualified scientists. As with other NRAO facilities, observing time will be based on scientific merit without regard to institutional affiliation.

REFERENCES

Bare, C., et al. 1967, Science, 157, 189.
Broten, N.W., et al. 1967, Science, 156, 1593.
Burke, B. 1969, Physics Today, 22, 54.
Cohen, M.H., et al. 1968, Science, 162, 88.
Gold, T. 1967, Science, 157, 302.
Moran, J., et al. 1967, Science, 157, 676.
Shapiro, I., 1967, Science, 157, 806.
Swenson, G., and K.I. Kellermann, 1975, Science 188, 1263.

DISCUSSION

BURKE: Let me begin the discussion by asking about the administrative management of the project at the present time.

KELLERMANN: The VLBA will be built and operated by the NRAO as a national facility, open to all qualified users. Many people in the university community have been involved for some years in specifying the requirements and the conceptual design. At present, there are about eight working groups engaged in various aspects of design. Some 60 of those serving represent universities, especially Caltech and MIT. Many people in this workshop audience are involved. Work has been in progress for 2 or 3 years and will continue.

Audience participant: What would be the incremental cost--over the present design--of making the dishes reasonably efficient at 3 mm?

KELLERMANN: The dishes as designed at 4 mm will have about the same effective collecting area as an ideally designed 10-m antenna. Surface panels, of about 0.2 mm, appear to be the limit that can be built with reasonably conventional techniques. The cost rises rapidly, to about $2.5 million per antenna if we want better panels.

5

SPECTRAL LINE STUDIES WITH A VLBA

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Long before the 1960s it was clear that many classes of astronomical objects had angular sizes much less than 1 arc sec. Further, it was recognized that some of the most fascinating astrophysical phenomena could only be explored with much higher angular resolution than was currently available. In response to this challenge, radio astronomers in Canada and the United States developed a technique call very long baseline interferometry, or VLBI for short, which increased angular resolution available to astronomers by nearly a thousandfold. Currently, astronomers are producing images of radio sources with an angular resolution of 0.0003 arc sec. Were the human eye to have this power, one could read these words from a distance of about 3000 miles. This paper will describe some current spectral line studies of galactic sources with VLBI techniques, and will close with a summary of improvements possible with the advent of the Very Long Baseline Array (VLBA) later in the decade.

If one examines an optical image of a spiral galaxy much like what our own Milky Way looks like, one will find many bright knots of emission. These knots are regions of recent star formation. Specifically, these are sites where stars 10 or more times as massive as the sun have recently formed, emitted copious ultraviolet photons, and ionized their placental environment. Near the brightest and most compact of these ionized regions (called H II regions) one commonly finds intense emission from molecules such as water (H_2O) and hydroxyl (OH). When radio astronomers first detected this molecular emission, they were quite puzzled by its spectral characteristics--high polarization, nonequilibrium line strengths, and very narrow line widths. The first VLBI experiments on these sources demonstrated that the radiation had the equivalent temperature of a 10^{11}K black body. This was far too high for thermal emission and implied that a coherent process--maser amplification--was involved.

Recent VLBI observations of OH masers have been very successful in mapping the emission. One advantage that spectral line observations have over continuum observations is that one can spectrally isolate a maser feature and use it as a calibration source. This allows the VLB interferometer to be phase-calibrated and full aperture synthesis maps to be constructed. VLBI synthesis maps have now been made for two OH maser sources, W3(OH) and W75N. These studies have significantly

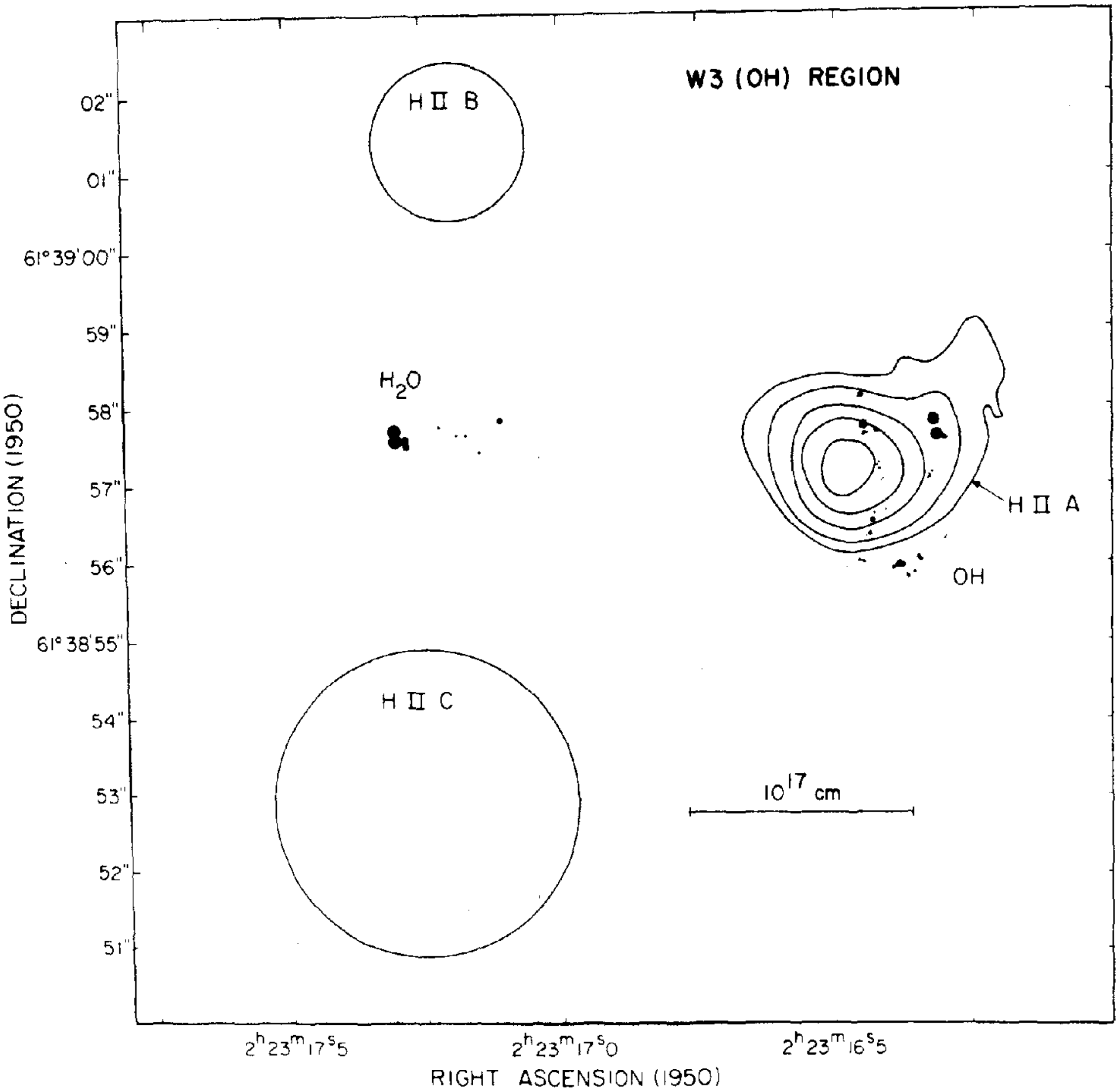

FIGURE 5-1 The region of W3(OH). The contours labeled H II A are 6-cm continuum emission. The OH maser spots measured are shown projected against H II A. The other H II regions are substantially weaker than H II A. The H_2O masers were measured in February 1977. The absolute position of the H_2O masers is accurate to ±0.5 arc sec. The linear scale is based on a distance of 2.2 kpc. (From Reid et al. (1980), Astrophys. J. 239:89.)

improved our understanding of maser characteristics and of the physical conditions surrounding newly formed O-stars.

We will now discuss the best-studied hydroxyl source, W3(OH), in some detail. Figure 5-1 shows the locations of some 70 OH maser spots relative to the contours of continuum emission at 6-cm wavelength from the compact H II region. This map shows that the OH masers congregate in clusters that are about 100 AU in diameter. These clusters contain

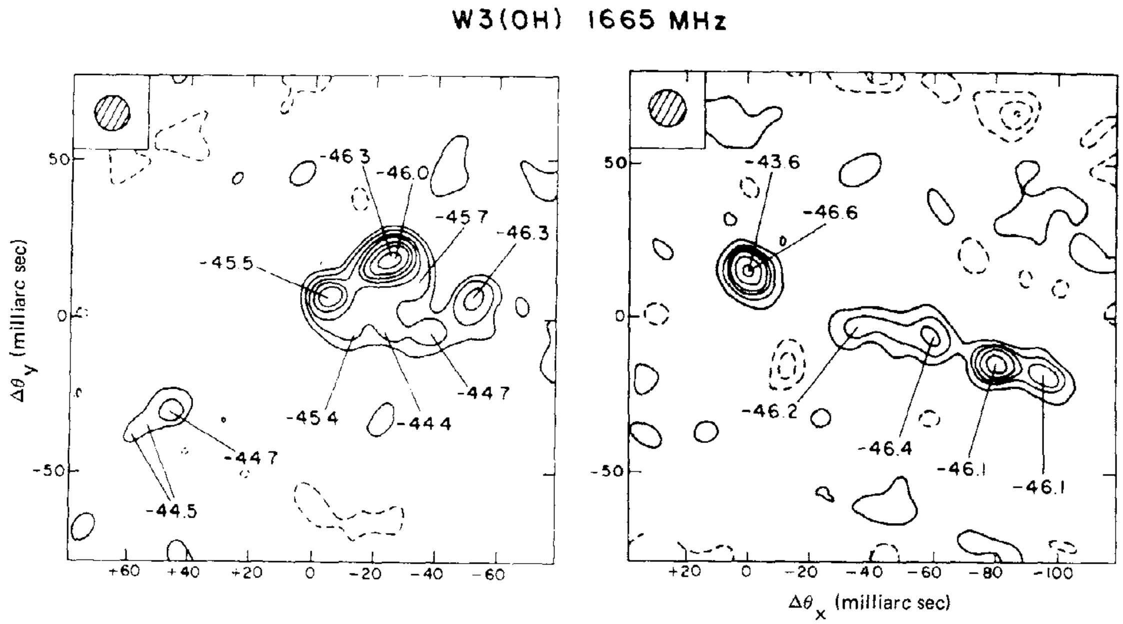

FIGURE 5-2 Integrated velocity maps of small regions of OH maser emissions within W3(OH). The contour plots are labeled with the location and LSR velocity of each component. Contour levels are 10, 20, 30, 40, 60, and 80 percent of the peak brightness in each map. The restoring beam used in the CLEAN process is given in the upper left corner of each map. (From Reid et al. (1980) Astrophys. J. 239:89.)

a mass roughly equal to that of Jupiter. What one "sees" when observing interstellar masers is therefore the ends of gigantic cosmic amplifiers roughly the size of our solar system.

In Figure 5-2 we present a view of two of these clusters at about 100 times magnification of Figure 5-1. The OH emission is presented as a contour map of intensity, with the Doppler velocities of individual components indicated by the numbers (in kilometers per second with respect to the local standard of rest). Since spectral observations have frequency as well as spatial information, one can display the four-dimensional information (intensity, frequency, and position on the plane of the sky) using color to represent frequency similar to the eye's perception of visible light. When this is done, one creates a radio photograph equivalent to what the eye would see were it (1) sensitive to radio waves, (2) the size of the United States, and (3) capable of spectral resolution of one part in one million.

In one of the fields presented in Figure 5-2 there are two maser components that fall precisely on top of each other but appear to have Doppler velocities of -43.6 and -46.6 km/s. These features are oppositely circularly polarized and are the result of Zeeman splitting of the hydroxyl line caused by the presence of a magnetic field. In W3(OH), nearly half of the frequency spread in the spectrum is due to Zeeman splitting and therefore is not kinematic. The magnetic field strength determined from the Zeeman splitting is about 5 mG.

After proper account is taken of the apparent velocity shifts due to Zeeman splitting, one finds that almost all clusters of OH masers have the same center-of-mass velocity. This velocity is red-shifted by about 6 km/s with respect to the velocity of the central star as measured by (radio frequency) hydrogen recombination lines that are observed from the H II region. Since the H II region is optically thick in the continuum at the low frequency of the OH transition (1.6 GHz), the masers must be in front of the H II region. The locations and velocities of the OH masers relative to the H II region therefore indicate unambiguously that the maser clusters are falling inward toward the central star. Thus we are sampling the remnant material out of which the newly formed star accreted.

We are fortunate when studying maser emission that the OH molecule has other observable transitions. One important transition occurs at a frequency of 6 GHz. Although very few telescopes have receivers capable of reaching this transition, some primitive VLBI observations of W3(OH) involving three stations have shown that one sees very clear Zeeman patterns across the entire spectrum. With full polarization observations of this OH maser emission (i.e., with a determination of the circular and linear polarization characteristics), one can determine the full three-dimensional magnetic field for many masing clusters. Such information is crucial for the understanding of star formation. In W3(OH), for example, the thermal pressure inside the H II regions is roughly equal to the ram pressure of the infalling neutral gas and also equal to the magnetic pressure in the region. This demonstrates that all of these forces play an important role in the collapse of interstellar material to form stars.

The strongest molecular maser sources are water vapor masers. Some water masers are particularly spectacular. Recently, one of the water maser spots in the Orion region flared up by many orders of magnitude over a period of months. It reached a peak flux density of more than one million Janskys (Jy). Intense water masers like this one can emit a large fraction of the entire luminosity of the sun in a single narrow line only 50 kHz wide. Translated to earthly terms, such a source has a spectrum similar to that of a radio station, except that it broadcasts nearly 10^{20} MW.

Water masers can be found in regions of star formation, but appear to be associated with earlier phases of stellar evolution than are OH masers. As for the OH masers, water masers form in groups of sometimes hundreds of spots. Each spot is about 1 AU in diameter and has a distinct Doppler velocity and position on the sky. The water masers in the Orion nebula have been studied in some detail with observations at several epochs. Such observations allow one to measure motions of individual maser spots on the plane of the sky (relative to one "reference" spot). The spots have been observed to move linearly with time for distances that are many times their diameters. The most direct interpretation of these observations therefore is simple force-free kinematic motion.

In Figure 5-3 we show the speed and direction of the motion of some of the water maser spots in the Orion region. The motions clearly indicate expansion from a central position near the Kleinmann-Low (KL

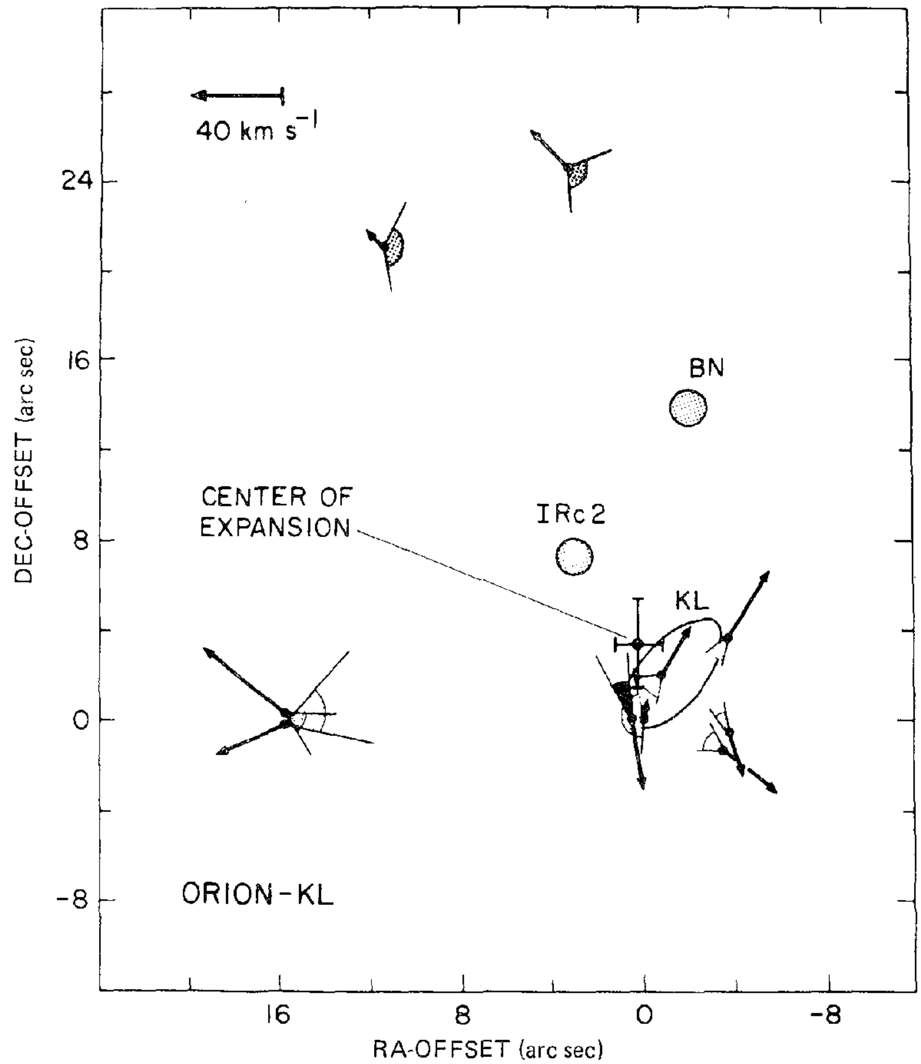

FIGURE 5-3 Two-dimensional proper motions and the center of expansion in Orion-KL. Shown are all proper motion vectors (for the cases with declination-motions) with length proportional to their transverse velocity, and error bars (1 σ) indicated by error cones (stippled). The best estimate for the center of the 18 km/s flow from the model is shown with 1-σ error bars (position: $05^h\ 32^m\ 46.8s \pm 0.1s$, $-05°24'27" \pm 2"$ (1950)). For comparison, positions of some of the infrared features in Orion-KL also are indicated (stippled regions). BN is the Becklin-Neugebauer object, KL is the core of the extended 20 μm Kleinmann-Low Nebula. The compact infrared source IRc2 is the location of the SiO maser in Orion. All velocity vectors are relative to the center of expansion; that is, they have been corrected for the motion of the reference feature from the model parameters. (From Genzel et al. (1981), Astrophys. J. 244:884.)

in figure) infrared nebula. Both contraction and rotation can be ruled out, unambiguously, from such observations. These observations, coupled with recent infrared observations, indicate that a hitherto undistinguished infrared source, IRc2, is a massive star with a luminosity of about 10^5 solar luminosities and hence is the primary energy source in the region. IRc2 has an impressive outflow of mass, roughly one billion times as powerful as the solar wind. Observations of water masers may be one of the best ways to study winds associated with forming stars.

We now turn to another water maser source, W51, which lies halfway across the Milky Way. The water masers in this region have been mapped and motions observed. In contrast to the Orion source, no organized motion, such as expansion, is found. Instead, the motions of the water maser spots appear to be random. This suggests that the mass outflows in this region are interacting strongly with their surrounding molecular cloud, resulting in a turbulent interface.

One can use the statistical properties of this apparently random motion to determine distances to the star-forming regions by the classical technique called "statistical parallax" by optical astronomers. Briefly, this technique works as follows: one obtains radial velocities (e.g., in kilometers per second) from Doppler shifts directly from the source spectrum. One measures angular motions on the plane of the sky (e.g., in arc seconds per year). In order to convert angular motions to linear velocities, one must multiply by the (unknown) distance to the source. Therefore, provided the motions are random, the dispersion of radial velocities will be equal to the dispersion of angular motions scaled by the distance, and measurement of the dispersions yields the distance.

The statistical parallax for W51 indicates a distance of 7.0+/-1.5 kpc, a distance about 20 times greater than directly measurable with optical techniques. A procedure, similar in principle to statistical parallax, can be applied to the Orion water maser motion data to determine its distance. This involves modeling the expanding flow and solving for a distance parameter by least-squares techniques. It yields a distance of 480+/-80 pc, which is in agreement with optical estimates, which range from 400 to 500 pc. Given a sufficiently large sample of maser spots, the distance to water maser sources can be determined with an accuracy of typically 10 to 20 percent anywhere across the galaxy.

Water masers have been detected in nearby spiral galaxies. Future observations with very sensitive arrays should be able to map their motions also. At a distance of 1 Mpc, water maser spots with relative motion of 30 km/s would have angular motions of about 5 microarc sec/yr. Since one degree of interferometer phase on an intercontinental interferometer operating at a 1-cm wavelength corresponds to 1 microarc sec in angle, such measurements appear possible. Certainly, a direct measurement of a distance to another galaxy would be exceedingly important to our understanding of the size and age of the universe.

Turning to the future, we eagerly await the construction of the VLBA. As outlined in the Field Committee report (Astronomy Survey Committee of the National Research Council, 1982), a large array of radio telescopes spanning the United States from Hawaii to New England would dramatically improve our VLBI capabilities. In particular, the VLBA would roughly double the number of telescopes currently used for VLBI in the United States. The VLBA telescopes would reach a wavelength as short as 7 mm, which represents a factor of about 5 improvement over present telescopes. This is particularly important for spectral line studies because of the strong maser lines of water (at 1.3-cm wavelength) and silicon monoxide (SiO at 7 mm). The VLBA would have baselines up to 8000 km, nearly 3 times longer than those currently in the United States. Equally important, the VLBA would have good coverage for baselines of 200 km (and hopefully even shorter), which is about 3 times shorter than for the present telescopes. This would open up many new areas of galactic study, such as the study of Red Giant stars, which also have intense maser emission from their circumstellar envelopes.

One important improvement that the VLBA would have for spectral line studies is in the area of cross-correlation processors. The VLBA processor would be about 50 times more powerful than existing spectral line processors. It will be designed for spectral line work with full polarization capabilities and high spectral resolution. In addition, by sampling the data at four levels (instead of two levels currently used) and at a higher rate, the VLBA will achieve an additional sensitivity increase of about 30 percent.

Combining all of the improvements cited above, the VLBA should revolutionize spectral line observations. We look forward with great anticipation to studying the many new objects available to the new instrument. With the array we should be able to observe both ends of the star formation cycle: from the forming of the stars out of the interstellar material to their evolving into red giants, which largely resupply the interstellar medium via stellar mass loss. We can anticipate the study of both luminous masers and "dark" absorbing hydrogen gas, and the determination of the three-dimensional magnetic field vectors and the three-dimensional motions of gas from many classes of objects. And, finally, of course, we look forward to the great variety of unknown objects and phenomena of the future.

DISCUSSION

ROMAN: The slide indicates that the tenth antenna is in Europe. To what extent can the VLBA work with antennas on other continents, either Europe or Australia?

REID: That is actually the eleventh antenna and is shown on the slide to indicate that the array could be used effectively with some of the powerful telescopes in Europe or with those that will exist elsewhere in the future. Much thought has gone into developing at least the processing capacity to handle 14 or more telescopes in the array at essentially little additional cost. Adding a telescope in Europe or Japan--maybe China--would be a powerful addition to this sort of array.

WEILER: I am interested in your statistical parallax methods. Because you are looking at very highly beamed and nonisotropic sources, how do you determine selection effect?

REID: It is difficult to explain beaming. The emission is very intense because it is beamed. Most people think that one sees emission essentially beamed at you, but from all sides, so that if you walked about the source you would see emission from almost all angles. You might not see the exact same spot, but presumably you would see another spot. Let's put it this way. The full source is not aimed at us.

We studied the possibility of systematic errors if one had an only partial distribution of the histograms I showed, and, indeed, that is probably the limiting error at the moment in our understanding of the distances to these sources, because we have only two sources so far that we have looked at.

Let me go to the slide and show you. With this source (W51) we had a case where we were getting a somewhat biased distribution at the time we did the experiment. We know from other studies of molecules and of hydrogen recombination lines that the radial velocity in this region is about where that arrow is (56 km/s). We have a mostly one-sided radial velocity distribution here, which isn't true at all times in this source. When we looked at it a couple of years earlier, we found a lot of features that we just weren't able to map in this study. We assumed that this was the correct center of emission for the radial distribution and calculated the standard deviation based on that. Had we assumed it was in the center, it would have changed the distance by about 10 percent. When we quoted errors of about 15 percent we were limited to about 10 percent by systematic error and to a similar percent by random fluctuations, and we added them in quadrature. However, all indications are that if one looks at these sources, at least over a reasonable time span, one sees essentially an unbiased distribution from the stars.

Audience participant: Can you do this with SiO masers, or are they not complex enough?

REID: No one has tried, because we don't have the array capabilities--short enough baselines--to do a good job on SiO masers. The same could be said of hydroxyl masers that appear to be undergoing contraction around these newly forming stars. There is the hope of measuring the inflow, and if one can measure not only the radial inflow but the motion along points that are not in the radial direction, one could determine distances that way. With hydroxyl masers we have a longer wavelength and lower angular resolution, so a longer time baseline is needed. It is available, because those masers continue for a longer time.

Audience participant: Can't you use the excited state and overcome some of those problems?

REID: Yes, an excited OH transition at higher frequencies would give higher resolution, but little work has been done on it, primarily because large numbers of antennas do not have good 6-GHz receivers.

BURKE: Do you need more receivers, or are the present frequencies sufficient?

REID: I would like to see the 6-GHz, excited OH transition included in the array. That possibility has been discussed for a couple of years; that is, whether we really need that frequency receiver since we have a 5-GHz receiver, of which there are 27 at the VLA site.

BURKE: Could we have a response to that comment from Dr. Kellermann?

KELLERMANN: A 6-GHz receiver is planned.

Audience participant: From the point of view of the spectral line requirements, how much total bandwidth do you want to be able to analyze, regardless of how it is broken up into smaller bands?

REID: How much bandwidth and the numbers of channels needed to get adequate spectral resolution in the array is a complicated question. We have tried to address it by looking at various case studies. For the higher frequencies, where you get less velocity for a given bandwidth, we would like bandwidths in the tens of megahertz, especially for the water transitions, which cover several hundred kilometers per second in Doppler shift. We worked it out fairly carefully. If we would get about 1000 spectral channels per baseline, that is a fairly good number for almost all studies. At the OH transition we don't need that much bandwidth, since we are down to well below 1 MHz. There we need extremely high spectral resolution, since these maser lines are quite narrow. Again, about the same numbers of channels are needed, especially if one does polarization work where the spectral channels are divided into four groups for each of the four correlations. So we need bandwidths from below 1 MHz up to low tens of megahertz.

Audience participant: There is a Canadian proposal for a very long baseline array. If we assume that eventually it is funded, what would those antennas add in value to this particular array in the applications that are proposed?

REID: For spectral line application we need a short base line to open up the evolved-star studies. So, if, say, 10 U.S. stations were designed in such a way that they could be complemented by 4 Canadian stations, the result would be an array with short spacings, and that would be exceedingly valuable to spectral line applications.

BURKE: I think we should return to the subject of the Canadian interface tomorrow morning, when Alan Rogers summarizes current status and future plans. That would be an excellent time to discuss how the Canadian plans might fit in.

ROGERS: You mentioned studies of emission sources covering two wavelengths, which fortunately we are planning to incorporate. I wonder about other frequencies--I know there aren't any other masers discovered--but other frequencies and absorption studies. Are there any special requirements that you can think of that would require very good instrumental performance? I am thinking particularly of certain kinds of absorbing studies of strong HI sources. Do you see any application for them?

REID: Yes, I do. I don't see any problems in the characteristics of the VLBA, as planned, that would hinder that. The level of sampling would have a bearing on this kind of application. I might also mention the need for a 21-cm hydrogen line, which has not been fruitfully explored with present arrays, and for the 43-GHz silicon monoxide line, which is one of the very important lines in the evolved stars that we would like to see with shorter baselines.

6

ASTROPHYSICAL OBJECTIVES

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ABSTRACT

The Very Long Baseline Array (VLBA) will combine high angular resolution, high sensitivity, and wide frequency coverage with full-time availability. This will make it extremely powerful for astrophysical studies. At first the main objects of study will probably be quasars and active galactic nuclei, but the increased sensitivity will provide a good opportunity for the study of gravitational lenses, binary stars, galactic jets, pulsars, the galactic center, and other weak objects. Thus, it is impossible to predict what the main efforts on the array will be 10 years hence.

A major advantage of the array over present Very Long Baseline Interferometry (VLBI) systems will be its excellent geographical coverage. The array will provide maps with much higher dynamic range, so that we will see in good detail the structure of the jets and hot clouds and the magnetic fields. This is important if we are to understand the physics in these objects.

Quasars and active galactic nuclei contain an extraordinarily powerful but unknown engine. Many people speculate that a spinning black hole provides the energy and also the alignment axis for the commonly seen jets. Studies with present VLBI systems have already revealed apparent "superluminal" effects. Evidence from X-ray emission and radio variability are powerfully suggestive of bulk relativistic motion. This is very intriguing because there is nothing like this on earth and even, as far as we know, in the entire Milky Way. Since these objects are variable, they need to be studied repeatedly, over a long period of time. With present VLBI systems we have been able to find eight "superluminal" sources, and only three of them have even minimal coverage. This is wholly inadequate for detailed studies, and it is hoped that this situation will be rectified by the array. If good coverage can be obtained on several dozen of these objects, then we should be able to understand their statistical behavior and their inner workings, and perhaps even derive an independent value for the Hubble constant, which describes the size of the universe.

Studies at the Very Large Array (VLA) have shown how increased resolution and sensitivity have opened up new areas of research. Some examples include extragalactic jets, "radio-quiet" quasars, and

planetary rings. The increased power of the VLBA will similarly allow the exploitation of new areas of astrophysics. For example, cosmic gravitational lenses may be fairly common, but so far only two are known because they are weak. The array may make it possible to study many of these lenses and thus to have an independent method of arriving at the masses of galaxies and clusters of galaxies. This bears directly on the "missing-mass" problem--one of the fundamental problems in astrophysics today.

II. Geodesy

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7

GEOPHYSICAL REASONS FOR MONITORING CONTEMPORARY PLATE MOTIONS AND THE EARTH'S ROTATION

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ABSTRACT

Brief descriptions are given of a number of types of scientific information that can be expected from studies of present tectonic plate motions, distortions in seismic zones, polar motion, and changes in the earth's rotation rate. Contributions that could be made by the Very Long Baseline Array (VLBA) through intensive observations after large earthquakes and through regular monitoring during calibration periods are emphasized.

The basic picture of plate tectonics is well known. Essentially, rigid plates are assumed to move at uniform rates over long periods. Where plates run into each other, one plate usually is subducted, so that it goes down beneath the other into the upper mantle. Stick-slip motions often occur at the boundaries between plates, with stress and strain accumulating for periods of perhaps a century before a large earthquake occurs. Irregular motion due to the buildup and release of stress associated with earthquakes is normally assumed to be much reduced at distances of more than a few hundred kilometers from the boundaries.

The NASA Crustal Dynamics Project and similar projects in other countries have as one of their three main objectives a thorough check on worldwide plate tectonic motions. A necessary initial step is careful measurement of the stability of the major plates. How much internal deformation is occurring must be known before we can interpret changes in the distance between two points in the interiors of different plates.

To me, the most impressive result so far from the Crustal Dynamics Project is the consistency of the length for the Haystack-Owens Valley baseline measured by very long baseline interferometry (VLBI) over a 5-year period with root-mean-square deviations of about 3 cm and no evidence so far for a secular change. This baseline from Massachusetts to east of the Sierras in California crosses many geological regions, including particularly the Basin and Range Province, which lies west of the Colorado Plateau. Previous estimates of the rate of extension

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across the Basin and Range Province were between a few millimeters per year and 2 cm/yr, but these were long-term average estimates based on the geological record. Actual distortions can be quite episodic. It is difficult at present to establish confidence intervals for the absence of length changes on the Haystack-Owens Valley baseline because planned improvements in the measurement techniques to reduce known systematic error sources are still being made. However, it would be surprising if the actual rate of extension were as large as the upper end of the suggested range of values.

Since the extension across the Basin and Range Province is the largest expected in the interior of the North American Plate, the prospects appear to be good for at least a major part of the plate to be quite stable. Whether this will be true for the Pacific Plate remains to be seen, since the Pacific Plate is substantially thinner and moves considerably more rapidly. It also will be important to determine whether significant distortion is occurring for the Indo-Australian Plate, which is undergoing a strong collision with the Eurasian Plate.

As the stabilities of the interiors of some of the other plates are checked, it will become possible to determine the present relative motions of a number of the major plates. The long-term average rates over roughly 3 million years are believed to be known from global plate motion studies with an accuracy of about 1 cm/yr, but the question of interest is whether the rates can be variable over considerably shorter time scales. This clearly depends on the forces that drive and retard the plate motions, which are not yet well understood. For the Pacific Plate as an example, the largest forces are estimated to be the following: the downward force on the subducting slab at the front of the plate, because it is cooler and denser than the surrounding material; the resistance of the upper mantle to having the subducting slab thrust down into it; and the gravitational force on the rear part of the plate, which causes it to slide down off the East Pacific Rise. The first two forces nearly balance each other, and may provide a velocity-regulating mechanism for the motion of the downgoing slab. The gravitational sliding force may be the main force causing the rest of the plate to keep up with the subducting slab.

If the above picture is roughly correct, it is hard to see why the main velocity-determining forces would change much in less than a few million years. The height of the East Pacific Rise could vary in principle, but there does not seem to be evidence for large changes in short periods. The most time-variable forces are likely to be those due to stress buildup and release in the fault zones at the boundary where major earthquakes occur. The fault plane force resisting the plate motion is believed to be a lot smaller than the resistance to the downgoing slab, but still the dominant force for producing transient effects. The main question thus seems to be whether the relatively low viscosity asthenosphere that underlies the plates will damp out the variations in the resistive force within a few hundred kilometers of the boundary. Calculations say that it will, if we take the usual range of values for the asthenospheric viscosity based mainly on postglacial rebound in Canada and Fennoscandia. In that case, present plate motion rates would equal the long-term average ones. However, it seems quite possible that there will be surprises. For example, the asthenospheric viscosity values come from rebound measurements in continental areas, and the viscosity could be lower under a rapidly moving oceanic plate.

In addition to determining present tectonic plate motion rates, VLBI is expected to contribute strongly to studies of the major seismic zones. One important question concerns the long-term strain accumulation patterns, which can provide constraints on the elastic properties of plates at their boundaries. In the regions surrounding the San Andreas Fault system in California, regular measurements are made about once a year over networks of about 1000 baselines by using modulated laser distance measuring devices. The line lengths are typically 10 to 30 km, and aircraft are flown along the lines to determine the atmospheric correction to the distance measurements, so that an accuracy of about 3 parts in 107 is achieved. VLBI measurements with high-mobility stations are being used to determine somewhat longer baselines throughout the seismic zones and in nearby areas in order to provide new information on the longer wavelength part of the strain accumulation pattern. Typical baseline lengths are 100 to 500 km, and the expected accuracy over the longer distances is considerably higher than can be achieved by present ground measurement techniques. The measurement time necessary per site currently is one day.

In addition to monitoring the long-term strain accumulation pattern, it is of major importance to determine whether acceleration of the strain rate occurs locally shortly before a large earthquake. If variations are to be observed as frequently as every 2 weeks or so at points every 10 or 20 km along the major faults, the number of measurements required per year is large. They probably would be done using radio signals from the Global Positioning System (GPS) satellites or some other approach, but would be tied to reference points within a few hundred kilometers of the seismic zones that are located at fixed VLBI and satellite laser ranging stations.

Of comparable importance is the monitoring of postseismic strain changes after a large earthquake. A combination of accelerated creep on fault segments adjacent to the area of the fault break or below it and viscoelastic relaxation in the asthenosphere can cause rapid surface strain changes during the first few days and weeks. Observations of these changes would be of high value in understanding the structure of the fault region. Mobile VLBI stations would be moved into the area as rapidly as possible to provide an accurate reference framework for intensive measurements using GPS satellite signals and other techniques.

Another active area of geophysical research where VLBI plays a major role is the study of polar motion and variations in the earth's rotation. Polar motion corresponds to motion of the z axis of an essentially crust-fixed reference system with respect to the axis of rotation. The main features observed are a 14-month-period free precession of the solid earth with respect to the rotation axis plus quasi-annual and semiannual motions due mainly to seasonal mass displacements.

At present, we do not understand either the excitation or the damping of the 14-month-period motion, which is called the Chandler wobble. The main known sources of excitation are changes in the inertial tensor for the earth due to very large earthquakes and meteorological effects. However, neither of these separately appears to account for more than perhaps 25 percent of the excitation. Damping is difficult to measure because of uncertainty about when excitation is occurring and the large observational noise in previous observations. The change in polar motion after a great earthquake will be observable by VLBI measurements, and the much lower noise level should help in understanding the damping mechanism.

One of the important scientific reasons for wanting to investigate polar motion is the possibility of finding out about large fault displacements, which may precede or follow major earthquakes. If such displacements occur rapidly enough that they can be separated from other sources of Chandler wobble excitation, then we may be able to determine how much extra motion occurs. Occasional large aseismic motions not associated with earthquakes at all also may be detectable by this means, and be difficult to observe in any other way.

Changes in the earth's rotation rate with periods of as little as 2 weeks have been detected by VLBI measurements. Such changes correlate well with variations in the zonal angular momentum of the atmosphere, as determined by worldwide meteorological data. One scientific objective of improved rotation measurements is to find out whether the correlation remains good at considerably shorter periods. How much of the transfer of angular momentum from the atmosphere to the solid parts of the earth is due to surface shear stress on the oceans versus shear stress on land or winds blowing across the mountain ranges is not yet well understood. The transfer to the oceans would lead to some delay in the angular momentum showing up in the rotation of the crust and mantle.

The VLBA could make major contributions to obtaining some of the important types of geodynamics information discussed above, without a large loss of observing time for astronomy and other applications. One valuable contribution would be to make considerable observing time available for some period after very large earthquakes, so that the chances of accurately measuring changes in polar motion would be enhanced. Improved information on the earth's rotation during such periods also would help in providing a better reference system for measurements of postseismic displacements near the fault zone by high-mobility VLBI stations. Such VLBA observations would be particularly valuable in the case of very large earthquakes in North America, where the fixed stations would be working directly with the high-mobility stations.

Another valuable way in which the VLBA could contribute to geodynamics is through routine observations during calibration periods. If the quantity of data obtained and the observing program are adequate, such data would aid in increasing the accuracy of polar motion and earth rotation information, and in improving the time resolution. In addition, if a station in Alaska should be included in the array, the improvement in the time resolution for checking on the stability of the location for this station compared with what would be done under other programs probably would be significant.

From the viewpoint of geophysical applications of the VLBA, station locations in Alaska, Hawaii, and California would be particularly valuable. Although other factors may favor Puerto Rico over Alaska, and the Caribbean area also is of major interest for geodynamic studies, the plate tectonic motions involved are considerably slower than those occurring along the coast of Alaska and the Aleutians. Thus an Alaskan station probably would have more chance to contribute as a local reference station to postseismic measurements, which could provide considerably increased understanding of the mechanical properties of subduction zones. In addition, stations in Alaska and Hawaii would provide valuable connections to VLBI observations in Japan. If observations from a VLBI station in Japan could be resumed soon after a very large plate boundary decoupling earthquake there, it might be possible to watch the postseismic transient displacement of a substantial part of the boundary of the Eurasian Plate with respect to Alaska and Hawaii. Excellent geodetic networks exist for detecting postseismic distortions within Japan, but relating the displacements accurately to more distant reference points would be quite valuable.

It should be mentioned that accurate laser range measurements from both fixed and mobile stations to the Laser Geodynamics Satellite (LAGEOS) also are expected to contribute to a number of the scientific questions discussed above. However, this technique is the only other one besides VLBI that is likely to contribute strongly to observations over distances considerably larger than the widths of seismic zones. It is expected that comparisons of the results from the two methods, which have quite different error sources, will help very much in determining the accuracy that is achieved.

DISCUSSION

CANNON: I would like to comment on the question of polar motion excitation and earthquakes. What has to occur to change the pole path is a change in the inertial tensor of the earth, which is affected by second-degree components of the displacement field of an earthquake. I am sure that Dr. Bender is aware of this, but it is insufficient to look only at whether the earthquake was a large-magnitude one and when it occurred. It is also necessary to know the displacement and direction of faulting as well. When you take these factors into account, the correlations look much better. This is work that has been done at York University by a colleague, Douglas Smiley.

BENDER: I would like to mention that some of the calculations of Kanamori and Sopar, for example, using the fault-plane motion in the great Chilean earthquake, would indicate displacements of some 50 cm in the center of rotation for the pole path. So the effects of earthquakes should be big enough to observe with the new techniques, although it is much more difficult to sort out in historical data.

8

POLAR MOTION AND EARTH ROTATION

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INTRODUCTION

In addition to the complex motions of the earth in space that can be described by a set of translations and rotations of the axis of rotation (spin axis), the physical body of the earth also wobbles in a complex manner with respect to the spin axis, and the rate of rotation varies. The wobble, known as polar motion, has an amplitude of a few tenths of a second of arc. The variations in the rate of rotation cause non-uniformities in the length of day (lod) of milliseconds, and in Universal Time (UT1) of tens of milliseconds of time.

The sensible effects of these phenomena are variations in the astronomic latitudes, longitudes, and azimuths used to orient and control distortions in geodetic control networks, so that, while it may at first seem to be of purely astronomical interest, monitoring of polar motion is of critical importance to the practice of geodesy. This is reflected in the central role geodesists have played in studies of the subject ever since the Swiss mathematician Leonhardt Euler first derived the mathematical equations suggesting the possible existence of the phenomenon in 1765.

HISTORICAL REVIEW

During the century that followed Euler's work, several outstanding scientists, including LaGrange, Liouville, Glyden, Darwin, Kelvin, Helmert, and Tisserand, refined the mechanical theories of rotating bodies and applied them to the case of the earth, concluding that the polar motion should be a simple harmonic wobble at a period of 305 days. Attempts to detect polar motion did not succeed until almost the close of the nineteenth century. Then, in a period of less than two decades the wobble was detected, an internationally supported observational campaign verified the detection, and an international monitoring service (the International Latitude Service) was founded, which operated continuously for more than 80 years. Many individuals and organizations contributed to this amazing leap forward, among the most notable being the American geodesist, Seth Carlo Chandler, the U.S. Coast and Geodetic Survey (now the National Ocean Service of

NOAA), and the International Geodetic Association. The observations soon showed that the polar motion was much more complex than the theory had anticipated. The model of a simple wobble with period of 305 days was displaced by a more complex model of a 12-month forced motion and a 14-month free wobble. Additional complexities in the observed polar motion could not be definitively explained, and had to be deferred until a longer span of observations could be accumulated. The issue was reopened in 1940 by Sir Harold Jefferies, who argued that the 14-month wobble represented the "natural frequency" of the earth, which was essentially invariant but would suffer phase and amplitude discontinuities attendant to seismic events. In fact, he argued that it was almost certainly seismic energy that maintained the polar motion. The potential of gaining geophysical information was one of the primary reasons for the establishment of improved polar motion monitoring services, the International Polar Motion Service and the Bureau International de l'Heure (BIH) in 1962. The BIH was also assigned responsibility for monitoring and publishing the variations in UT1.

By the close of the 1960s the theory of continental drift had matured into plate tectonics, and the demands grew for geodetic measurements with a temporal resolution of about 1 day and a spatial resolution of a few centimeters over distances as large as thousands of kilometers. The only techniques that could possibly meet these requirements involved the observations of extraterrestrial objects. Most pertinent to this workshop, of course, are the interferometric observations of extragalactic radio sources (quasars) by the technique known as very long baseline interferometry (VLBI). By the mid-1970s, research supported by the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) had produced the third generation MARK III VLBI system that contained all of the necessary ingredients for operational geodetic surveying. The geodetic community has been quick to seize this opportunity, and reminiscent of that extraordinary period almost exactly a century ago, the study of polar motion and earth rotation has grown to nearly feverish levels (NGIC 1982).

PROJECT POLARIS

In 1977 the National Geodetic Survey of the National Ocean Service, NOAA, undertook to develop a new polar motion and earth rotation monitoring system, using VLBI. Project POLARIS (Polar-motion Analysis by Radio Interferometric Surveying) comprises the development and operation of a three-observatory VLBI network to regularly monitor polar motion with an accuracy of 5 to 10 cm and UT1 to 0.1 ms of time. Early in the planning of project POLARIS, it became apparent that the polar motion and timing information to be derived would be useful to other federal agencies, and NASA and the U.S. Naval Observatory (USNO) became partners in the project. The first POLARIS facility, located at the Harvard Radio Astronomy Station (HRAS), near Ft. Davis, Texas, began operations in September 1980. The Westford POLARIS Observatory, located near Boston, Massachusetts, began operations in June 1981, and

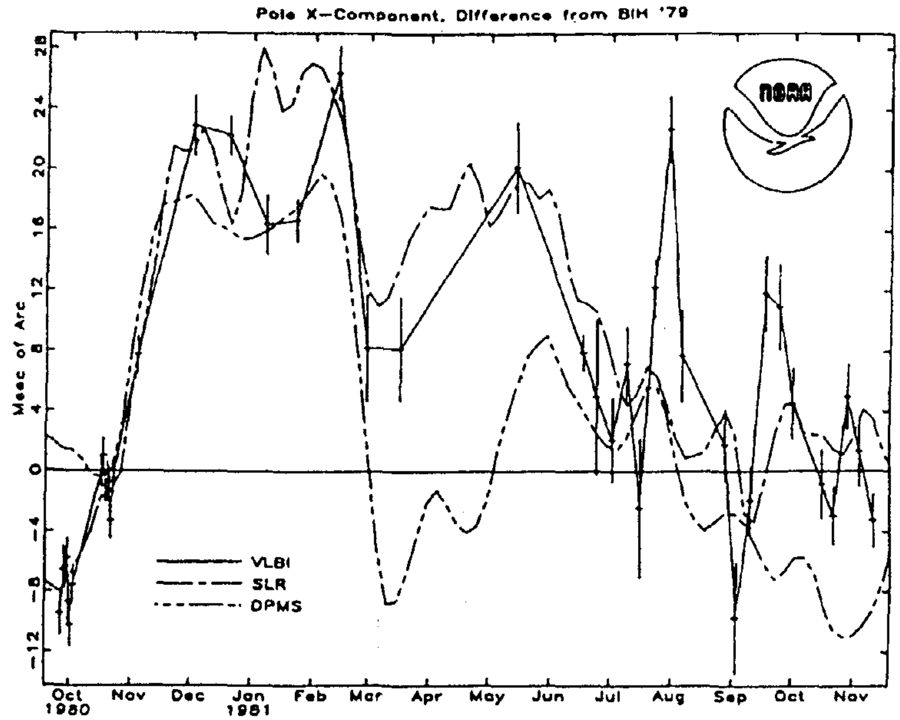

FIGURE 8-1 POLARIS polar motion results.

the HRAS-Westford Interferometer has performed one 24-h observing session per week ever since. Examples of the polar motion and UT1 results obtained from this series of measurements are presented in Figures 8-1 and 8-2. The third POLARIS observatory, located at the USNO Timing Sub-station near Miami, Florida, is scheduled to become operational in September 1983, coincident with the start of international project MERIT.

The collaboration among federal agencies in the application of advanced technology to the earth sciences now extends far beyond project POLARIS. Five agencies, NOAA, NASA, NSF, the U.S. Geological Survey, and the Department of Defense, have formulated and are pressing forward with a Federal Implementation Plan for the Application of Space Technology to Crustal Dynamics and Earthquake Research (ICCG 1982).

PROJECT MERIT

In 1978 the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) established a Joint Working Group of the Rotation on the Earth. The working group initiated project MERIT (Monitor Earth Rotation and Intercompare the Techniques of observation and analysis (Wilkins and Feissel 1982)). The objectives of the project are (1) to foster the development of new techniques for the measurement of the variations in the rate and axis of rotation of the earth, (2) to obtain precise data on earth rotation in order to

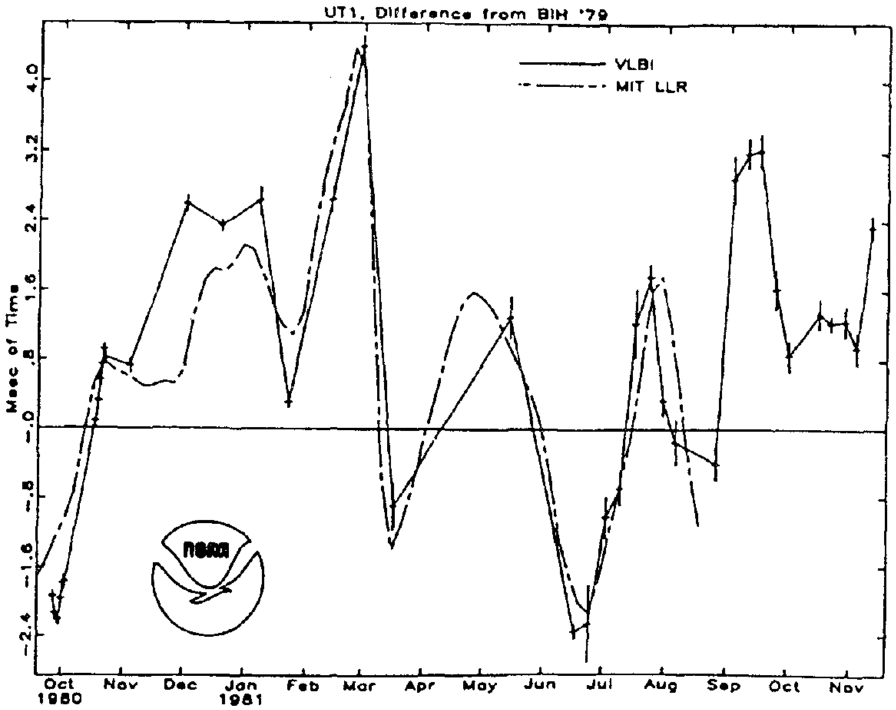

FIGURE 8-2 POLARIS earth rotation results.

increase our understanding of the causes and effects of the variations, and (3) to make recommendations on the observational basis and organizational arrangements for future international services in earth rotation. The program of activities includes (1) an initial short campaign of observations that was performed from August through October 1980 to test the techniques and improve the arrangements for international cooperation, (2) a main campaign from September 1983 through October 1984 by all suitable techniques, and (3) periods of planning, data analysis, and review.

INTERNATIONAL RADIO INTERFEROMETRIC SURVEYING (IRIS)

A consortium of geodetic agencies in the Federal Republic of Germany (FRG) is developing a dedicated geodetic VLBI observatory at Wettzell, FRG. The observatory is scheduled to become operational during 1983 and the POLARIS-Wettzell network is expected to provide the definitive VLBI measurements of polar motion and UT1 during the MERIT campaign. Looking beyond the MERIT campaign, the National Geodetic Survey (NGS) and FRG Consortium plan to continue to work closely, and in 1983 the organizations signed a cooperative agreement that will remain in effect as long as it is deemed beneficial to the participants. The agreement established project IRIS (International Radio Interferometric Surveying), which is intended to serve as a foundation for multinational geodetic VLBI programs. Application has been made to the IUGG and

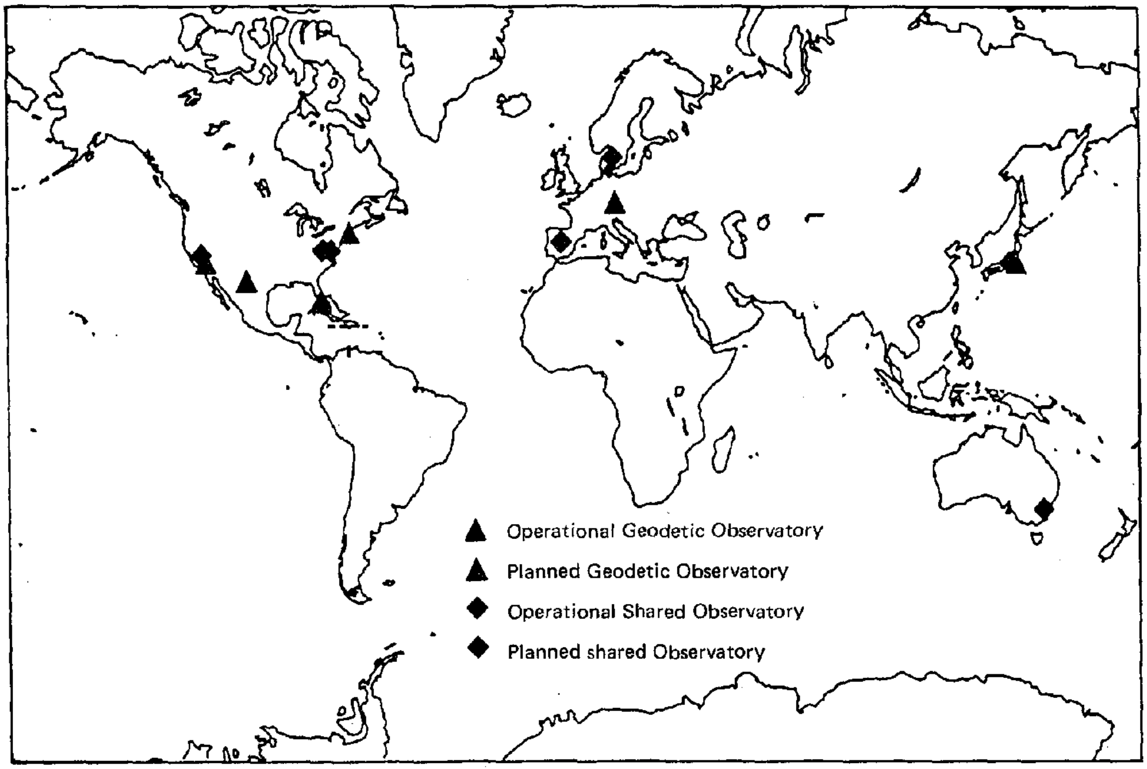

FIGURE 8-3 Observatories with operational MARK III or K3 VLBI data requisition systems circa September 1983.

COSPAR to establish IRIS as a subcommission of IAG Commission VIII. This is expected to be approved at the IUGG General Meeting in Hamburg, FRG, in August 1983.

COMPATIBILITY OF FACILITIES

Figures 8-3 and 8-4 show a projection of the VLBI facilities that are likely to become operational during the 1980s. The spatial distribution of the facilities is far from optimal, but certainly adequate to address many of the fundamental questions about plate tectonics, polar motion, and earth rotation, assuming, that is, that the observatories are instrumented in a manner to make cooperative VLBI observations practical. Not just possible, but truly practical.

The outlook is excellent. All of the permanent observatories, including both the dedicated geodetic and shared facilities, as well as the mobile and transportable units shown in Figure 8-4, will be equipped with either the MARK III or the Japanese K3 system. The K3 system is carefully made to be fully compatible with the MARK III, even to using identical tape transports. All of the correlators listed in Figure 8-4 should be able to process tapes from any of the observatories and provide the observables in a standardized format.

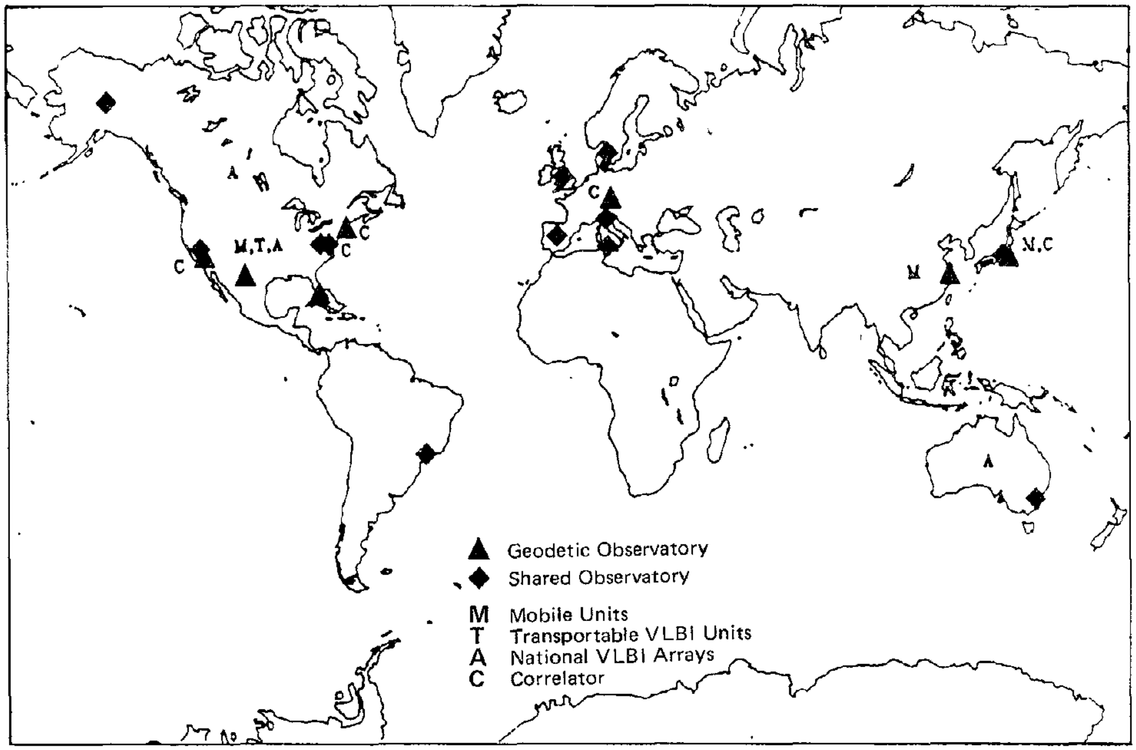

FIGURE 8-4 VLBI facilities projected to be operational circa 1990.

The picture is not as clear or as promising concerning the national VLBI arrays being planned for Canada, Australia, and the United States. I believe that the MARK III-K3 format, including the instrumentation tape recorders, should be considered the obvious "option of choice," only to be discarded if an overwhelmingly more attractive system is identified. Certainly, the VLBA should be designed to make observations to any of these more than 20 observatories scattered around the world practical--even convenient.

CONCLUDING REMARKS

The MARK III VLBI system has proven reliable, versatile, and operationally sound for geodetic applications. There is a growing awareness of the power of VLBI, and the geodetic community is moving quickly to apply that power to the solution of problems posed by the modern earth sciences. Several nations have already begun to develop programs and facilities that will lead to a global network of geodetic VLBI observations by the close of this decade.

What then is the potential role of the VLBA in geodesy? The answer to that question depends somewhat on the compatibility of the VLBA and the geodetic VLBI network. Even if the VLBA were not at all compatible with the geodetic VLBI network, it could independently produce geodetic measurements, as well as astrometric products that would be used by the geodetic community, for example:

- Radio source catalogs containing source locations, flux, structure, and temporal variations.
- Periodic measurements of the interstation vectors.
- Periodic determinations of polar motion and UT1.
- Improved determinations of precession and nutation.

By making the VLBA sufficiently compatible with the geodetic VLBI network that joint observing sessions become practical, the VLBA stations could serve as fundamental points in the Conventional Terrestrial Reference System (COTES). The development of COTES is essential to geodetic monitoring of plate motions and therefore to nearly every aspect of geodynamics. The VLBA contribution to geodesy and geodynamics could be increased even further by modest investments in Global Positioning System geodetic receivers and the inclusion of facilities to host other advanced surveying systems, particularly mobile VLBI and satellite laser ranging units.

It is clear that the VLBA and geodetic VLBI networks are potentially highly complementary and with the commitment to cooperation evinced by the multidisciplinary workshop, the VLBA can only be greeted with enthusiastic support by the geodetic community.

REFERENCES

Interagency Coordinating Committee for Geodynamics (1982) Federal Implementation Plan for the Application of Space Technology to Crustal Dynamics and Earthquake Research. 113 pp.

National Geodetic Information Center (1982) Geodetic Applications of Radio Interferometry, Proceedings of Symposium No. 5, International Association of Geodesy General Meeting, Japan, May 7-8, 1982. NOAA Technical Report NOS 95 NGS 24. Rockville, Md. 334 pp.

Wilkins, G.A., and M. Feissel (eds.) (1982) Project MERIT: Report on the Short Campaign and Grasse Workshop with Observations and Results on Earth-Rotation during 1980, August--October/ Herstmonceux, England: Royal Greenwich Observatory.

DISCUSSION

Audience participant: What is the GPS referred to in your discussion?

CARTER: It is a satellite system called Global Positioning System that is being developed by DOD. It consists of 18 satellites in three or four orbits transmitting signals in L band. These can be used to establish your position anywhere on the surface of the earth at any time. It was developed as a navigation system, but the signals can be used for geodetic purposes. It should be fully operational by 1987-1988. Six satellites are already up.

ROMAN: It is fairly well established in astronomy that every time you change the resolution to a higher value you learn something you didn't know. What constrains your time resolution to the observation of 1 to 5 days, and if it isn't constrained by money or operating procedures, have you reason to believe that there are no changes on smaller time scales?

CARTER: There is some published information showing the power cutting off at high frequencies. Also, there is some reason to look at the structure of the earth and arrive at some cutoff in frequencies. Primarily, however, the rationale for 1 to 5 days is financial as much as anything. It takes large resources to support daily observations. Currently, we don't have those resources.

USING THE VLBA FOR OBTAINING EARTH ROTATION PARAMETERS

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ABSTRACT

The Very Long Baseline Array (VLBA) has many of the desired characteristics of an array for measuring earth rotation parameters and can lead to new types of UT1 and polar motion data because of its unique properties. Probably the two most serious concerns are the rather weak measurement of the y component of the pole and the availability of the array for measuring earth rotation parameters. Close interaction of the geophysical community with the necessary process of array calibration can lead to a mutually satisfactory result as to the availability of earth rotation data and a properly calibrated array. Collaborative measurements with other antennas and arrays in Europe or Japan can yield satisfactory measurements of the y component of polar motion.

INTRODUCTION

In this short paper on the relevance of the VLBA for obtaining the earth rotation parameters (UT1 and polar motion), I want to emphasize that the user community is just as diverse with just as many conflicting requirements as any group of radio astronomers interested in continuum or spectral line observations, extragalactic or solar system physics, or millimeter to meter wavelengths. I therefore make no attempt to represent the earth rotation community, some of whom need fast measurements, some of whom require the ultimate in accuracy, and others of whom are willing to settle for what they can get cheaply.

I will first describe array characteristics that are important for determining the earth rotation parameters and then review some of the proposed VLBA characteristics that are relevant. An error budget will be proposed that leads to expected performance of the VLBA for this use. Throughout, possible desired methods use of the array will be mentioned.

Desirable Array Characteristics

For geodynamical measurements such as UT1 and polar motion, probably the single most important array characteristic is stable instrumentation. By this I mean an instrument that changes so little with time that small changes are observable. The times involved may be short, like the time scale of a day for a typical measurement, or longer, like the century time scale of historical data to examine for correlations. Therefore to be of significant use, any array should not be changed: feeds, receivers, cables, electronic instrumentation, and recorders should be beyond the reach of "knob twisters." Antennas should be connected firmly to the continental plates and well monumented. They should be capable of observing down to the local horizon to be able to remove atmospheric terms from the geometric terms.

While it is desirable to have long baselines available, many of the observables are best determined on shorter baselines where there is greater mutual visibility of sources. A compromise is involved, and for a dedicated array local baselines (i.e., North America) are probably reasonable. Yet it is necessary to include Europe or Japan in probably less frequent, but still regular measurements to yield a strong solution for the y component of polar motion.

A long east-west baseline is desirable (but not necessary) for obtaining UT1, and the VLBA has this in the form of the Puerto Rico to Hawaii baseline. It is an especially interesting baseline because it spans the Caribbean Plate, the North American Plate, and the Pacific Plate. This may allow local plate motion to be directly removed to obtain the true earth rotation parameters.

To obtain strong polar motion measurements, it is necessary to have orthogonal baselines. The VLBA does not have as long a north-south (y component) baseline as its east-west baseline, but given the geographical constraints, the array probably could not be improved significantly. As noted above, international cooperative measurements involving Europe or Japan are necessary to correct this problem.

Relevant VLBA Characteristics

Almost every array characteristic is relevant when one is trying to use the VLBA for obtaining earth rotation parameters. These will be divided into six major areas and each discussed briefly.

The present proposed antenna sites for the VLBA cover the North American continent and even extend to the Pacific Plate (Hawaii) and the Caribbean Plate (Puerto Rico) as shown in Figure 9-1. As mentioned in the previous section this is most desirable. The present dedicated POLARIS array, shown in Figure 9-2, has a polar projection that is strong for measuring the x component of polar motion (PM). Planned use of European antennas will provide adequate coverage for the y component. The polar projection of the VLBA (Figure 9-3) displays an improved coverage even without anticipated international baselines. Further, the shorter baselines provide useful redundancy for data quality and the use of triangles of baselines has been shown to be a powerful data analysis tool.

The antennas and receivers have been planned to be wide-band, and fully compatible with measuring earth rotation parameters. It should be emphasized that the international standard band for observing at

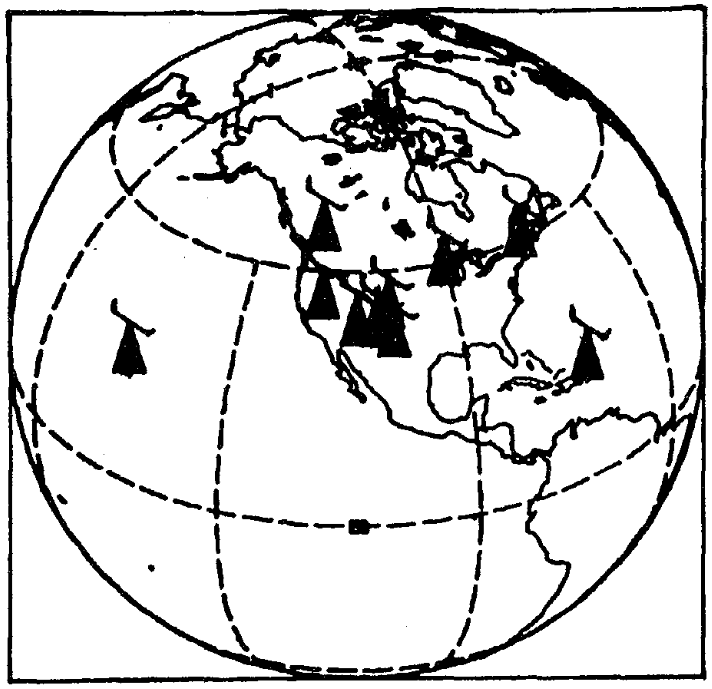

FIGURE 9-1 Proposed VLBA antenna sites.

present--dual S/X bands--is the most important receiving band. There may be future applications that could use dual band measurements at other frequencies, so including wide-band dichroic mirrors is urged for the higher frequency pairs.

The VLBA recording method must be compatible with the international MARK III or K3 systems used for measuring earth rotation parameters to facilitate joint international ventures.

I understand the correlator will have spare station capability over the 10-station array. This can be utilized to tie in other antennas or arrays to generate improved earth rotation parameters while allowing the full array to be used to provide redundancy (or better measurements in shorter time). It will be important in the joint international measurements.

The computer software must be available for distribution and on display for error detection, yet allowed to change only under tight control. I do not anticipate problems in this area, but urge close cooperation between the two communities early in the development to ensure a quality product.

Further, much of the VLBA calibration necessary to produce astronomical maps could be of direct use for measuring earth rotation parameters if properly taken. The Naval Research Laboratory is willing to cooperate with the array management, as we have in the past on the VLA, to ensure the utility of the calibration data for earth rotation. At present, the VLA is calibrated approximately every 6 weeks; the VLBA will require calibration more frequently. This large body of data,

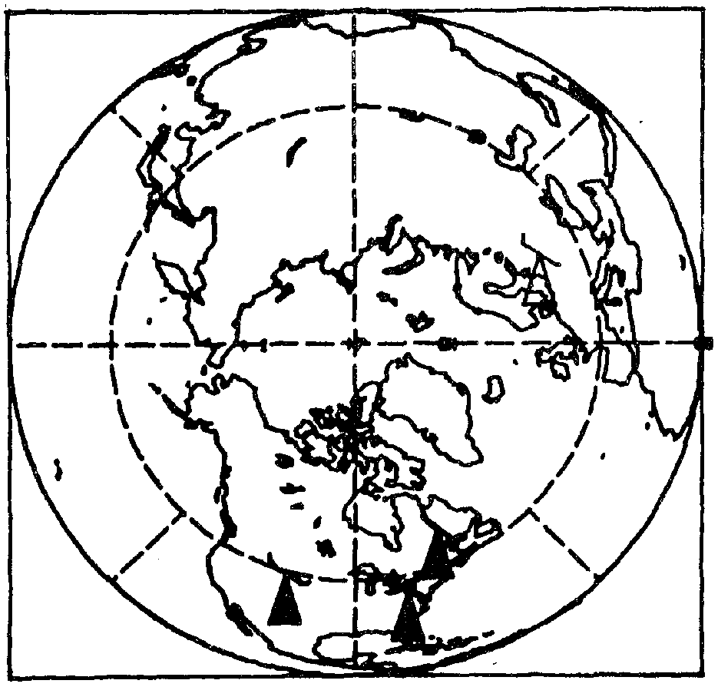

FIGURE 9-2 Present dedicated POLARIS network as seen from the North Pole.

taken at regular intervals in a unified manner can greatly impact the usefulness of the VLBA for determining earth rotation parameters.

Error Budget Estimates

The current wisdom as to the error budget on baseline length on long (400 km) baselines is presented in Table 9-1. This estimate is from an October 1982 workshop of crustal dynamics VLBI experts. By the time of the VLBA the present research on water vapor radiometers (WVR) is expected to pay off, and the water vapor term of the troposphere should be in the 0.5 to 1.0 cm range as shown. At present, without working WVRs this term can be as large as 3 to 9 cm in the worst cases. The relatively unimportant source structure term could be made negligible by using data from VLBA maps. It appears, however, that the total number is going to be in the 2 cm range for error in baseline length. Details of how to allocate this error into the baseline components related to x and y of polar motion and UT1 are uncertain without details about observing schedules, and so on, but the numbers indicated are probably representative.

SUMMARY

In conclusion, the VLBA has many characteristics of a desirable array for measuring earth rotation parameters. It is probably difficult to

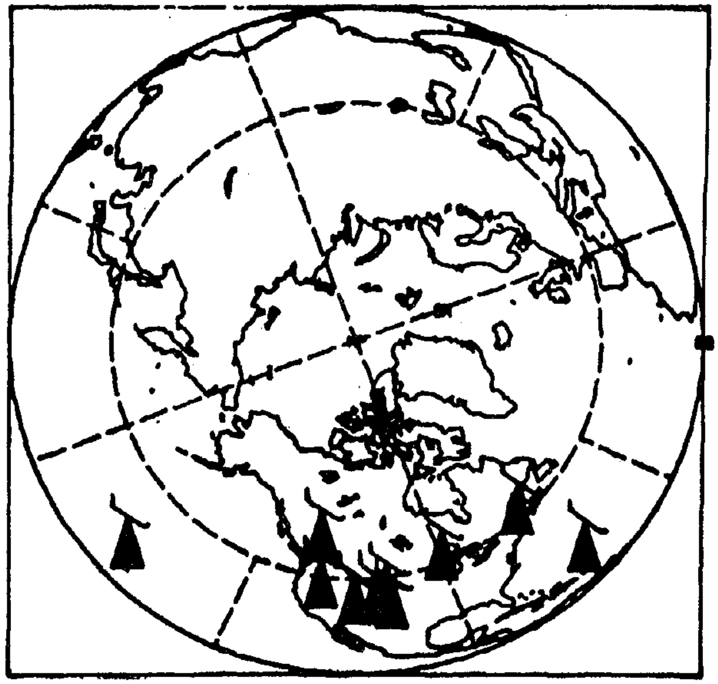

FIGURE 9-3 Proposed VLBA as seen from the North Pole.

significantly improve the site coverage while confined to North America. Joint international experiments will be expected to improve the measurement of the y component of polar motion and to further tie the coordinate system to other continental plates to remove any possible local plate motions.

TABLE 9-1 Error Budget Estimates (Precision)

	Root Sum of Squares (RSS) (cm)
Source structure	0.3
Ionosphere	0.2
Troposphere	
Wet (WVR)	1.5
Dry	0.5-1.0
Instrumental	1.0
Total baseline length	2 cm rms
Polar motion	$\leq$6 cm ($\leq$2 milliarc sec) in pole
Total UT1 RSS	$\leq$60 μs in UT1

The continuous use of such a precise instrument by astronomers will lead to new types of earth rotation measurements because a valuable data bank of ancillary performance (weather models, clock drift and quality, and so on) will be obtained even when the instrument is not directly involved in measuring earth rotation parameters, thus decreasing the degrees of freedom during earth rotation measurements.

Finally, the earth rotation parameters will be a valuable by-product of careful array calibration.

DISCUSSION

Audience participant: One comment and one question. When we show the array that we talk about essentially for a POLARIS Array now, we do in fact have the German station involved, and that does give you quite a bit of y, so that will not be a problem. On one of your charts you showed a concern about how the recordings are going to be done. That is a major concern, to the geodetic community right now, the compatibility of the systems with the MARK III system in particular. Are we going to have noncompatibility? Are we going to have to transcribe tapes from one system to another?

SPENCER: Are you going to have to have correlators that can process multimedia and so forth? That becomes very important when you bring in the other antennas around the world and try to do ad hoc experiments.

Audience participant: Between the MARK III system and the K3 system, we are talking about some 1000 observatories that we know are going to have MARK III or K3 systems.

SPENCER: But isn't the K3 system fully compatible?

Audience participant: Yes. So we will have at least 1000 observatories around the world that will be compatible. The question is, is this array going to be compatible with that system? If so, some justification of why it is not compatible will be required.

KELLERMANN: Recording technology is evolving rapidly, and at some point we are going to have to change our standards for the recording technology. I don't know what technology is going to be used for the VLBA itself, but it can easily be made compatible with any existing system. You just have to get the bits off the tape, and then what happens to them afterwards is easy to arrange. But I can't help being concerned. For example, the United States has the most primitive television system in the world because in 1948, when color television came along, there was insistence that it be compatible with the pre-war television system. All the rest of the world has achieved more efficient systems, but we still have the old system because we insisted on compatibility. At some point we are going to have to drop what is already a 6- or 7-year-old system. By 1988 it is going to be more than a decade old.

Audience participant: It is not just the U.S. systems that are a concern. Japan's K3 system is another example. I don't know what the Canadian system is going to be, but I think it is a serious concern.

KELLERMANN: We have been perhaps too concerned about compatibility with the Canadian radio astronomy system compared with the other geodetic systems, but I don't think there is any problem in using a combination of these techniques and still getting fully compatible data. That certainly is the immediate goal.

NIELL: Many people have been talking about the dichroic system and the dual S/X. Clearly, one of the things that you want for astrometry and geodesy is very wide bandwidths. I think there is some concern about the bandwidth that you can get with the dichroic systems that are being used for S and X. I don't know if there are more recent developments, but there may be limitations on the bandwidth you can get with dichroic systems, at least at S and X bands.

SPENCER: What is the present bandwidth on the dichroic?

NIELL: Ninety megahertz at X band.

SPENCER: We are currently using about 400 at X band, so that would be a serious limitation.

CLARK: On the DSN stations, the present dichroics are implemented for their dual S/X, which are relatively narrow band requirements. They have to be able to transmit several hundred kilowatts through the dichroics, and they are worried about absolute losses through them, not just in the sense of a little spoiling of system temperature but how hot they actually get. I think that the careful design of dichroics can eliminate that problem.

10

CONTRIBUTIONS OF THE VLBA TO OPERATIONS AT THE U.S. NAVAL OBSERVATORY

Dennis McCarthy
U.S. Naval Observatory

The Naval Observatory has the responsibility of providing estimates of pole position and UT1-UTC to a number of users as rapidly as possible. We must also provide predictions of the values of these earth-orientation parameters for the future. For this we use a coordinate system defined in space by the position of stars or quasars as our inertial coordinate system. In Figure 10-1, this ephemeris coordinate system is rotating with an adopted angular speed, and it is well-defined in terms of the nutation and precession matrices. However, we make our observations on the face of the earth within a terrestrial coordinate system that appears to be rotating with respect to that in the ephemeris inertial system. The three angular earth orientation parameters--x, y, UT1-UTC--enable us to describe the complete rotation between these systems.

In observing from the surface of the earth, we usually observe reference vectors. For classical astronomy we have used the direction of the vertical as the reference vector; now we are using baselines from either very long baseline or connected-element interferometry for the determination of the earth's orientation. These observations are related to the variation in the pole position and UT1-UTC. We are responsible for providing this information to our users.

In trying to make use of the data that we have available to us, a number of aspects must be considered. Not only do we consider the internal precision of the data that we have to work with, but we also must consider the accuracy of the data, that is, how precise they are with respect to some standard reference systems. To determine the accuracy, it is necessary to investigate the possible systematic errors existing in the observations. The problem is to model the systematic errors involved in each of the observational techniques and their consistency, that is, how variable those systematic error models are over time. This is an area in which we anticipate that the Very Long Baseline Array (VLBA) will provide substantial help.

As has been mentioned in previous chapters, we also have to consider the time resolution or the period between the data points. How often do we need data? Further, availability is an important consideration; that is, how long a time interval will there be from the time of the observation to the time of actual reduction of the data? For our purposes, we need timely estimates of pole position and

UT1-UTC. Therefore the length of time from actual observation to reduction of the data is a key concern.

Here is a brief description of the U.S. Naval Observatory (USNO) algorithm for the determination of earth orientation parameters. While it is similar to those of the Bureau International de l'Heure (BIH) or the International Polar Motion Service (IPMS), there are substantial differences. Observations are filtered to get smoothed data sets; systematic corrections are generally applied to the observations, and they are then combined to provide estimates of the variations of the reference vectors. Together with some assumed station coordinates, these are used to determine the past values of the x, y, UT1-UTC. Predictions of these parameters are then made using this information.

The VLBA could help us in the estimation of the systematic corrections. Each technique has its own systematic corrections, which may be due, in part, to the definition of its coordinate system, and the reduction procedure. It is crucial that we be able to evaluate the systematic errors correctly.

The systematic errors that we are concerned with are such things as William Carter described in Chapter 8. Figure 10-1 shows the differences with respect to the BIH of the time and polar motion components of the USNO connected-element results. You will see an annual difference with respect to the BIH. This is the kind of thing we see for each of the techniques when we make use of their observations to determine earth orientation.

Figure 10-2 displays the spectrum of the residuals with respect to the BIH of the Doppler pole position in x. Figure 10-3 shows the power spectrum of the University of Texas quick-look x polar coordinate residuals as determined from laser ranging to LAGEOS. Each of the techniques is characterized by similar types of spectra.

It is also important to investigate the consistency of each of these techniques in comparison with one another. Figure 10-4 shows the in-phase co-spectrum of the difference between each of the techniques and the BIH values of x. We can see that this indicates, for example, that the Smithsonian Astrophysical Observatory and the University of Texas laser-ranging results seem to agree that the BIH has some sort of error in the low frequencies. It is in dealing with this kind of problem that we expect the VLBA to make a contribution.

To summarize the VLBA contribution, if we are limited to infrequent observations from the VLBA, then this kind of information would be useful, because it would be able to provide us with another data source for the investigation of the systematic errors of each of the techniques. If we had frequent observations of the interstation baselines available to us quickly, then we could also use this information in a routine way to provide estimates of pole position and UT1-UTC.

In addition, the VLBA contribution would provide improved definition of the coordinate systems and improvements in the models that we use for the prediction of pole position. We would then be able to better determine how often we need to make these observations to provide the best estimates of pole position and time.

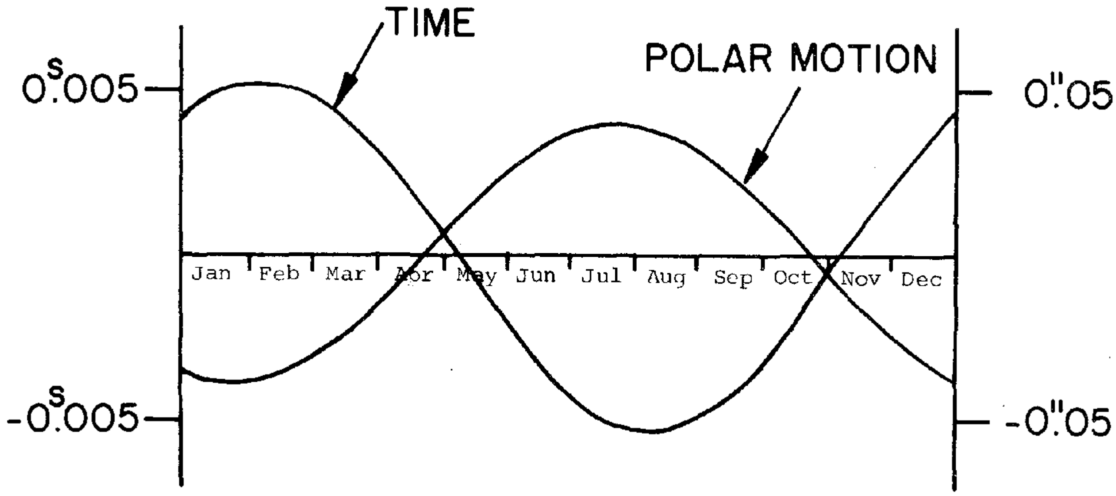

FIGURE 10-1 Systematic differences of Connected-Element Interferometer earth orientation parameters with respect to BIH-derived values.

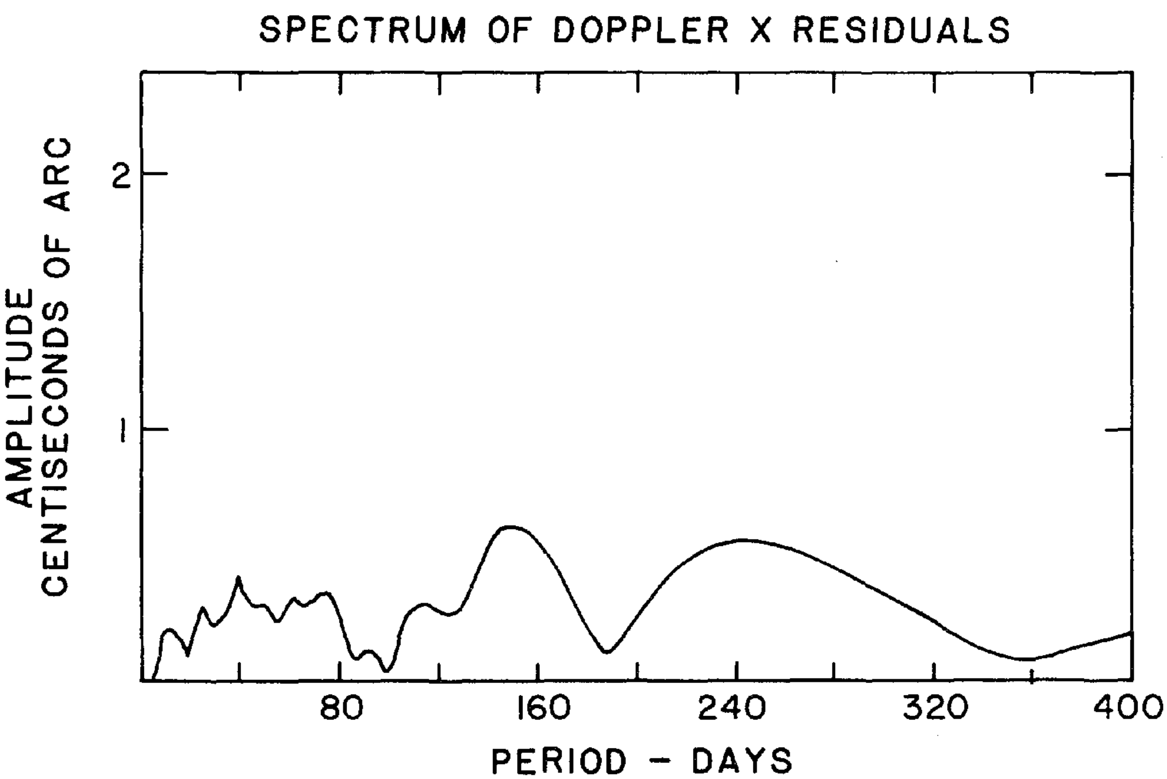

FIGURE 10-2 Amplitude spectrum of residuals in x polar coordinate derived from Doppler satellites with respect to BIH values.

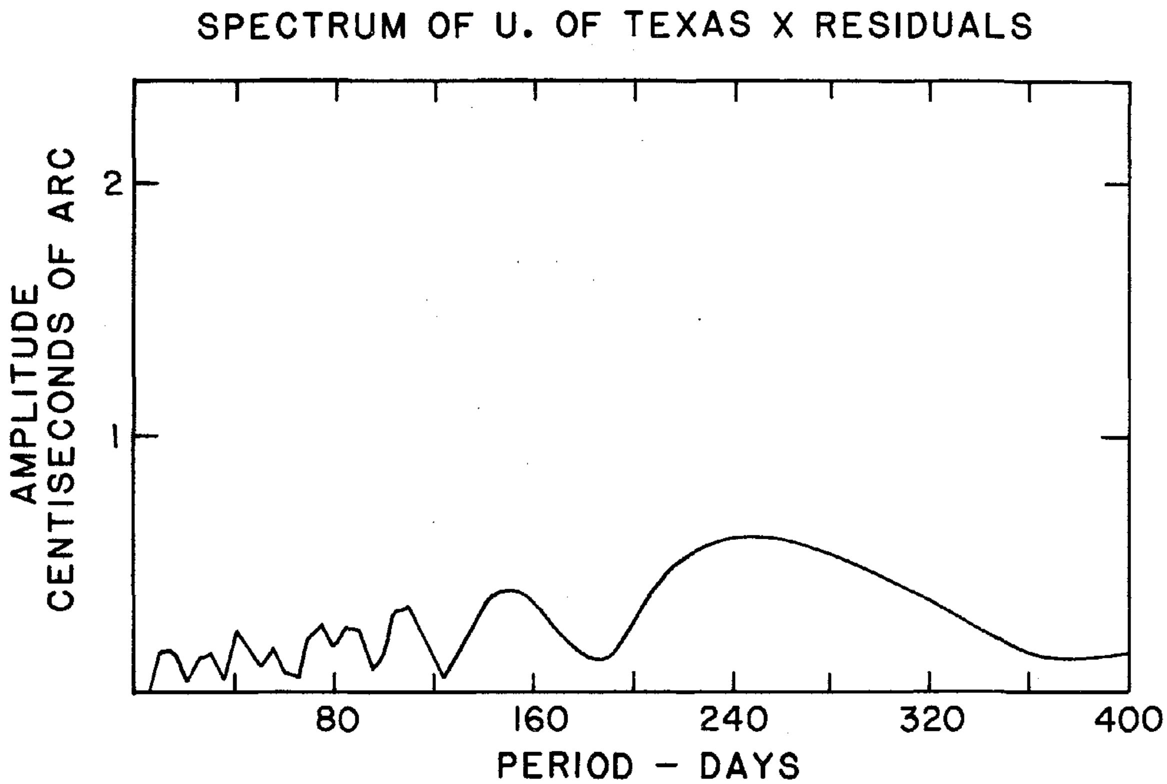

FIGURE 10-3 Amplitude spectrum of LAGEOS x polar coordinate with respect to BIH values.

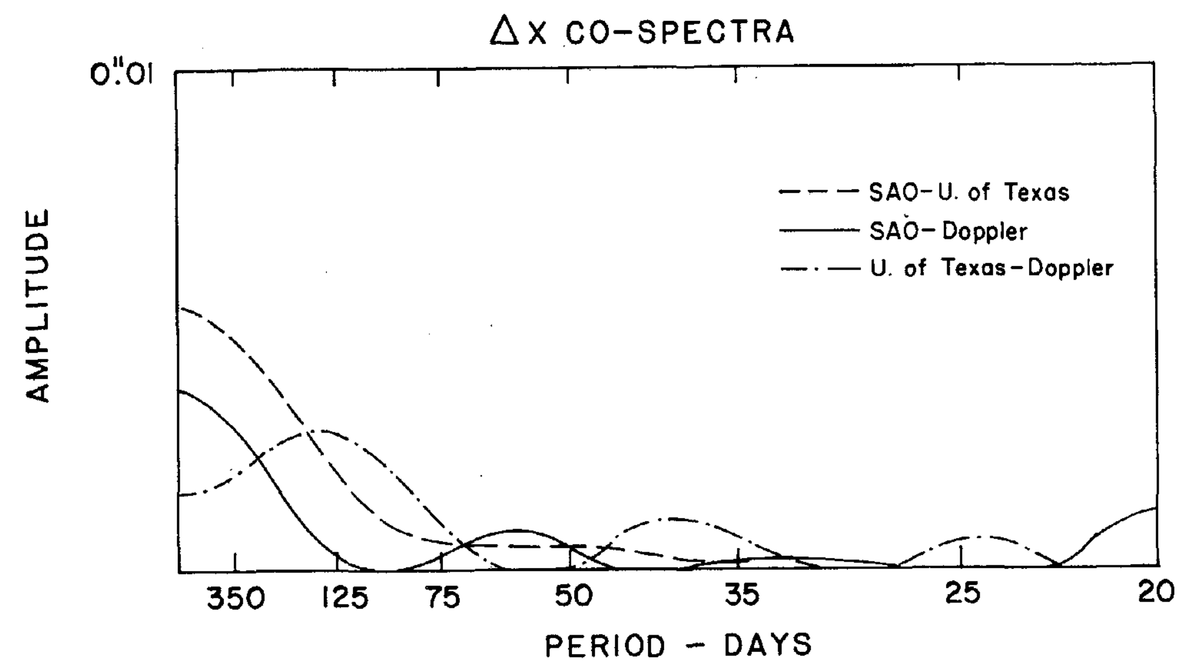

FIGURE 10-4 Amplitude co-spectra of residuals in the x polar coordinate derived from various techniques.

DISCUSSION

Audience participant: What does "frequent" mean in the context of your presentation?

McCARTHY: How often do we need the observations.

Audience participant: What do you consider "frequent" in relation to your criteria?

McCARTHY: We want an observation every 5 days.

BURKE: Have there been discussions of the mutual use of the same calibration data for astrometry and astrophysics on a VLB system?

McCARTHY: I don't know of any.

Audience participant: This aspect has been considered; in fact, such use is assumed.

BURKE: What are the reasons for a strictly 5-day interval?

McCARTHY: In pole position, 5 days may be too strict. We don't see power in the spectrum at 5 days; a somewhat longer time is needed. We do see evidence of very short period changes in the spin angle on the spin vector.

BURKE: Does it have to be strictly periodic 5-day intervals?

McCARTHY: No. If observations are available once every 3 days, or once every 6 days, that is sufficient. It is not critical that it be precisely 5 days.

REID: Since most of the polar work has been done with about three baselines, why does it take one day of observation with a ten-station array, which would have 45 baselines, to get the numbers you need? Why not 2 or 3 h?

McCARTHY: That would be adequate. There is no requirement that one day of integration time be used.

Audience participant: You don't need closure around 25 h?

McCARTHY: No.

COATES: The question seems to be how variable can the spacing and the data points be. Do you really have to have equal spacing on the data points? And that goes back to the question of analyzing time series with equal spacing versus nonequal spacing.

Audience participant: We are used to having quite unequal spacing in the treatment of astronomical data.

11

THE CRUSTAL DYNAMICS PROJECT

Robert J. Coates
NASA Goddard Space Flight Center

Peter Bender described the scientific significance of measuring the global plate motions and the regional deformations taking place along the edges of plates, which are in collision. Back in the late 1960s, NASA initiated the development of systems using artificial or natural space objects for the direct measurements of the global and regional plate motions. The two techniques developed by NASA were satellite laser ranging and very long baseline interferometry (VLBI). Since the subject of this meeting is VLBI, this paper will concentrate on the VLBI aspects of the NASA program.

The status of the technology in the late 1960s was that the astronomy community had developed VLBI and this technique had been used in pilot experiments to measure baselines between stations. The accuracy of these early measurements was about 1 m. NASA began a program to develop and improve VLBI systems that would be able to achieve accuracies of the order of a few centimeters. NASA developed the MARK III VLBI system as a total system for geodetic measurements. The system included the measurement systems to be used in the field, the correlator system for processing the data, and the analysis system for determination of high-accuracy baselines. The key features of the MARK III field system were the uses of a wide-band dual-frequency receiver, a 112-mbps data recording terminal, a phase calibrator for end-to-end system calibration, meteorological sensors and water vapor radiometers for calibration of the tropospheric propagation, and an automated computer-controlled operation of the system.

By the late 1970s, both the VLBI and laser-ranging techniques were developed to sufficient accuracy to begin operational use for measurements of plate motion and deformation. NASA established the Crustal Dynamics Project in 1979 for that purpose. The science objectives of the Crustal Dynamics Project are to improve our knowledge and understanding of the regional deformation and strain accumulation related to large earthquakes in the plate boundary region in western North America; the contemporary relative plate tectonic motions of the North American, Pacific, Nazca, South American, Eurasian, and Australian plates; the internal deformation of continental and oceanic lithospheric plates with particular emphasis on North America and the Pacific; the rotational dynamics of the earth and their possible correlation to earthquakes, plate motions, and other geophysical phenomena; and regional fault motions and strain accumulation in several areas of high earthquake activity at subduction plate boundaries and strike-slip boundaries.

The project organization involved the participation of a large number of organizations in the United States and overseas. For example, the development of the MARK III system involved a team of people from the Goddard Space Flight Center, Haystack Observatory, Massachusetts Institute of Technology, Smithsonian Astrophysical Observatory, National Radio Astronomy Observatory, and Jet Propulsion Laboratory (JPL). Many of the foreign VLBI stations are owned and operated by organizations in the local country. In the United States, five government agencies are involved in the Crustal Dynamics Project: NASA, the National Geodetic Survey (NGS) of NOAA, the U.S. Geological Survey, the National Science Foundation, and the Defense Mapping Agency. The NGS POLARIS Project and the NASA Crustal Dynamics Project are coupled through interagency agreements. NASA and NGS jointly implemented VLBI stations for the POLARIS network at Ft. Davis, Texas, and Westford, Massachusetts, and are currently implementing the third station in Richmond, Florida. This was described in detail in Chapter 8 by W. Carter.

The Crustal Dynamics Project has developed three basic types of VLBI field stations. The first MARK III systems were permanently installed in VLBI observatory stations, such as Haystack Observatory. The second type of MARK III station is called a Transportable VLBI Data Station (TVDS), consisting of all of the geodetic VLBI electronics that are needed to make a naked antenna into a geodetic VLBI station. This TVDS system is brought into various appropriate antenna sites for short-term measurements. Third, highly mobile VLBI stations were developed by JPL for the rapid deployment to a large number of sites in a regional deformation measurement program. This permits the measurement of the relative positions of a large number of sites with only a few VLBI stations.

Figure 11-1 is a map of California that shows the locations of fixed VLBI base stations and site locations for the deployment of the mobile VLBI systems for the measurements of regional deformation. The fixed VLBI stations are at Owens Valley, California; Goldstone, California; and Ft. Davis, Texas. Mobile VLBI number 1 (MV-1) has a large 9-m antenna that is difficult to transport from one site to another, so that station is also used as a fixed base station at Vandenberg Air Force Base. The Mobile VLBI 2 system and the Mobile VLBI 3 system use 4- and 5-m antennas, respectively, and are easily transported from site to site. In a typical observing campaign, as shown in Figure 11-1, the base stations are operated for all measurements, and the two highly mobile systems occupy pairs of sites in a configuration that would measure the specific baselines of interest to the scientists. Figure 11-1 also shows the main fault lines in California. The measurements with the VLBI are designed to get measurements of the relative motions of the many sub-blocks that are divided by the many faults. The measured baselines crisscross the critical faults so that there is a very good determination of the total motion in the region.

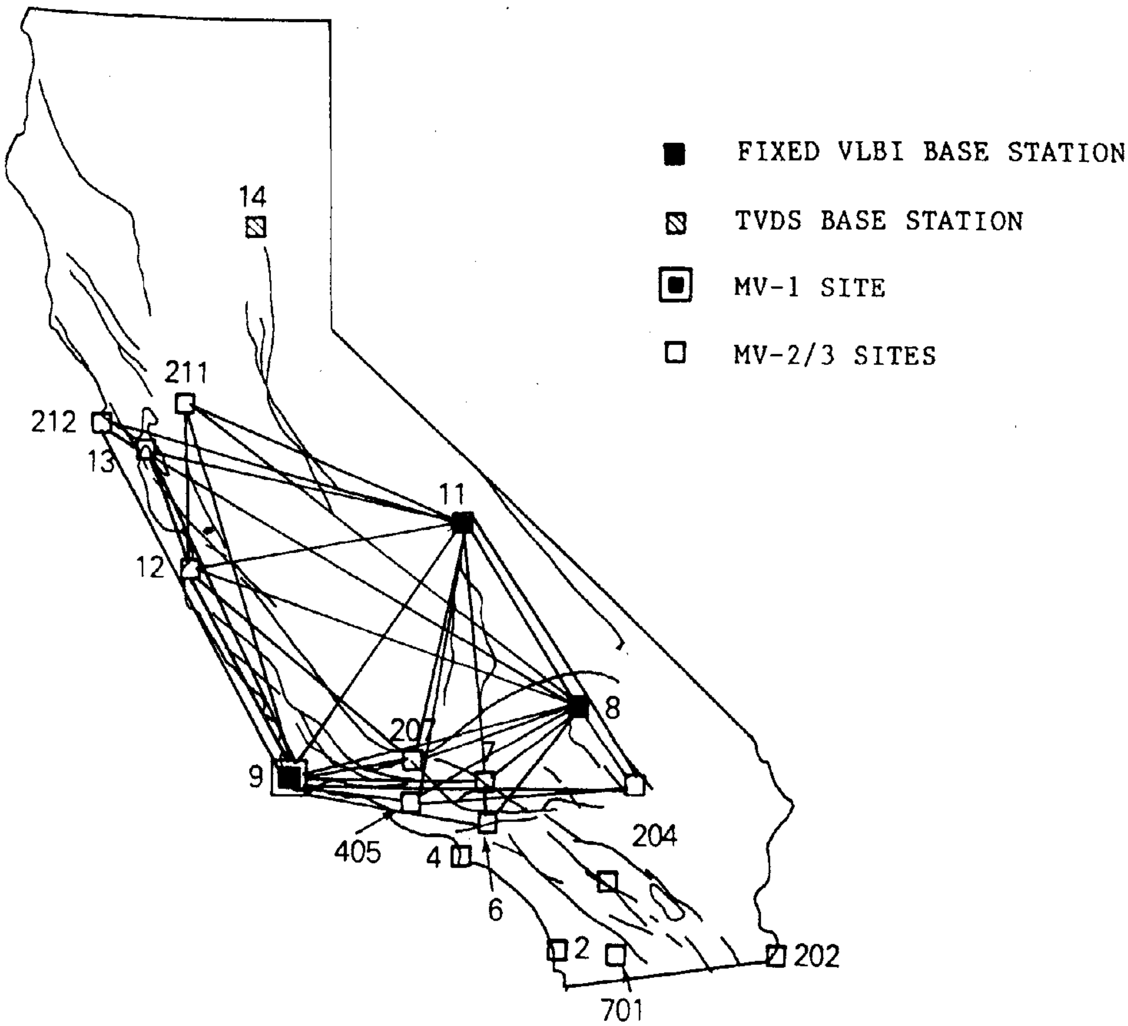

FIGURE 11-1 Regional deformation in California.

Figure 11-2 shows another measurement campaign with the VLBI, which extends the measurements into the central part of the United States. This type of campaign is aimed at measuring the deformations of the North American Plate extending from the boundary in California into the stable central region of United States. Starting in 1984, the mobile VLBI systems will be deployed in Alaska and Canada for measurements of regional deformation associated with the subduction of the Pacific Plate under Alaska and the Aleutian chain. A TVDS system will be installed in the NOAA antenna at their Fairbanks, Alaska, station to make a VLBI base station for these measurements. Figure 11-3 shows the locations of the sites for the mobile VLBI. The sites at Sand Point and Cape Yakataga are in seismic gap areas that are predicted to be sites of future very large earthquakes.

The global network being implemented by the Crustal Dynamics Project for the measurements of plate motion as well as polar motion and UT is shown in Figure 11-4. The solid squares are stations that are

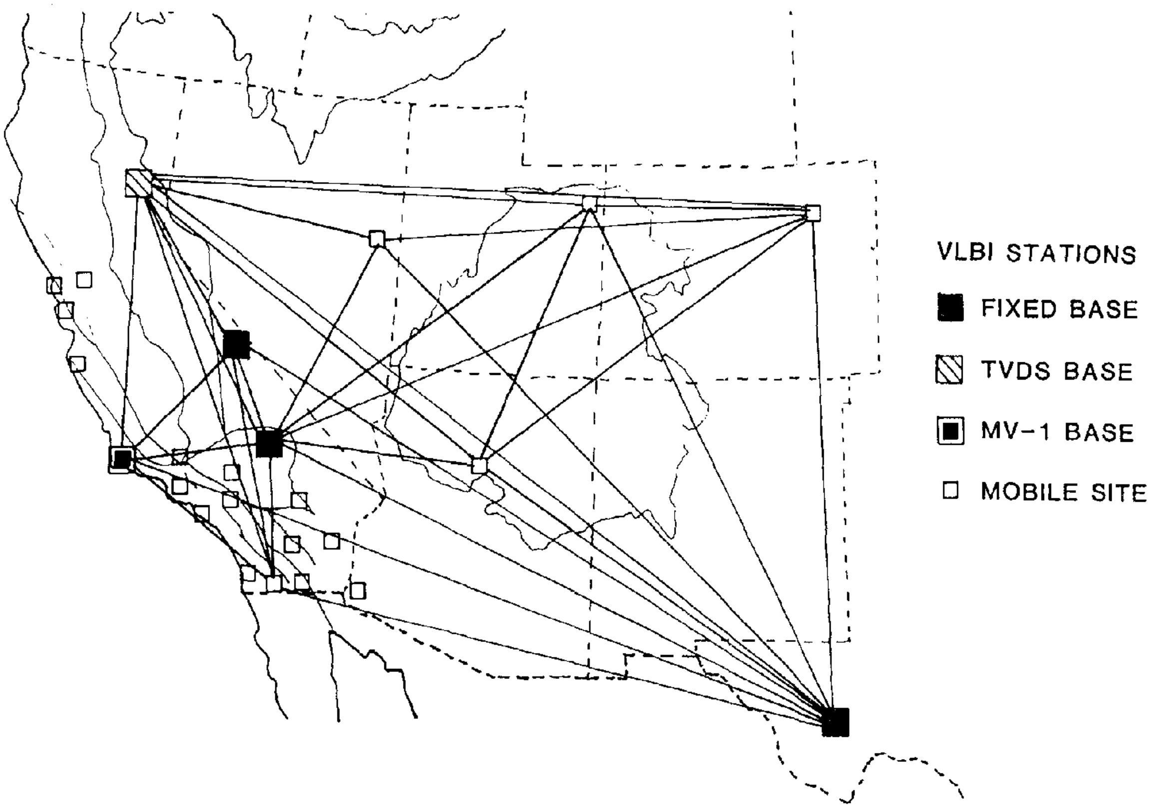

FIGURE 11-2 Regional deformation and plate stability in the western United States.

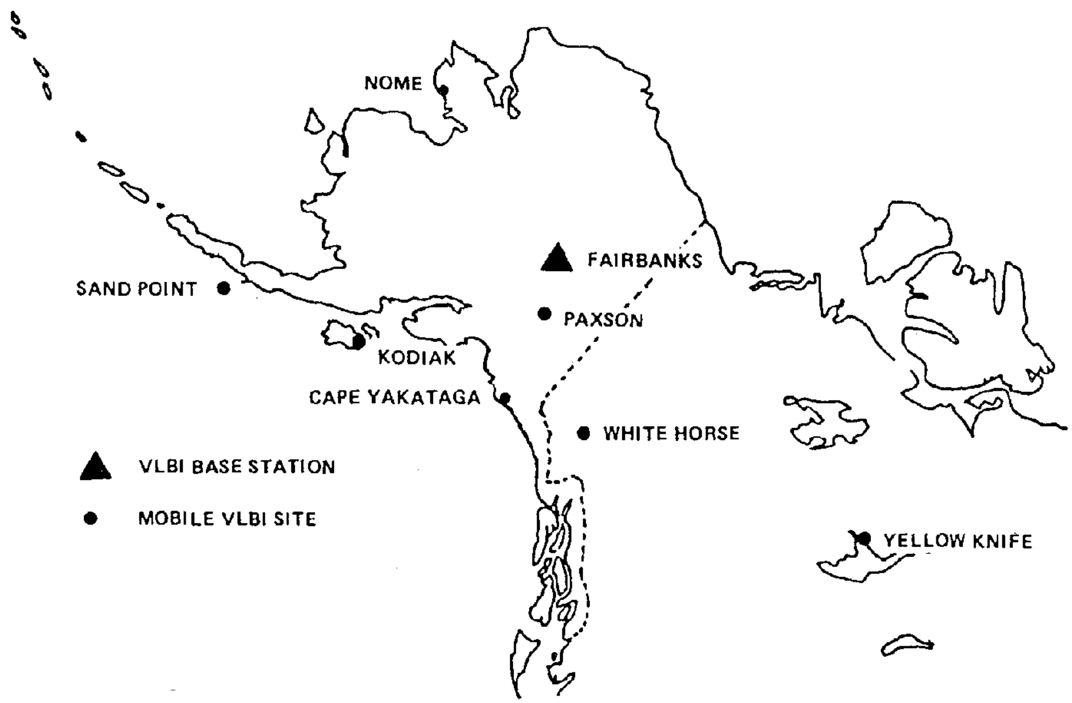

FIGURE 11-3 Regional deformation sites in Alaska and Canada.

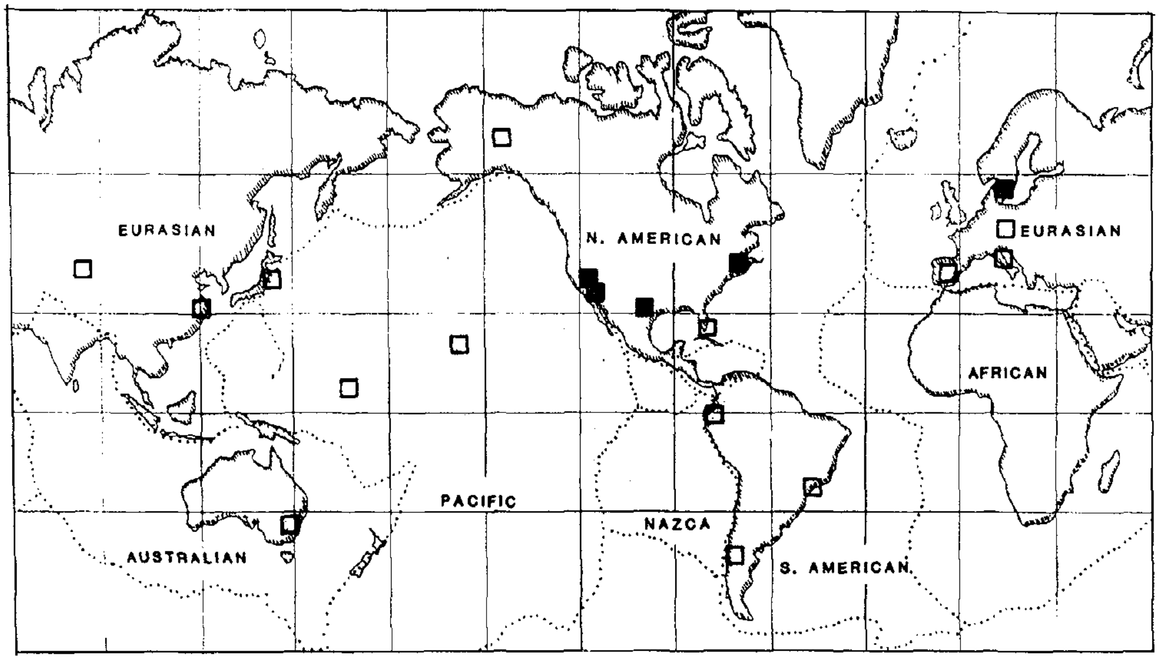

FIGURE 11-4 Plate motion and PM/UT.

being used operationally for crustal dynamics measurements. The open squares are station locations for facilities that are either under construction or are planned for future operations under the Crustal Dynamics Project. The stations at Westford and Ft. Davis are the stations jointly implemented by NGS and NASA and are the two operating stations for the POLARIS network. The station at Richmond, Florida, also part of the POLARIS network, is currently under construction and is expected to be operational by the end of the year. The stations at Owens Valley and Goldstone, California, are the base stations used for the mobile VLBI measurements. The station in Fairbanks, Alaska, is the TVDS station that I discussed earlier, which will be operated for the first time in 1984. The European station at Onsala, Sweden, is a Swedish station that has been participating with the project in measurements of plate motion between North America and Europe and in the POLARIS polar motion measurement program. Germany is currently building a VLBI station at Wettzell to be used as a dedicated geodetic station. This will be used in conjunction with the POLARIS stations for operational measurements of polar motion and UT as well as plate motion. The Italians are also building a VLBI station at Bologna, Italy. It is planned to upgrade the Deep Space Network (DSN) station at Madrid, Spain, with a new feed and a MARK III capability to be able to use that station on occasion for geodetic measurements.

In South America the Crustal Dynamics Project plans to bring TVDS systems into the Itapetinga Radio Observatory near Sao Paulo, Brazil, and into the former NASA tracking stations at Santiago, Chile, and Quito, Ecuador. For measurements in the Pacific, the project plans to deploy TVDS systems to existing range antennas on Hawaii and Kwajalein to be used in conjunction with the stations in Alaska, Japan, China, Australia, and Europe. In Japan, the Kashima station is being implemented by the Radio Research Laboratory. In Australia, the DSN station is planned to be upgraded to have a MARK III-type capability by 1985. In China, the Shanghai Observatory is proceeding to build VLBI stations at Shanghai and at a location further inland on the Eurasian Plate.

It is planned that by 1984 all of the stations shown in the Northern Hemisphere will be operating in a global program. Figure 11-5 shows a polar projection map of the stations in North America, the Pacific, Asia, and Europe. This map shows the baselines that will be measured with the configuration of stations. These stations will provide direct measurements of the plate motions between the North American, Pacific, and Eurasian plates, and a measure of the stability of the North American, Pacific and Eurasian Plates, and will contribute to the international MERIT campaign for the measurement of polar motion and UT.

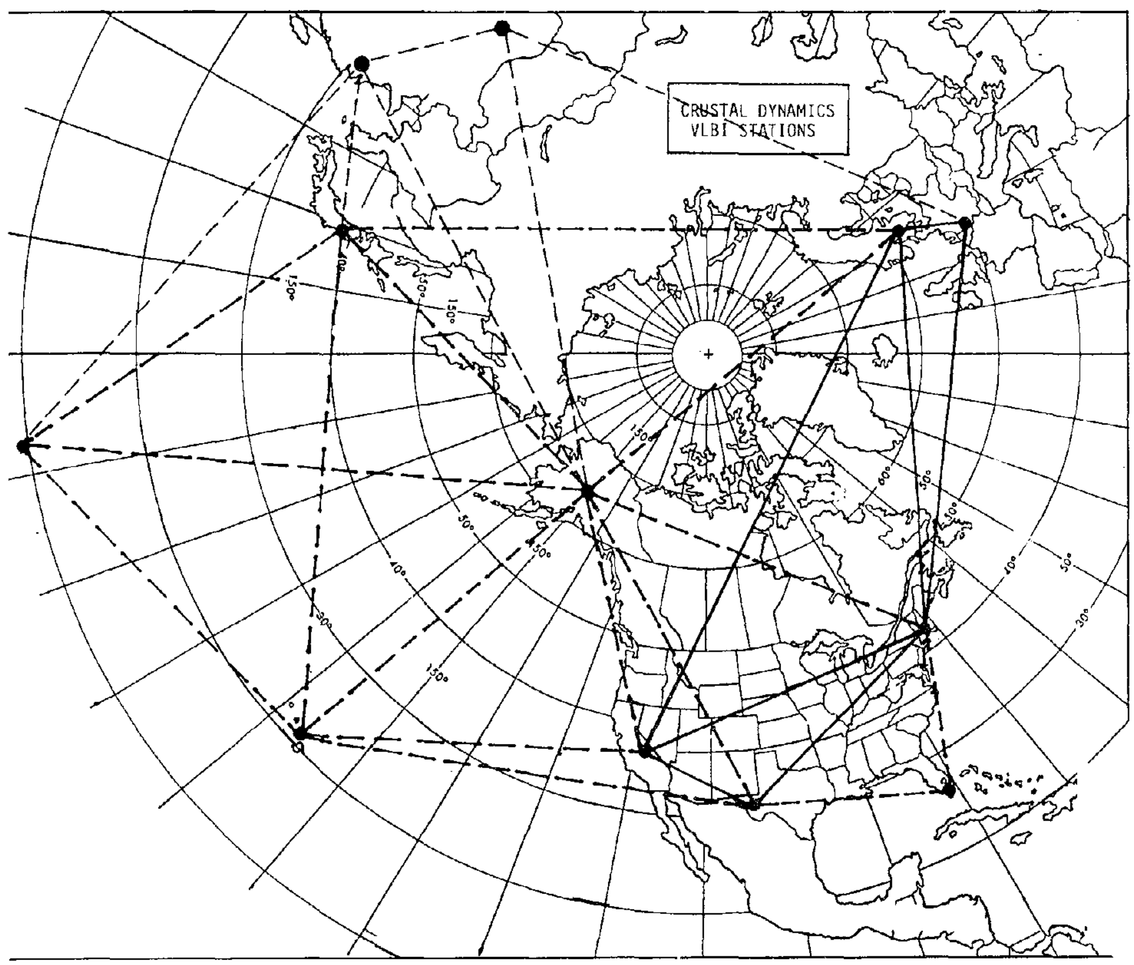

FIGURE 11-5 Crustal dynamics VLBI stations.

It is NASA's intent that the Crustal Dynamics Project serve as the beginning stepping-stone leading to a regional and global program of geodetic measurements that are carried on by operational groups within the various countries around the world. In the United States, the National Geodetic Survey is planning to take over the operation of the mobile VLBI systems and the associated base stations in order to continue the measurements in the United States started by the Crustal Dynamics Project. This group of stations will become the National Crustal Motion Network (described by William Strange in Chapter 22). NGS will assume this operational responsibility in 1985 and will continue direct support of the Crustal Dynamics Project through 1988. This is the date of the formal end of the Crustal Dynamics Project. The NASA Geodynamics Program will continue this type of activity after 1988 through new projects that will be formed. The degree of future activities by NASA in geodetic VLBI depends upon the extent of involvement of U.S. and foreign operating agencies in the continuation of this type of measurement program. It is clear that VLBI measurements for plate motion, crustal deformation, and polar motion and UT will be continued for a long period of time.

The Very Long Baseline Array (VLBA) is scheduled to become operational at about the end of the Crustal Dynamics Project. Many of the VLBA stations are in close proximity to the United States stations used by the Crustal Dymamics Project. Specifically, the VLBA stations in Massachusetts, Texas, California, and Hawaii appear to be quite suitable for providing continuing geodetic measurements to the scientific community. In order for this to happen, it would be necessary for the VLBA to be compatible with the MARK III system that is in use throughout the world in the observatories shown on the map. In addition, it would be necessary to have the array capability to operate in the global mode in conjunction with the worldwide group of observatories. The next chapter, by Thomas Clark, will discuss in more detail some of the features of the systems that would provide maximum capability in interfacing with the global community. At the beginning of this paper it was mentioned that the Crustal Dynamics Project also uses satellite laser ranging for this type of geodetic measurement. One reason for using two kinds of systems is that it enables the intercomparison of the performance of the two systems as a means of determining the errors in each of the systems. This is about the best way of calibrating these high-accuracy systems. In the Crustal Dynamics Project, approximately 30 percent of the measurements are made by both systems, so that we have a very careful check on the performance. If the VLBA were to be used in the geodetic community, then a provision would be needed for the occasional occupation of the same sites with laser systems or other high-accuracy geodetic systems for the purposes of maintaining calibration of the VLBI systems.

A third type of system is in the planning for use by the Crustal Dynamics Project. This is the recently developed Global Positioning System (GPS). Several groups have just produced specialized GPS receiving systems designed specifically for centimeter-level geodetic measurements. The achievement of this high accuracy does require that the orbit of the GPS satellites be determined very accurately. Thus it is planned to locate a few GPS receivers at the same site as VLBI antennas. These receivers will be at known locations, as determined by VLBI, and will be able to track the GPS satellites in order to determine the position of the satellite to the centimeter level. It appears that in the future, the VLBA could be utilized for this type of GPS fiducial mark location. This application will be discussed in more detail by Charles Counselman in Chapter 21.

12

MEASUREMENTS OF CRUSTAL MOTION

Thomas Clark
Goddard Space Flight Center

In this chapter I will describe what is being done in the making of precision geodetic measurements with very long baseline interferometry (VLBI). A few months ago a number of practitioners of geodetic VLBI tried to assess our error budgets; the composite chart in Figure 12-1 is the result. John Spencer (in Chapter 9), in referring to polar motion and UT, used the right-hand column and took the optimistic view that we had water vapor radiometers (WVRs). Please note that the wet troposphere is the dominant error term in each of the sums shown and that much of the uncertainty arises because WVRs are only now coming into use in an experimental way for calibrating data. They are not available for all stations and do not yet constitute a proven geodetic tool, although they have produced some interesting results.

We are reaching a point at which the baseline measurement seems to be good to about a fringe. Once we reach the level of a fringe, and can trust our calibrations to get to the level of a fringe, then another step forward will be possible. We should then make use of the actual fringe phase on the sky as a much finer ruler within which to make geodetic measurements. We have attempted to use that technique. Several years ago, between the Haystack and Westford observatories (a 1.24-km baseline), we showed that with that technique, even with independent oscillators, we could achieve millimeter-level measurements. However, we must have calibrations commensurate with those numbers.

The current levels of achievement are in the 1- to 3-cm range, except for the local vertical, where the troposphere acts as an additional corrupting agent. Uncalibrated tropospheric contributions, especially on short baseline measurements, essentially raise and lower the apparent level of the station.

The scientific community wants to improve measurements in the vertical to follow the response function of the lithosphere--the perturbations in the crust following earthquakes--and to try to find out more about the nature of the fluid down there. Improving measurements in the vertical is currently a major activity.

Let us now discuss measurements on motion (or nonmotion) seen with VLBI. Peter Bender showed in Chapter 7 a chart of our Haystack to Owens Valley measurements, which now extend over more than 6 years, with some 50 observations. We have detected no motion at levels of

CONTRIBUTIONS TO "BOTTOM LINE" BASELINE RESULTS				
	400 KM			4000 KM LONG BASELINE LENGTH
	VERTICAL	HORIZONTAL		
		TRANSVERSE	LENGTH	
• INSTRUMENTATION	1.4 CM	0.9 CM	0.9 CM	1.0 CM
• IONOSPHERE	0.2	0.1	0.1	0.2
• DRY TROPOSPHERE	1.5	0.6	0.8	0.5-1.0
• WET TROPOSPHERE (1)	4.0/<9.0	0.5/1.0	0.6/1.2	1.5/<3.0
• UT1/POLAR MOTION (2)	0.6/1.3	0.6/1.3	≅ 0	≅ 0
• SOURCE STRUCTURE	0.3	0.3	0.3	0.3
• AGGREGATE RSS ESTIMATE	4.6-9.3 CM	1.4-2.0	1.4-1.7	2.0-3.3 CM

(1) FIRST NUMBER ASSUMES WVR, SECOND ASSUMES THE USE OF MODELING OR SURFACE METEOROLOGY DATA

(2) ASSUMES 10-20 CM A PRIORI DATA (E.G. POLARIS, SLR OR LURE)

FIGURE 12-1 VLBI error source summary: crustal dynamics project configuration based on one-day measurement sessions (consensus of VLBI working group in preparation for Oct 82 investigators meeting).

under 1 cm/yr; it is about 3 mm/yr, with 1-σ formal standard error. None of us believes 1-σ formal standard errors, so I have called it less than one.

The Westford-Fort Davis Baseline, which resulted from the POLARIS measurement effort that William Carter alluded to in Chapter 8, has also shown a nondetectability of baseline motions at levels of about 1 cm/yr. This finding is based on about 2 years of data, including approximately 100 observations.

With these two sets of 50 and 100 repeated determinations, we are better able to consider the VLBI as a geodetic tool, and to ask, regardless of the size of the formal standard error, how do measurements repeat? If one assumes that there were no motions at the baselines, the RMS repeatability of measurements is at the 2-cm level; it is in accord with the error chart that I showed.

Another baseline for which we have some 10 years of observations and some 35 measurement points extends from Haystack to Green Bank, 850 km; findings there are under 1 cm/yr of motion. In addition, as was reported at a meeting just before this one, the triangle comprising an antenna at the Jet Propulsion Laboratory (JPL), the Owens Valley antenna, and an antenna at Goldstone was also showing under 2 cm/yr of motion on any of the legs of the triangle, ranging from 200 to 400 km. The findings are based on about six to eight observations per baseline.

All the stations, with the exception of Puerto Rico and Hawaii, are located on the North American Plate (8 of the 10 stations). The proposed Puerto Rican station would be located on the Caribbean Plate, which is moving to the right at about 2 cm/yr velocity, while the Hawaii station would be located on the Pacific Plate.

Let us look now at some regional aspects of tectonics. The two New Mexico observatories are on opposite sides of the Rio Grande Rift. The Rio Grande River is a rifting river caused by separation of the plate across that boundary. Clearly, there is still some current geological activity; the mountains in the area have shown fairly recent volcanic activity, and hot springs and hot vents are prevalent throughout the Rio Grande Valley area. With the connected-element radio link between these observatories and the Very Large Array (VLA), it should be possible to measure spreading across the Rio Grande Rift, which in this epoch is unlikely to be more than 1 or 2 mm/yr but could prove to be an interesting technique synthesis.

The Owens Valley site is located within a few kilometers of the largest earthquake in North America, which occurred in 1872. The extensive volcanic activity and block faulting that occurred as a result of the 1872 earthquake, extending from Lone Pine nearly to Bishop, are easily observed. Because of the antenna located in Owens Valley, some interesting data for aperture synthesis might be obtained. Furthermore, at the moment a large amount of volcanic activity is anticipated slightly to the northwest of the Owens Valley Observatory at Mammoth Lakes, where a hot puddle of molten rock seems to be extruding upward.

Not all earthquake activity is in California. In 1803, one of the highest energy earthquakes that ever occurred in North America was at New Madrid, Missouri. It was felt, and broke glass, as far away as Pittsburgh.

To provide a slightly larger perspective on the VLBA, I took Figure 12-2 from an old document: it includes many of the right stations. Based on conventional tectonic wisdom, where the velocities are derived with time constants of hundreds of thousands to millions of years, the expected velocities between certain stations are of some interest. The Hawaiian station would be expected to move 3.1 cm/yr. The pole of rotation of the Pacific Plate as it moves up goes through New England, so the velocity in length with respect to Haystack is quite small, but the Hawaiian station would be expected to move at velocities in the 1 1/2- to 3-cm/yr range with respect to the rest of the VLBA. Therefore, fairly frequent recalibrations of the array should be planned, and there is the possibility of some interesting free aperture synthesis.

Let us now discuss some geophysical problems relevant to the array. The use of polar motion and UT as a means of measuring global atmospheric circulation has been mentioned by Peter Bender. Since the total angular momentum of the spinning earth system has to be conserved, the earth must slow down as the atmosphere increases speed. By measuring the earth's slowing, one can determine how the integrated winds are blowing. Meteorologists might find this information useful, if for no other reason than as a way to check their independent determinations of integrated winds over the surface of the earth. There are many gaps in their measurement strategy because they lack observatories in a number of places where they would be desirable.

From:	Onsala	Effelsberg	Kashima	Brazil	Hawaii	Kwajalein	Arecibo
To:	---------- NORTH AMERICAN PLATE ----------						
Haystack	+1.7	+1.9	-0.4	-0.2	+0.8	+0.5	+0.4
NRAO	+1.7	+1.9	-0.5	-0.4	+1.5	+1.2	+0.4
Ft.Davis	+1.5	+1.6	-0.8	-0.7	+3.1	+2.8	+1.7
OVRO	+1.4	+1.5	-0.9	-0.6	+1.6	+2.3	+1.5
Alaska	+1.0	+1.1	-0.7	-0.2	-5.2	-2.3	N/A
Algonquin	+1.7	+1.9	-0.5	-0.3	+0.4	+0.4	+0.6
To:	---------- PACIFIC PLATE ---------						
Hawaii	-2.7	-2.0	-8.7	+3.5	-	-	N/A
Kwajalein	-4.0	-3.6	-9.4	+2.4	-	-	N/A
To:	---------- EURASIAN PLATE --------						
Onsala	-	-	-	+1.1	-2.7	-4.0	N/A
Effelsberg	-	-	-	+1.3	-2.0	-3.6	N/A
Kashima	-	-	-	-0.1	-8.7	-9.4	N/A
To:	---------- SOUTH AMERICAN PLATE ----------						
Brazil	+1.1	+1.3	-0.1	-	+3.5	+2.4	-1.3
To:	---------- CARIBBEAN PLATE ---------						
Arecibo	-0.6	-0.6	N/A	-1.3	N/A	N/A	-

FIGURE 12-2 Interplate velocities (in centimeters per year) for proposed VLBI baselines. Calculations by G. Mead (NAS/GSFC) based on model of Minster and Jordan.

Water distribution on the earth might become detectable through polar motion and UT. For example, if the Eurasian Plate had heavy snowfall one year and North America had only light snowfall one winter, the distribution of mass on the surface of the earth would change, causing the earth to tilt with respect to the inertial rotation axis.

The core-mantle interface and the dynamics of the core are of continuing interest; polar motion and UT will provide information about them.

Finally, quake precursors or postcursors and the response of earthquakes are additional kinds of VLBA data and output that could have great impact on society.

In regard to plate deformation, I mentioned the spreading across the Rio Grande Rift and that Owens Valley is a dynamic area. One of the fundamental assumptions of plate tectonics is that certain parts or lumps of plates are fairly rigid entities. If they were found to be slushy, then much of plate tectonics theory would have to be revised. The VLBA will present some intriguing possibilities for plate motion determinations. The VLBA would provide a very good antenna for Hawaii and the Pacific Plate. The Crustal Dynamics Project attempted to find an available site in Hawaii. Such a site would be advantageous. If there is any choice in the order in which antennas for the VLBA are built, I would like to see one in Hawaii before termination of the Crustal Dynamics Project in 1988.

The Caribbean Plate is another focus of interest. Based on the Caribbean Basin Initiative, NASA has augmented the Crustal Dynamics Project to permit extensive measurements in the general Caribbean Basin area. Arecibo, or the Puerto Rican area, would complement that program.

Measurements to many other points on the earth would also be advantageous, as Robert Coates emphasized in Chapter 11.

Let us consider how geodesy will be done in the 1990s. First, I believe that there will be polar motion and UT networks of the type described by William Carter in operation (see Chapter 8), and that every few days, independent of the array, these will deliver polar motion determinations at accuracies of better than 1 milliarc sec and UT1 at better than 40 microtime seconds. Those networks, combined with radio astronomy facilities and tracking stations around the world, including the VLBA, could be linked a few times a year to form special grids for measuring global-scale plate tectonics. These measurements should be at the 1 or 2 cm level by the 1990s.

Velocities, as I showed earlier, are measured in centimeters per year. Therefore a measuring program to follow plate motions would be possible; it would probably be a little too long a program for a graduate student project. Whether it would be undertaken as a calibration for the VLBA or as a scientific measurement in its own right would have to be decided.

In addition, sparse transcontinental-scale (1000-4000 km) measurements will be made a few times a year with VLBI, using all existing stations, to collect data on the stability of the plates and to serve as fiducial points to co-locate receivers and systems as part of the Global Positioning System (GPS) or its successor to do routine surveying on a dense scale. Measurements on the sparse transcontinental scale are needed only a few times a year because there would be a set of GPS satellites that essentially define a stable geometric grid. As long as the plates are not moving, one could rely on the integrity of that grid and use the co-located GPS stations daily for calibrating the orbit of the satellites.

My view, then, on the frequency of use of the VLBA for geodetic purposes is that only a few measurements a few times a year would be needed. However, even on those time scales it could be quite useful. More dense measurements in time for polar motion and UT, and more dense measurements in space for geodetic grids, would be done by other networks in conjunction with the VLBA.

In conclusion, a few words about what the geodetic community will need from the VLBA. Because the geodetic community will have its own networks, some degree of compatibility between the instrumentation chosen by the VLBA and that used by the geodetic community will be required. At present, that would mean MARK III and S and X band frequencies. Those are not necessarily numbers to be maintained in perpetuity, but they would be current requirements for compatibility. Further, in planning the VLBA there should be a philosophical commitment to achieving proper calibration of the data, using phase calibrators, and WVRs, allowing for two frequency measurements for the removal of ionospheric biases, and the like.

Routine VLBA calibrations, both reduced baseline data (possibly on polar motion and UT) as well as the raw VLBI data (the delay-rate observables) should be made available to those in the geodetic community who may be working with much more precise models of the earth for their analyses than might be in place in the array. Thus from the outset data should be exportable, not only at the baseline level but also at the more fundamental level coming from the correlator.

The VLBA should be usable in international networks. International networks are essential not only for astronomy but also for geodesy, because global-scale plate tectonics issues are worldwide concerns. Sites of particular geophysical interest include Hawaii, which is the only good radio telescope on the Pacific Plate; Puerto Rico, because it would be a unique facility on the Caribbean Plate; and the linkage between the VLA and the two sites in New Mexico. Various subelements of the array will present opportunities for geophysical measurements of intrinsic interest. The ability to make use of these subelements will be important.

I assume that time on the VLBA will be allocated on the basis of competitive proposals, as has been done at other national facilities. The geophysical sciences should be considered as competitive sciences for the purpose of proposal evaluation. I anticipate that members of the geophysics community will submit proposals for use of the array for geophysical measurements.

I also think that it would be desirable to allow for co-location of GPS at the VLBA sites, or at least at several of the VLBA sites. It will be important to have some representation of the geophysics community on steering and advisory committees for management and operation of the array.

Finally, I agree with William Carter that the VLBI community, which will be working independently, will need the source maps, source fluxes, source coordinates, and other data coming out of the array.

DISCUSSION

CANNON: I want to congratulate you on a complete picture of what would be required in the array installation. I would like to add one comment: The great strength of these techniques for geophysical applications is that they are insensitive to the gravity field. In a sense, that is also a weakness, for much classical geodesy is related to determining the shape of the geoid--interpreting the geoid in terms of subsurface structure. In the Canadian proposal, we are considering co-locating absolute gravimeters at selected sites as well, because both Global Positioning System Network (GPSN) and the VLBA technique will not tie to the gravity field at all.

CLARK: They don't have to be co-located. But if you are going to have a facility, it might as well be at the same site.

HEILES: When you say the Crustal Dynamics Project will end in 1988, what does this mean?

CLARK: Current plans call for ceasing operation in 1988, when R&D activity should have reached a state where instrument systems will have been turned over to agencies that are more responsive to operational needs. The same was true for weather satellites: NASA did the early developments. When they became operational tools we turned them over to NOAA.

FLYNN: The geodynamics program will continue past 1988. That is, we are writing a program plan for continuation of these types of measurement activities to complement what will be done in operational agencies to which we are turning over some--not all--of the equipment.

COATES: One thing both Dr. Clark and I neglected to mention is that the measurements we are talking about for baselines are a few parts in 10^9 in the precision; there is no good way to calibrate that a priori. We will have to continue to use competitive systems. The Crustal Dynamics Project is using satellite laser-ranging to make the same baseline measurements in 30 percent of the cases for direct intercomparison to calibrate both systems. They have different error sources, so running them together is quite useful. In the future for global and even local measurements, there should be provision for other techniques as part of the calibration program.

CLARK: Yes. There are investigators from the geophysical sciences and geodetic measurement sciences who may want to be able to obtain additional information for special purposes. We may need more ground around each antenna.

SHAFFER: The sites should have some established reference point. That is, VLB astronomers tend to think of the antennae as theirs, but there should be some fiducial mark on the site so that others can bring in a device and locate, too, without a great deal of difficulty.

CLARK: That service has been provided by the National Geodetic Survey (NGS). Dr. Strange might address this when he talks about the National Crustal Motion Network.

III. Astrometry

13

OVERVIEW OF ASTROMETRIC PROBLEMS

Gart Westerhout
U.S. Naval Observatory

Astrometry is the determination of positions, motions, and coordinate systems and the entirety of the products of these observations. It is generally separated into two areas: fundamental and relative.

Fundamental astrometry consists of the determination of a reference frame based on the positions of a number of suitable objects--stars optically and quasars in radio astronomy. Determination of the coordinate system to which these positions are referred is an integral part of the measuring and reduction process. Traditionally and historically, the zero points of this coordinate system are referred to the dynamics of the solar system.

Because the stars used in the fundamental reference frame have tangential motions (called proper motions), determination of these motions is an integral part of the determination of a fundamental reference frame. Without them, the reference frame would be useless at times other than its epoch of observation.

These may be considered platitudes. "We know all this." We also "know" that a fundamental reference frame based on quasars does not suffer from proper motion effects--or does it? The classical zero point of the radio reference frame, quasar 3C273, is changing shape. Study of internal motions of numerous quasars are part of the Very Long Baseline Array (VLBA) program. We cannot make any assumptions about the quality of the radio reference frame. Determining its quality, as in the optical case, must include studies of individual motions.

But let me dwell on the stars a bit longer. A knowledge of the proper motions of large numbers of stars has a direct and fundamental impact on many basic areas of astronomy. Three such areas are stellar kinematics, stellar dynamics, and clusters and associations. Each of these, in turn, can be broken down into a number of subareas or problems as follows (taken from the Astrometry Working Group of the Field Committee Study):

1. Stellar kinematics
   a. Local space motions of different types of stars
   b. Velocity gradients
   c. Solar motion
   d. Galactic rotation (Oort's constants)
   e. Statistical and secular parallaxes

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f. Comparison with kinematics of gas and dust
g. Determination of precession

2. Stellar dynamics
a. Effects age/size/density of clusters and associations
b. Spiral structure and its evolution
c. Orbits of halo and disk objects
d. Galactic gravitational potential

3. Clusters and associations
a. Membership
b. Distance and calibration of the magnitude scale
c. Expansion/contraction, internal kinematics
d. Relation between kinematics and age/chemical composition

I will not dwell upon all of these areas. Let me just expand on a few basic ones. Limitations of accuracy and systematic errors in the fundamental proper motion system as well as a paucity of data are forcing upon us a highly simplified and certainly unrealistic model for galactic kinematics; examples are galactic rotation and ellipsoidal velocity distribution. Statistical parallaxes for the disk stars and halo stars, upon which studies of their luminosities and kinematics depend, are insufficient to aid further the rapid development of astrophysical theory of stellar evolution. These stars include types crucial to the determination of the distance scale. Details of stellar evolution, for example of RR Lyrae and CH stars, are insufficiently understood.

More accurate proper motions are needed to allow more adequate modeling of the galactic velocity field, study of the dependence of parameters of the velocity distribution on location within the galaxy, and the behavior of the galactic potential perpendicular to the galactic plane. More accurate proper motions would also make it possible to discover the relationship between kinematic properties and physical characteristics, such as chemical composition in various parts of the galaxy; to test the reality of the missing-mass hypothesis; to improve the determination of the dynamical local standard of rest; and to derive a better understanding of star formation and spiral structure from improved analysis of Gould Belt dynamics.

What does all this have to do with the VLBA? It has been long known that modern fundamental catalogs differ substantially from the fundamental system FK4, and most of them in the same way. From the studies by Schwan and Fricke in Heidelberg, who are preparing the new FK5, it is abundantly evident that there are major systematic errors in the FK4. These are system errors, and they occur all across the sky. They include the proper motion system. What system errors will there be in the FK5? Where do they come from? Can future optical measuring technology avoid them?

Such questions pop up whenever a new fundamental coordinate system is established. And they can be approached realistically only when fundamentally (pardon the pun) different techniques can be compared. The radio reference frame uses a new technique. What are its internal (zonal) systematic errors? Does one really find them when comparing one radio catalog with another? Obviously, the answer is that the relationship between the radio and optical fundamental systems needs to be determined with an eye toward finding the ultimate flaws in both. We cannot start adjusting one by "assuming" the other is better before we have proven it. Therefore, the expression "tying the optical to the radio frame" is not an appropriate one.

But this is the province of Kenneth Johnston (see Chapter 14). I am sure he will allude to the fact that direct comparison of positions is difficult. The faint quasar images cannot be measured fundamentally with any current optical technique. Schemes using the USNO 61-in. reflector and other telescopes to compare positions of faint quasar images with bright fundamental stars are being explored. The European astrometry satellite HIPPARCOS, if successfully launched in 1986-1987, when teamed up with Space Telescope, would provide an excellent means of comparison. Proposals have been made to tie SiO masers into the quasar reference frame, and their parent stars into the optical frame. And then VLBA might be able to observe a limited number of "real" stars, which would indeed be the ultimate solution.

I have concentrated on the proper motion system as the area most directly underlying many fields of astrophysics. But I should not omit mentioning the value of star or quasar positions as "fixed" positions, especially in the field of solar system studies. Accurate positions are a must for following planetary motions, whether they be optical positions of stars or radio positions of quasars. The quasar reference frame developed by Jet Propulsion Laboratory (JPL) was in response to the direct need of deep space guidance.

The next few chapters will address other pitfalls in astrometry, or perhaps I should say "other problems that the VLBA might be able to solve." Precession, nutation, other motions of the earth, and the dynamical reference frame and its relation to the FK5 and radio reference frame have all caused problems in fundamental astrometry that the VLBA may be able to set aside--at least for a while. I have not addressed "relative astrometry," i.e., motions of objects relatively close together, or motions inside objects. The latter, in fact, is bound to be an important part of the VLBA observing program. I fancy calling that astrometry, and come to the conclusion that the VLBA is to a considerable extent an astrometric instrument par excellence, assisting in many of the classical astrometry areas, from motions of the earth out to galactic structure and dynamics and the extragalactic distance scale.

DISCUSSION

<u>REID</u>: One thing that might be noted is that with a dedicated array we can make rapid measurement on a source that flares. We can't do that with the present array. We can see stars that suddenly flare, and do something through this line system in that way.

<u>WESTERHOUT</u>: We could if we built that into the operating system. However, many investigators would dislike being thrown off a telescope because someone else wanted to observe a flaring star.

14

TOWARD THE DEFINITION OF AN INERTIAL REFERENCE FRAME

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INTRODUCTION

Extragalactic radio sources are the most distant objects known. As such their angular motions on the celestial sphere should be minimal when compared to motions of bright nearby (3,000 light years) stars that define the fundamental reference frame, FK4. Measurements of motions between extragalactic sources that are located in close proximity on the celestial sphere (Shapiro et al. 1979) have shown the relative motions of the quasars 3C345 and NRAO 512 to be less than 0.5 milliarc sec/yr. Therefore it is feasible that catalogs of the positions of extragalactic radio sources define an almost inertial reference frame against which motions of objects on the earth, motions of the earth, objects in the near-earth environment (satellites), and objects on the celestial sphere (planets, stars, and galaxies) may be determined. Thus fundamental radio source catalogs are of great interest to a wide variety of scientific disciplines such as astrophysics, astrometry, geodesy, and geophysics.

Coordinate reference frames now in use are based upon the positions of optical objects. These reference frames contain over a thousand stars; i.e., the FK4 contains 1535 fundamental stars, and the future FK5 system will have over 5000 stars. Radio astrometry is still in its infancy, and before available radio source catalogs are discussed, some estimate should be made of the number of available sources. The earlier low-frequency Cambridge and Molongo surveys were followed by the higher frequency (2.5 and 5 GHz) pencil beam surveys (Pauliny-Toth et al. 1978; Shimmins et al. 1975), which position to arc minute accuracy almost all radio sources with flux densities greater than 0.6 Jy (1 Jy = 10^{-26} W/m^2Hz) at absolute value of galactic latitudes greater than 10°. These surveys indicate that there are approximately 1500 extragalactic sources of intensity greater than 0.6 Jy over the entire celestial sphere. Johnston et al. (1980) estimate 20 percent of these sources will have their dominant emission in unresolved components of size of order milliarc seconds, making these sources suitable for defining an inertial reference frame. The number of sources in future radio catalogs may be extended to over several thousand using the proposed VLBA, as it will be able to precisely determine the position of sources as weak as 50 mJy.

Recent high angular resolution surveys of radio sources have confirmed these estimates. In a survey of a complete sample at a radio frequency of 5 GHz of extragalactic radio sources of flux density greater than 1 Jy north of declination -40° and galactic latitude greater than an absolute value of 10°, 262 sources were found to contain 90 percent of their flux density in components less than 1 arc sec (Ulvestad et al. 1981). In another survey at 2.3 GHz, Preston and Moribito (1980) found that 52 sources display a flux density greater than 1 Jy, 210 sources flux density greater than 0.5 Jy, and 665 sources flux density greater than 0.1 Jy on scale sizes less than 5 milliarc sec.

The distribution of sources should be uniform over the celestial sphere in order to precisely measure the relative positions of antennas for applications in geodesy and geophysics. A reasonable density distribution could be one source every 400 square degrees or approximately 103 sources uniformly placed over the entire sky. These should be the brighter sources (1 Jy at 5 GHz), visible with a minimum size antenna pair (each antenna 20 m in diameter), have small apparent sizes (~1 milliarc sec) and positional stability. A catalog that comes closest to this goal is the JPL catalog defined by O. Sovers et al. (private communication, 1982).

A radio catalog is also of great interest in understanding present reference frames. A working group of Commission 24 of the International Astronomical Union (IAU) was formed during the colloquium "Modern Astrometry" in 1978 to coordinate the identification of radio sources and their optical counterparts with a view toward the determination of precise positions, which will lead to an investigation of the relationship between the optical and radio frames. This working group has thus far identified 236 sources distributed over the celestial sphere. There is a paucity of sources south of -40° declination, but research is progressing that will find appropriate sources.

AVAILABLE PRECISE CATALOGS

The positional precision of radio source measurements has constantly improved over the last 30 years. Here we will deal only with precision because radio measurements of the position of extragalactic objects are made with respect to the instantaneous pole of rotation of the earth at the time of measurements. Therefore the celestial positions reported depend upon the models for earth motions such as polar motion, spin axis motion such as precession, and nutation, as well as revolutionary motions about the earth-moon barycenter and solar system and solar galactic motions. The accuracy of the measurements depends upon the antenna geometry used. East-west antenna geometries give very poor positional accuracy near the equator. Thus the Cambridge measurements by Elsmore and Ryle (1976) made with an east-west baseline yielded a precision of 0.03 arc sec near the zenith (declination 40°) and were substantially degraded at declinations below 20°. Wade and Johnston (1977) measured 34 sources ranging in declination from -20° to +70° to accuracies below 0.08 arc sec. In 1978, Fanselow et al. (1980) measured sources from declination -40° to +70° with a precision below 0.03 arc sec.

Table 14-1 presents a summary of high-precision catalogs with quoted positional precisions of 0.1 arc sec or less containing a large number of sources. The catalogs are divided up into those determined by connected link interferometry and very long baseline interferometry (VLBI). The precision of the catalogs varies from 0.10 to 0.003 arc sec. The radio frequencies of the measurements are between 2 and 8 GHz. Earlier measurements were made at only one frequency. The later catalogs of Hilldrup et al. (1983), Kaplan et al. (1982), Ma et al. (1983), Purcell et al. (1980), and Shaffer et al. (1982) were made at two frequencies between 1.4-2.6 and 4.9-8.4 GHz in order to eliminate the delay path length in the ionosphere as a cause of systematic error.

It is very difficult to compare the catalogs because the earlier work was expressed in terms of the standard B1950 epoch. The constants involved in precession, nutation, other earth rotation parameters, as well as time scales are not expressed as exactly in this system, which is based upon the fundamental catalog FK4, as in the new standard epoch J2000, which is based upon the new FK5 system. For example, the precession constant in the earlier system differs by 0.01 arc sec per year from that of the FK5 system. The IAU adopted resolutions during the general assemblies of 1976 and 1979 establishing the FK5 fundamental reference frame. However, exact transformation to the FK5 system cannot be performed until the catalog containing the stars defining the reference frame is available. One can see from the epoch of observations of the different catalogs that this effect is very important. Before attempting to directly compare catalogs, one should look for rotations between the coordinate reference frames. This will occur even when positions are expressed in the standard J2000 epoch of the FK5 reference frame. These rotations will lead to improved knowledge of the effects of earth rotation parameters and of motions of the earth, sun, and galaxy. The precession of the "best" catalogs in Table 14-1 is of the order of a few milliarc seconds, and these are VLBI catalogs. These catalogs were made from observations obtained over a period of several years. In contrast, the connected-element catalogs are made from only three or fewer observing epochs spaced at most by a year. The catalog claiming the highest precision (Ma et al. 1983) was reduced in a manner compatible with the J2000 reference epoch. The common sources from the Ma et al. (1983) catalog compare favorably with the other catalogs within the errors of the other catalogs. For example, the root sum of the squares of the differences for 16 common sources in the Ma et al. (1983) and the O. Sover et al. (private communication, 1982) catalogs is at the 3-milliarc sec level.

Evidence for the stability of the reference frame defined by extragalactic radio sources can be demonstrated by the repeatability of the positions in the various catalogs. The position of the very variable source BL Lac appears to be stable at the 2-milliarc sec level for the period 1978-1982. The flux density from this source has recently undergone variations in intensity by a factor of 5, indicating several outbursts in the 1980-1981 time frame. The milliarc second

TABLE 14-1 Catalog of Radio Source Positions

Authors	Instrument	Number of Sources	Precision (arc sec)	Observing Epoch	Reference Epoch
<u>Connected Element Interferometry</u>					
Elsmore and Ryle (1976)	Cambridge	55	0.03	1973.1;1974.2	1950
Elsmore (1982)	Cambridge	25	0.03	1979.8	1950
Hilldrup et al. (1983)	VLA	29	0.02	1980.0	1950, 2000
Kaplan et al. (1982)	Green Bank	16	0.01	1979.9	1950, 2000
Perley (1982)	VLA	393	0.05	1981.0	1950
Wade and Johnston (1977)	Green Bank	34	0.03	1975.4	1950, 2000
Ulvestad et al. (1981)	VLA	250	0.10	1979.10	1950
<u>Very Long Baseline Interferometry</u>					
Clark et al. (1976)	U.S.-Europe	18	0.04	1973.9	1950
Purcell et al. (1980)	Madrid-Goldstone-Tidbinbilla	117	0.01	1978.0	1950
Shaffer (1982)	U.S.-Europe	48	0.005	1981.5	2000
Ma et al. (1983)	U.S.-Europe	21 MK II	0.002	1975.2	2000
		71 MK III	0.001	1981.2	2000
O. Sovers et al. (private communication, 1982)	Madrid-Goldstone-Tidbinbilla	117	0.002	1077; 1978	2000

structure has been shown by R. Phillips and R. Mutel (private communication, 1983) to be that of a typical superluminal source in which the radio core dominates the emission with one-sided emission moving away from the central core with an apparent velocity in excess of the velocity of light.

RELATIONSHIP WITH OPTICAL REFERENCE FRAMES

The radio interferometric technique defines the instantaneous source declination, but leaves the zero point of right ascension to be uniquely defined. Optical astronomers define the zero point of right ascension in terms of the dynamical reference frame of the planets by designating the first point of Aries as the zero point. Radio astronomers have attempted to align their coordinate reference frame as follows: (1) Adjusting the right ascension of a radio source with a known optical counterpart to be coincident with the optical position. The occultation position of 3C273B measured by Hazard et al. (1971) has been used by many. The position of several optical counterparts of radio sources has been measured at the 0.05 arc sec level (de Vegt and Gehlich 1978). (2) Adopting the position of a known optical star such as Algol to be coincident with its associated variable radio emission. At this writing the position of the continuum radio emission associated with 16 stars has been measured (Johnston et al. 1983). The position of the maser emission associated with stars has also been measured (Bowers et al. 1983). (3) Relating the zero point to the dynamical solar system reference frame by measuring the radio position of known solar system objects such as asteroids (Johnston et al. 1982) or orbiters of planets. All these measurements are in their infancy.

NEEDS FOR FUTURE VLBA MEASUREMENTS

Future VLBA measurements of source positions need to be made as follows:

- These observations should be expressed in a uniform manner on the standard J2000 reference epoch on the FK5 reference frame defined by the IAU system of astronomical constants as defined by the resolutions passed at the 1976 and 1979 general assemblies. The data should be expressed so that the complete observable can be reconstructed. This is extremely important because only with this knowledge can the data be analyzed for precise determination of earth rotation parameters, precession, nutation, etc. These data must contain the epoch of observations, the delay and delay rates, etc.
- The observations should be made using the following: (1) dual radio frequencies to eliminate ionospheric effects, (2) wide radio bandwidths (400 MHz) to ensure highest accuracy, and (3) incorporation of water vapor radiometers and weather stations to calibrate atmospheric effects.
- Source structure should be measured at timely intervals in order to remove this effect from the catalog positions.

- A core list of approximately 50 sources should be established. These sources should be primarily used as the calibrators for measuring precise baselines.
- The right ascension zero point should be established by a single extragalactic source.

The use of two frequencies, synthesized wide radio bandwidths, and water vapor radiometers was introduced as part of the advanced MARK III VLBI system built by the Haystack Observatory and Goddard Space Flight Center as part of the NASA Geodynamics program.

SUMMARY

The precision of radio source catalogs appears to have reached the 3-milliarc sec level. The positions of these radio sources independently define an inertial reference frame. The reference frame in which these positions are expressed to allow comparison between catalogs does not at this time have this precision. Therefore as a holding measure, it is recommended that future radio catalogs be expressed in the FK5 reference frame using the standard J2000 reference epoch for cosmetic comparison of results. For detailed comparison, means should be established so that the basic observables can be recovered in order that positions of common quasars from different catalogs can be compared in a fundamental way. By detailed comparison, improved values of the constants involved in defining precession, time scales, the nutation series, other earth rotation parameters, and galactic motions will be determined from the rotations and translations of the coordinate reference axes of the different catalogs needed to align the individual sources.

REFERENCES

Bowers, P., J.J. Johnston, and J.H. Spencer. 1983. Submitted to Astrophys. J.

Clark, T.A., L.K. Hutton, G.E. Marandino, C.C. Counselman III, D.S. Robertson, I.I. Shapiro, J.J. Wittels, H.F. Hinteregger, C.A. Knights, A.E.E. Rogers, A.R. Whitney, A.E. Niell, B.O. Ronnang, and O.E.H. Rydbeck. 1976. Astron. J. 81, 599.

de Vegt, C., and U.K. Gehlich. 1978. Astron. Astrophys. 67, 65.

de Vegt, C., and U.K. Gehlich. 1981. Astron. Astrophys. 101, 191.

Elsmore, B. 1982. Abhandlungen aus der Hamburger Sternwarte Band X heft 3, 129.

Elsmore, B., and M. Ryle. 1976. Mon. Notic. Roy. Astron. Soc. 174, 111.

Fanselow, J.L., O.J. Sovers, J.B. Thomas, F.R. Bletzacker, T.J. Kearns, G.H. Purcell, D.H. Rogstad, L.J. Skjerve, and L.E. Young. 1980. IAU Colloquium No. 56, Warsaw.

Hazard, C., J. Sutton, A.N. Argue, C.M. Kenworthy, L.V. Morrison, and C.A. Murray. 1971. Nature 233, 89.

Hilldrup, K., E.B. Fomalont, C.M. Wade, and K.J. Johnston. 1983. submitted to Astron. J.

Johnston, K.J., D. Florkowski, C.M. Wade, S. Dick, and E. Holdenried. 1983. in preparation.

Johnston, K.J., P.K. Seidelmann, and C.M. Wade. 1982. Astron. J. 87, 1593.

Johnston, K.J., J.H. Spencer, G.H. Kaplan, W.J. Klepczynski, and D.D. McCarthy. 1980. Celestial Mech. 22, 143.

Kaplan, G.H. 1981. United States Naval Observatory Circular No. 163.

Kaplan, G.H., F.J. Josties, P.E. Angerhofer, K.J. Johnston, and J.H. Spencer. 1982. Astron. J. 87, 570.

Ma, C., et al., 1983, in preparation.

Pauliny-Toth, I.I.K., A. Witzel, E. Preuss, H. Kuhr, K.I. Kellermann, E.B. Fomalont, and M.M. Davis. 1978. Astron. J. 83, 451.

Perley, R. 1982, Astron. J. 87, 859.

Preston, R.A., and D.D. Moribito. 1980. Radio Interferometry Techniques for Geodesy, NASA Conf. Publ. 2115.

Purcell, G.H., J.L. Fanselow, J.B. Thomas, E.J. Cohen, D.H. Rogstad, O.J. Sovers, L.J. Skjerve, and D.J. Spitzmesser. 1980. Radio Interferometry Techniques for Geodesy, NASA Conf. Publ. 2115.

Shaffer, D. 1982, paper presented at the Union Radio-Scientifique Internationale meeting, Montreal, January 1982.

Shapiro, I.I., J.J. Wittels, C.C. Counselman III, D.S. Robertson, A.R. Whitney, H.F. Hinteregger, C.A. Knight, A.E.E. Rogers, T.A. Clark, L.K. Hutton, and A.E. Niell. 1979. Astron. J. 84, 1459.

Shimmins, A.J., J.G. Bolton, and J.V. Wall. 1975. Aust. J. Phys. Suppl. 1, 34, 63.

Ulvestad, J., K. Johnston, R. Perley, and E. Fomalont. 1981. A.J. 86, 1010.

Wade, C.M., and K.J. Johnston. 1977. Astron. J. 82, 79.

DISCUSSION

COHEN: These potential reference sources not only have internal motions but different centroids for different wavelengths; that has to be taken into account. This is very noticeable, for example, in 3C273.

JOHNSTON: You are right. Sources do vary with wavelengths, and this must be taken into account.

SHAPIRO: For the first time, I believe, we have measured the position in the sky of the center of brightness at one frequency with the center of brightness of another frequency, and the difference is 0.7 milliarc sec.

Although these sources are expanding and changing shapes at the rate of several tenths of a milliarc second per year, the core may well remain stationary in space. The only evidence we have is for the pair 3C345-NRAO 512, where the difference in position between what we think is the core of 3C345 and the unresolved point NRAO 512 drifts in angular position by less than a few hundredths of a milliarc second.

COHEN: Is the virtue of using BL Lac, which has large internal motions, as a primary right ascension reference that it is north-south?

JOHNSTON: No. BL Lac's virtue is its consistency. In all the measurements made over the last 10 years, its position is consistently on the order of a few milliarc seconds in these two catalogs and in other catalogs. I'm sure that some correction will have to be put into the structure, but with BL Lac the structure is fairly small scale. In going to cruder arrays to measure positions, I tried to pick a source with structure, but structure only on a small scale. Perhaps I should have picked A0235 plus 164.

HUGHES: Speaking as an official astrometrist, I believe the radio source reference frame is superb. However, I would like to point out sort of an astrometric Murphy's Law, which we have to deal with. For many, many years in the fundamental reference frame, the fundamental system was defined by relatively bright stars, third-, fourth-, fifth-magnitude stars, and one of the perennial problems in astrometry was to extend that to the fainter stars, say, eleventh and twelfth magnitude, and to bridge that gap of six or seven magnitudes.

It is a horrendous problem that introduces great error. Now we will have optical counterparts of seventeenth and eighteenth magnitude, and we will have to bridge it, except in the other direction. So, once again we will have the problem of bringing this excellent reference frame back to the twelfth or thirteenth magnitude. Unfortunately, we can't seem to end up with a good reference frame where the bulk of the stars that we might be interested in are located.

NIELL: Just one more comment on this right ascension reference. There is always the problem that once you have picked a source, even if it were a point source, in tying the two coordinate systems, you have the problem of uncertainty in the measurement of that one source itself. In the comparisons that have been done between, for example, JPL and Ma's work, there is always a right ascension offset that has to be taken out.

A small extension to the comparison that you did is that there now seem to be about 44 sources in common between the two systems, and the RMS difference in right ascension is about 4 milliarc sec for the 44 sources; for declination it is about 7 milliarc sec.

SHAPIRO: I would just like to point out that you don't have to take out a difference in right ascension between the two catalogs. You have that option, and, in fact, I believe it was rather small, only about 2 milliarc sec.

JOHNSTON: That is what I was trying to warn against: not to go through the commotion of trying to take out the zero point of right ascension.

WESTERHOUT: How can it be that in catalogs, each containing something like 200 sources or so, there are only 43 common? Is there that large a choice?

JOHNSTON: There are 41,000 square degrees on the sky, and we all pick our own sources!

15

ASTRONOMICAL CONSTANTS AND THE VLBA

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The International Astronomical Union (IAU) has recently adopted a new reference coordinate system that is based upon the FK5 star catalog, upon the new value of precession (Fricke 1971), upon a new relationship between Universal Time (UT) and Greenwich Mean Sidereal Time (GMST), upon a new reference equinox and epoch J2000, and upon a new model for astronomical nutation (Wahr 1981). The effect of changes and notes on their implementation are discussed in a paper by Kaplan (1981).

I would like to concentrate on the new versus the old reference system in order to note some of the changes and also to point out the type of problems one will deal with and resolve using a dedicated VLBA. While I will mention the old IAU system, as generally embodied in the FK4 star catalog, and the new IAU system, as it will be characterized by the forthcoming FK5 star catalog--as well as another system, that of the Jet Propulsion Laboratory (JPL) in the fixed 1950.0 frame--my comments can be interpreted in a more general way. If we consider the new system to be truly inertial and the old system to be that of an existing (or future) radio source frame--which may have some drift due to imperfect modeling or choice of astronomical parameters--then we can employ these concepts to discuss the relationships among several practical reference frames. Hence we can discuss some of the problems and interrelationships that must be considered in developing a new reference system.

I would also like to mention the work F.P. Stumpff of the Max Planck Institute (MPI) for Radio Astronomy in Bonn, West Germany, concerning the status of our current knowledge. As we will see, there is an inconsistency among the relationships that describe our best understanding of some of the fundamental astronomical constants. The possible role of the dedicated VLBA in resolving this important inconsistency will be noted.

Finally, I will briefly mention some current and some proposed efforts utilizing very long baseline interferometry (VLBI) techniques that could lead to a better understanding of fundamental reference frames and the system of astronomical constants.

FUNDAMENTAL REFERENCE FRAMES

In the old system (see Figures 15-1 and 15-2), our interpretation of measurements is based upon the reference frame defined by the FK4 star catalog. The relationship between a fixed frame (e.g., 1950.0) and a moving frame is defined by the conventional precession parameter of Newcomb (1898) and the Woolard (1953) series expansion of astronomical nutation. The derived quantity referred to as Universal Time is calculated from an adopted formula that related UT and the more fundamental (viz. observable) GMST. One requires a relationship between UT and GMST (or actually between atomic clocks and sidereal time) in order to relate a terrestrial system to a celestial system.

With this background, I would like to sketch the relationship between the old (FK4) system and the new (FK5) system, with the understanding that the concepts can be applied also to the development of a new radio system from a dedicated VLBA. In the establishment of the new system (Figure 15-3), our goal is to define a grid based upon extragalactic sources that show no apparent motion--that is, an inertial system. We set up an idealized system fiducial point, γ_0^N, which for the FK5 is the vernal equinox and which, for a radio system, may be an arbitrary agreed-upon natural source. Since we are observing from the earth, we need to relate our terrestrial frame to our idealized system. That is represented here generically by precession. An alternate fixed system might be that one, for example, labeled as "JPL 1950," which represents a second practical approximation to the idealized system. This alternate system, employing the same underlying model, may differ a constant rotation (E_0) from the other fixed system. In either case, the source has no apparent motion relative to the system origin γ_0^N.

The third system that I would like to mention is generically called the old system, as represented by the FK4. This old system rotates relative to the new (fixed) system, and the parameters relating the two are required in order to reduce one system to the other. In the future, such relationships would probably have to be considered in relating radio frames, optical frames, and earth-based frames, such as those one might derive from a dedicated VLBA, HIPPARCOS or the Space Telescope, and classical meridian circle data, respectively.

In establishing and in relating such reference systems, there is an intertwined relationship involving geophysics, geodesy, astrometry, astrophysics, and radio science. The determination of timing and polar motion relationships, for example, is necessary for deriving and maintaining an inertial reference system.

SOME FUNDAMENTAL RELATIONSHIPS

I would next like to mention the relationship among three fundamental parameters in astronomy and point out their apparent inconsistency and how a dedicated VLBA might help resolve our understanding. As noted on Figure 15-4, there is supposed to be a known relationship among (1) the mean motion, n_0, of the earth relative to a fixed frame; (2) its mean motion, L_1, relative to a moving frame (the equinox of date); and (3) the rotation rate (precession) between the two frames. Stumpff and Lieske (1983) have thoroughly investigated these relationships via numerical experiments and have obtained the results indicated in Figure 15-5. Their results indicate that there is an inconsistency among the inertial mean motion of a modern JPL ephemeris DE-102 (Newhall et al. 1983), the new (p^{IAU}) precession parameter (Fricke 1971) recently adopted by the IAU, and the generally accepted motion of the sun, L_1^N, due to Newcomb (1898) relative to the equinox of date.

The value of Newcomb, although old, formed the basis for the astronomical understanding of uniform time (Ephemeris Time) prior to the era of atomic clocks, and it was used to derive the rate of our current atomic standards. It really cannot be disregarded simply on the basis of being old, even though, especially here in Washington, Newcomb's rather unique views on the possibility of flight are clearly not quite valid. The classically adopted results of Brown in Improved Lunar Ephemeris (Eckert 1954), for example, also suggest the same relationship. So there is a problem in our current understanding of these parameters and Stumpff and Lieske's results could be interpreted (Figure 15-6) as follows:

1. If the modern ephemeris DE102 from JPL is truly inertial and if Newcomb is correct, then the newly adopted precession is too large by 1 arc sec per century; or
2. If the DE102 is correct and if the new precession is correct, then the Newcomb value is too small by 1 arc sec per century; or
3. If Newcomb and the new IAU precession are correct, then the DE102 system is not inertial by 1 arc sec per century.

The derivation and verification of the new precession value make it probably one of the best-documented of all the astronomical parameters. It is based upon the analysis of relatively nearby stars, and hence an equally thorough investigation using the VLBA and extragalactic sources would go a long way toward resolving the inconsistency and thus lead to a better understanding of our model universe. The VLBA could be used (Figure 15-7) to independently determine the precession using quasars and could be employed to relate the solar system and extragalactic frames.

OTHER EXPERIMENTS

Other investigations that could be extended and further investigated via a dedicated VLBA include the establishment of the relationship between a radio source frame and the solar system frame (Figures 15-8 and 15-9), as recently attempted by Newhall and Preston (1983) of JPL. They related the VLBI frame to the planetary ephemeris frame via the Viking orbiter. Such investigations for a dedicated VLBA would be quite useful in this area. As noted in Figure 15-10, the proposed investigations of Muhleman and Berge of Caltech and Niell of JPL to observe Jupiter's Galilean satellites relative to radio sources offers another promising approach that could be employed by the VLBA.

The experiments of Lestrade (Paris), Mutel (Iowa), Phillips (Haystack), and Preston and Scheid (JPL) using RS Canum Venaticorum ($RSCV_n$) star would be another valuable type of experiment for a dedicated VLBA, in order to relate galactic motion to extragalactic frames (Lestrade et al. 1983). The employment of short-period pulsars could also be used to derive planetary system masses and other astronomical parameters from an analysis of their radio output. If we had beacons (i.e., well-behaved and understood radio sources) such as Apollo lunar surface experiments package (Alsep), one could employ them to relate reference frames.

Finally, the investigation of the relationships between radio-based frames, from a system such as the VLBA, and optically based systems such as HIPPARCOS, the Space Telescope, and the FK5, would lead to much information regarding our understanding of the solar system, the local galactic frame, and the extragalactic frame.

- REFERENCE FRAME – PRECESSION
  – RELATIONSHIPS AMONG FRAMES
- ASTRONOMICAL NUTATION
- TIMING AND POLAR MOTION

FIGURE 15-1 Astronomical constants.

- "OLD" SYSTEM:

FK4	STAR CATALOG
	"OLD" PRECESSION p^C
	CATALOG DRIFT ("EQUINOX DRIFT")
1950.0	EQUINOX
NEWCOMB	RELATIONSHIP BETWEEN UT/GMST
WOOLARD	NUTATION

- "NEW" SYSTEM:

FK5	STAR CATALOG
	"NEW" PRECESSION p^I
	ELIMINATION OF CATALOG DRIFT
J2000	EQUINOX
NEW	RELATIONSHIP BETWEEN UT/GMST
WAHR	NUTATION

FIGURE 15-2 Transition between fundamental reference frames.

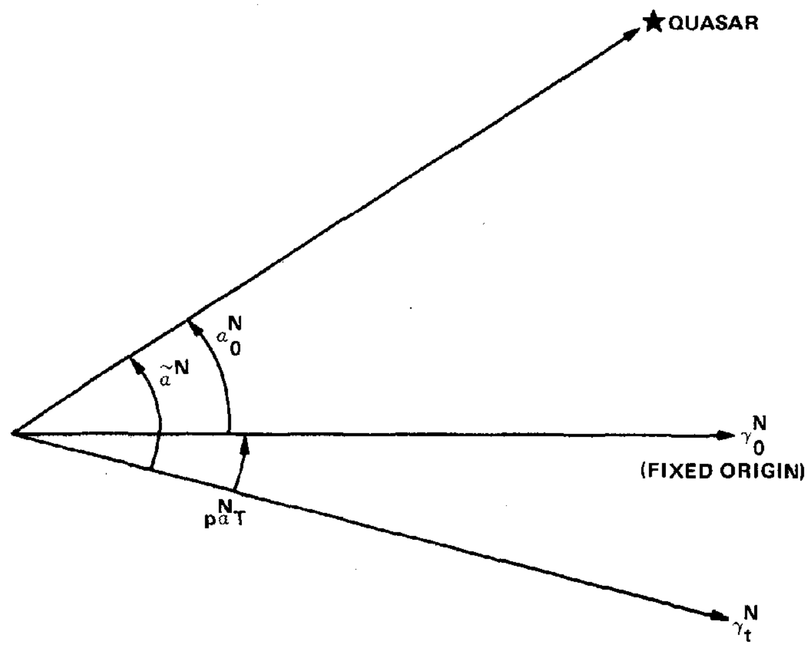

FIGURE 15-3a Comparison of systems the FK5 system.

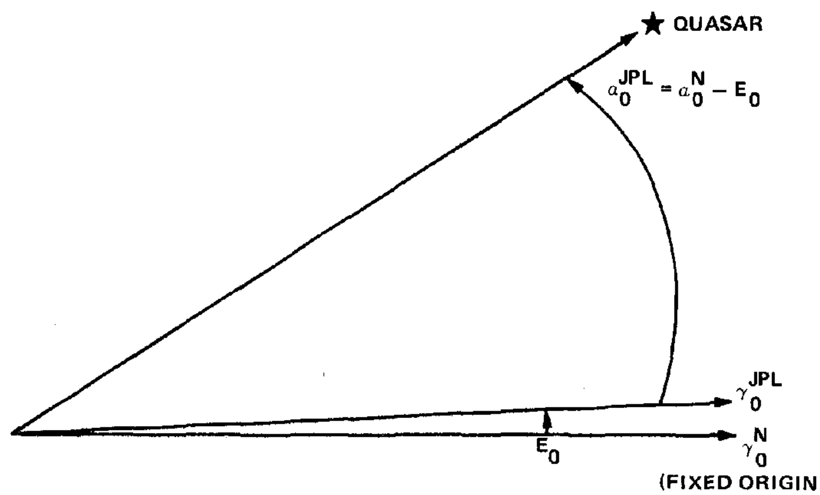

FIGURE 15-3b The JPL 1950 system.

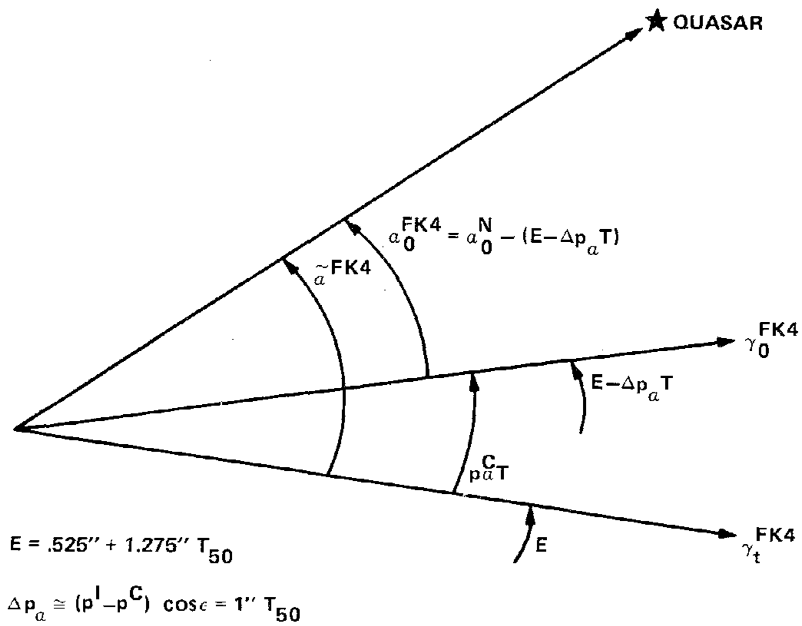

FIGURE 15-3c The FK4 system.

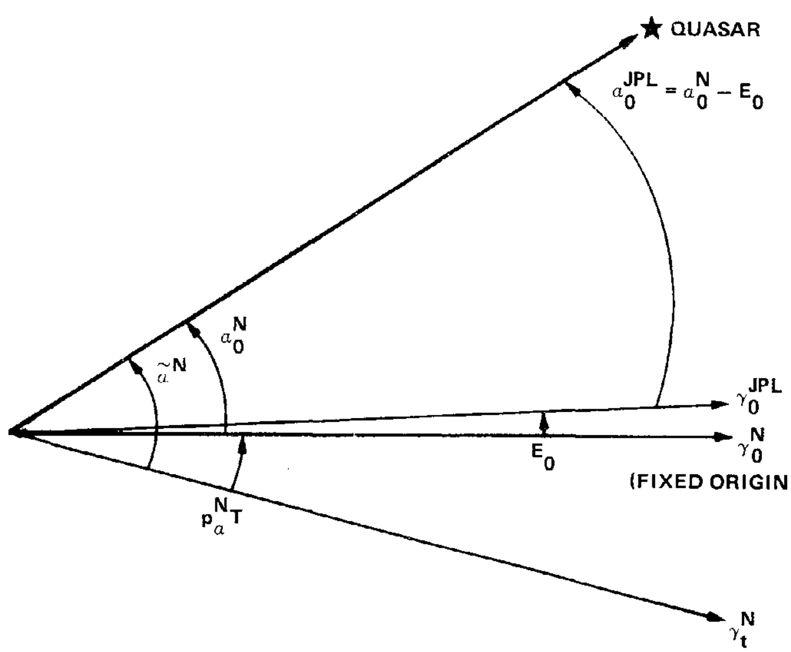

FIGURE 15-3d Comparison of systems: The FK5 system and the JPL 1950 system.

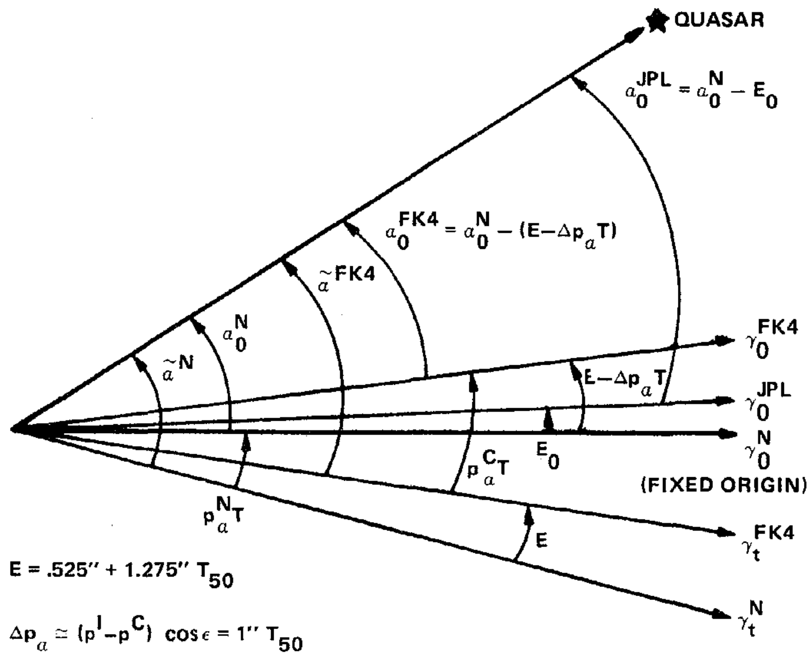

FIGURE 15-3e Comparison of systems: FK5, FK4, and JPL 1950.

- $\tilde{n}_0$ REAL MEAN MOTION OF EARTH-MOON BARYCENTER RELATIVE TO FIXED EQUINOX
- $\tilde{L}_1$ REAL MEAN MOTION OF EARTH-MOON BARYCENTER RELATIVE TO MOVING EQUINOX OF DATE
- $\tilde{p}_1$ REAL SPEED OF GENERAL PRECESSION IN LONGITUDE

$$\Longrightarrow \tilde{n}_0 = \tilde{L}_1 - \tilde{p}_1$$

FIGURE 15-4 Relationships among fundamental parameters.

$$n_0^{DE102} = L_1^{NEWCOMB} - p_1^{CONVENTIONAL} - 0.032'' \text{ PER CENTURY}$$

$$= L_1^{NEWCOMB} - p_1^{IAU} - 1.095'' \text{ PER CENTURY}$$

WHERE $p_1^{CONVENTIONAL}$ = "NEWCOMB" PRECESSION (THE "OLD" IAU VALUE)

p_1^{IAU} = NEW IAU PRECESSION (FRICKE, 1971)

FIGURE 15-5 Analysis of Stumpff and Lieske.

- IF n_0^{DE102} IS TRULY INERTIAL
  - AND -
  IF L_1^N OF NEWCOMB IS CORRECT
  - THEN -

⇒ THE NEW PRECESSION IS TOO LARGE BY 1.095" PER CENTURY

- IF m_0^{DE102} IS TRULY INERTIAL
  - AND -
  IF THE NEW p_1^I IS CORRECT
  - THEN -

⇒ THE NEWCOMB VALUE IS TOO SMALL BY 1.095" PER CENTURY

- IF L_1^N OF NEWCOMB IS CORRECT
  - AND -
  IF THE NEW p_1^I IS CORRECT
  - THEN -

⇒ THE DE102 MEAN MOTION IS TOO LARGE BY 1.095" PER CENTURY

FIGURE 15-6 Interpretation of results of Stumpff and Lieske (1983).

- AN INDEPENDENT DETERMINATION OF PRECESSION USING QUASARS
- A DETERMINATION OF THE RELATIONSHIP BETWEEN PLANETARY EPHEMERIS AND EXTRA-GALACTIC FRAMES
- AN INDEPENDENT DETERMINATION OF THE EARTH'S INERTIAL MEAN MOTION

FIGURE 15-7 Possible role of VLBA in resolving the discrepancy.

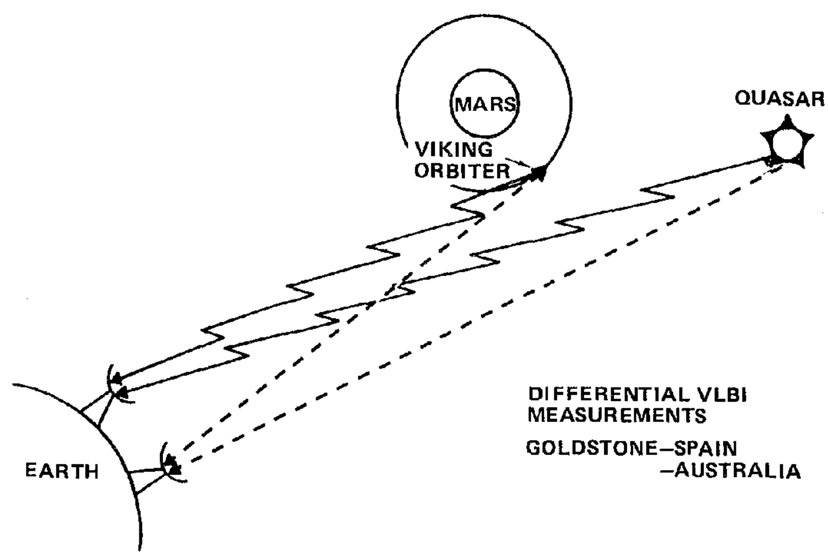

FIGURE 15-8 Viking Experiment, 1980 (Newhall and Preston, 1983).

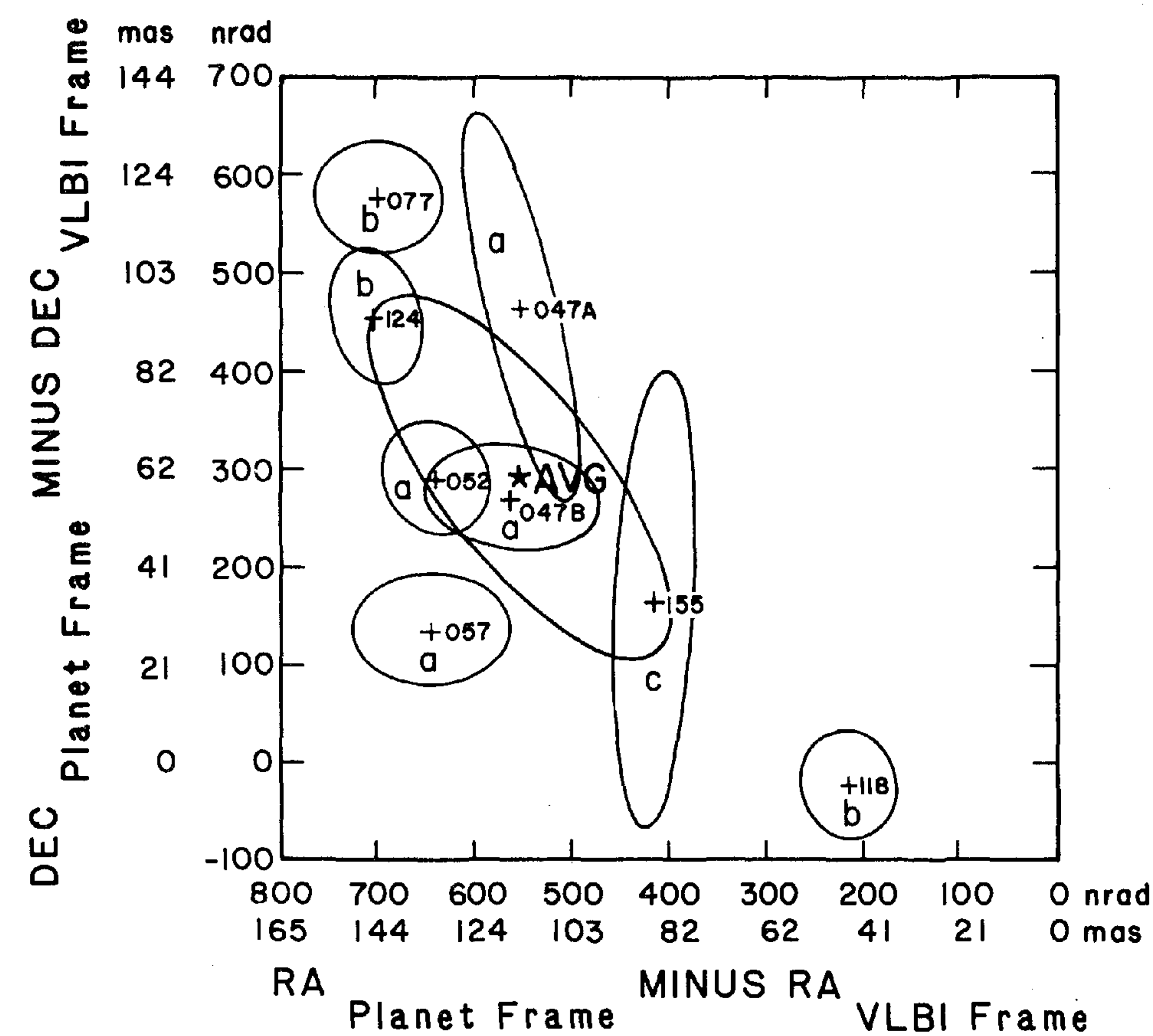

FIGURE 15-9 Offset between planetary (DE118) and VLBI (Catalog 1982-1) frames. Error ellipses include uncertainties due to source positions. Average offset in RA = 530 ± 100 nrad [0.11 arc sec ± 0.02 arc sec] and in DEC = 290 ± 150 nrad [0.06 arc sec ± 0.03 arc sec]. Sources: (a) 3C245; (b) GC1004 + 14; (c) OL064.5. Figure from Newhall and Preston (1983).

- GALILEAN SATELLITES [MUHLEMAN, BERGE CIT; NIELL JPL]
- RS CANUM VENATICORUM $RSCV_n$ STARS [LESTRADE BdL PARIS; MUTEL IOWA; PHILLIPS HAYSTACK; PRESTON AND SCHEID JPL]
- PULSARS
- BEACONS (ALSEP)
- SPACE TELESCOPE
- HIPPARCOS

FIGURE 15-10 Other possible experiments.

REFERENCES

Eckert, W. 1954. Improved Lunar Ephemeris 1952-1959. U.S. Government Printing Office, 1954.
Fricke, W. 1971. Astron. Astrophys. 13, 298.
Kaplan, G.H. 1981. U.S. Naval Obs. Circ. 163.
Lestrade, J.F., R.L. Mutel, R.A. Preston, and J.A. Scheid 1983. Astrophys. J., (submitted) (letters).
Newcomb, S. 1898. Astron. Papers Washington, 6, Part 1.
Newhall, XX, and R.A. Preston 1983. JPL. In press.
Newhall, XX, E.M. Standish, and J.G. Williams 1983. Astron. Astrophys. In press.
Stumpff, P., and J. Lieske 1983. Astron. Astrophys. In press.
Wahr, J. 1981. Geophys. J. Roy. Astron. Soc. 64, 705.
Woolard, E.W. 1953. Astron. Papers Washington, 15, Part 1.

DISCUSSION

HUGHES: A comment to clarify a point: The so-called equinox drift can also be characterized as a systematic error in the proper motions. Observationally, that is what causes it.

LIESKE: Yes, it's along the line of the magnitude question.

HUGHES: Precisely. It relates to the mean magnitudes of the clock stars in early catalogs; but it may be easier to understand in terms of a sytematic error in proper motions.

LIESKE: The main point is that once radio astronomers start getting results they are willing to accept and then begin to compare them over a period of time, they will find some of these effects and will have to interpret them.

16

IMPLICATIONS OF VLBA MEASUREMENT FOR EPHEMERIDES

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EPHEMERIDES

I have chosen to interpret the word ephemerides in its broadest sense and specifically to assume that it encompasses two meanings: (1) the knowledge of the motion of solar system objects and (2) the publications of astronomical data, specifically the *Astronomical Almanac*, which incorporate more than just solar system body positions.

PHILOSOPHY

Before I discuss the implications from Very Long Baseline Array (VLBA) measurements, it would be useful to discuss the philosophy behind our activities.

- We seek to provide the astronomical data required by astronomers, surveyors, navigators, geodesists, and space scientists, as consistent with the mission of the U.S. Naval Observatory (USNO). We seek to provide the data in printed form, machine-readable form, and, to the extent practicable, in algorithms or computer programs that permit calculations by the individuals themselves.
- We try to provide and publish the data to the extent possible in the form desired and as needed but with an effort to avoid special computations and special preparation of data.
- We seek to change the basis of the data as infrequently as possible, but, at the same time, we try to meet the accuracy requirements of the users. With the many changes that have been introduced in the last few years in the *Astronomical Almanac*, it may seem that we are changing too much too fast. On the other hand, when one considers that through 1983 the basis of some of the ephemerides were still Newcomb's theories from the late 1800s, perhaps we have been changing too slowly.

At the same time, we will provide improved data in machine-readable form, in many cases, since it is simpler to have different versions of the same quantities in machine-readable form than to have different printed versions.

• A new system of astronomical constants has been introduced and will be used beginning in 1984 (Kaplan 1981). Additionally, a new basis for the ephemerides of the sun, moon, and planets will be introduced in 1984, based on the DE200/LE200 integration at the Jet Propulsion Laboratory (JPL). We anticipate that these new bases will significantly reduce the systematic errors that were present in the old ephemerides (Table 16-1) and the known deficiencies in the astronomical constants. It is our expectation that this new system will satisfy the current accuracy requirements. It will permit the investigation of smaller corrections to the constants and ephemerides and a new class of effects that cause an order of magnitude smaller systematic errors.

• Traditionally, the theories have been more accurate than the observations, until the observations revealed the deficiencies in the theories. The theories were then improved, and the observations again revealed new deficiencies. Obviously, this process will continue, and perfection will never be achieved.

NEW INFORMATION ACHIEVABLE FOR EPHEMERIDES

Earth Orientation

The determination of the earth rotation parameters, including polar motion, has already been discussed.

Nutation

It is anticipated that systematic observations of astrometric positions of radio sources will permit the determination of improved values for the coefficients of the nutation theory. This would be an extension of the effort by George Kaplan (1982) to use the Green Bank connected-element interferometer and by others to use the very long baseline interferometer (VLBI) data to determine nutation coefficients.

Lunar Observations

If the regular transmitters left in the Alsep (Apollo lunar surface experiments package) systems on the moon could be reactivated, we would have radio sources on the moon that could be observed as an accurate means of measuring the angular positions of the transmitters. This should be a complement to the lunar laser-ranging data, which accurately measure the distance to points on the moon. An alternative possibility would be the placement on the moon of a new radio beacon, possibly as part of a new scientific instrumentation package.

TABLE 16-1 Pre-1984 Ephemeris Errors (averaged observed minus ephemeris differences)

	Right Ascension (sec)	Declination (arc sec)
Mercury	+0.14	-0.3
Venus	+0.10	-0.1
Mars	-0.12	0.0
Jupiter	-0.03	+0.3
Saturn	0.00	-0.3
Uranus	+0.03	-0.2
Neptune	-0.48	+0.8
Sun	+0.10	+0.1
Moon	-0.06	0.0

NOTE: Known systematic discrepancies:

Earth	The longitude may be in error by 0.5 arc sec.
Mars	Right ascension may be in error by as much as 0.2 sec at opposition.
Jupiter	Periodic errors reach about 0.3 arc sec in longitude and 0.5 arc sec in latitude.
Saturn	Periodic errors reach about 0.5 arc sec in longitude and 0.7 arc sec in latitude.
Uranus	Secular error in latitude of -0.3 arc sec per century.
Neptune	Secular runoff in longitude, -6.0 arc sec in 1975; periodic error in latitude.
Moon	Periodic errors reach about 0.5 arc sec in longitude and 0.2 arc sec in latitude.

Planetary Observations

If new planetary missions do take place, a radio source could be deposited on the surface of, or in orbit around, any of the planets. These sources could then be measured with the VLBA to determine accurate measurements of the positions of the planets. As in the lunar case, the radio beacon could be part of a scientific package deposited on the planetary surface, or in orbit. Table 16-2 summarizes the current observational accuracies and indicates the possibility of VLBA observations (Johnston et al. 1982, Newhall et al. 1982).

TABLE 16-2 Observational Accuracies

	Optical (arc sec)	Radar	Laser	VLA (arc sec)	Spacecraft
Sun	0.81				
Mercury	0.90	10 μs 1500 m			
Venus	1.00	10 μs 1500 m			
Mars	0.63	12 μs (1 μs) 1800 m			0.1 μs 0.25-2.5
μs					
Jupiter	0.50				50 μs
Saturn	0.53				
Uranus	0.37				
Neptune	0.45				
Pluto	2.50				
Moon	0.1 Occ 1.4		2.75 ns 42 cm		
Minor planets		0.25		0.1	
Stars		0.25		0.02	

Notes: VLBA should be able to provide 0.001-0.005 arc sec accuracy. Distance values are in one-way range uncertainties. Mars spacecraft are Viking Orbiter and Mariner. Values are based on residuals of individual observations. Occ indicates occultation observation.

Occultations by Radio Sources

The same practice as for optical observations could be used for occultations of radio sources (Kaplan 1977). The reduction of radio source occultation timings to the accuracy needed, of order 0.1 arc sec or better, is much more difficult, but it may be feasible. This technique provides a means of relating the different coordinate systems, which will be discussed later.

New Constants Determined

From observations of solar system objects, improvements would be anticipated for the equatorial radius of the earth, and the motion of the planets and their masses. From astrometric measurements of radio sources, improvements can be expected in the theory of nutation and constant of precession.

NEW REQUIREMENTS FOR THE ASTRONOMICAL ALMANAC AND ASTRONOMICAL DATA

Coordinate Systems

We should not degrade our observational data by the inaccuracy of its reference coordinate system. Similarly, we should not include the calculations of motions, which are not involved in the observations being taken. Thus in the future we are probably going to have to discuss and use at least five different coordinate systems, rather than the current practice based on an ill-defined origin and reference plane. At the present time the origin of our coordinate system, the equinox, is neither well defined nor well determined. The same can be said for the ecliptic plane. Thus we will seek to use different coordinate systems for different purposes and continually seek improvements in the accuracies of the relationships between these coordinate systems, but recognize that we are dealing with essentially independent coordinate systems.

An Inertial Coordinate System

This coordinate system will probably be based on observations of very distant radio sources that are felt to be motionless. The origin should be tied to the observational data themselves.

A Solar System Coordinate System

This coordinate system will be defined based on the dynamical equinox of some epoch and probably the invariable plane. It would be anticipated that all solar system objects would be calculated with respect to this system. It will have the characteristic of being an inertial coordinate system, whose origin is the dynamical equinox of some date. While the invariable plane is not observable as such, it is a fixed plane, so that it has a fixed pole that can be well defined and determined to observational accuracy in the various coordinate systems. Data can be placed on this system to the accuracy of definition by precise coordinate transformations.

A Star Catalog Coordinate System

This coordinate system will be tied to the observations of the stars with its origin based on a catalog system and probably the earth equatorial plane. This system may very well be magnitude dependent in addition to being catalog dependent. The FK5 system is an example of a star catalog coordinate system. It would be hoped, and probably attempted, that all star catalogs will be on the same system, but I think we need to recognize that there will be systematic differences. The Space Telescope will use a faint star catalog system as its guidance system, and positional data determined from it will be on that star catalog coordinate system.

An Earth-Based Coordinate System

This system incorporates the dynamics and rotational characteristics of the earth, which need to be related to the other coordinate systems. Positions of Greenwich and the axis of rotation vector will be incorporated in this coordinate system. Earth-based observations will, of necessity, be made in this coordinate system and then transformed into another coordinate system, if appropriate. The method of introducing improvements to constants will have to be seriously considered in the future, based on the implications as discussed by Williams and Melbourne (1981) and Zhu and Mueller (1982).

Special Purpose Coordinate Systems

The HIPPARCOS spacecraft will determine its own independent coordinate system. This again will be dependent on the magnitude of the objects observed and becomes an example of my opinion that the accuracy of the observations of a spacecraft, such as HIPPARCOS, should not be degraded by forcing them onto a less accurate reference system, or by incorporating motions such as the variations in the earth rotation into the reductions of such data.

VLBA can be anticipated to use a number of these different coordinate systems and may provide the most accurate means of determining the relationships between some of these coordinate systems. The VLBA should be able to determine the equator to an accuracy of 0.001 arc sec. In theory, although not demonstrated in practice to date, the ecliptic can be determined from pulsar timings to an accuracy of 0.1 arc sec.

The Very Large Array (VLA) is currently being used to observe minor planets, which can provide point sources at both radio and optical frequencies. It is possible that a very few minor planets may be observable with the VLBA and obtain accuracies better than the 0.1 arc sec that has been achieved for single observations to date.

It will be incumbent upon those of us providing accurate astronomical data to develop the most effective means of providing the relationships and the algorithms for calculating those relationships and providing the data in published, machine-readable, or algorithm form.

Time Scales

The same problems that have been discussed for coordinate systems are also present for time. To a large extent these problems have already been met and addressed, and hopefully the framework has been established for the different necessary time systems. For that reason we have a variety of time systems such as UTC, UTl, International Atomic Time, Terrestrial Dynamical Time, and Barycentric Dynamical Time. Again, the requirement is to provide the effective means, to the accuracy necessary, to relate the different time systems and to insure that the correct time system is being used for the application involved to the accuracy that is appropriate.

Astrometric Positions

As we continue to publish astrometric positions of objects, we can anticipate that the VLBA will provide an increased list of accurate positions. Also, the situation will change concerning what we can accurately provide in the Astronomical Almanac and what can most effectively be provided in machine-readable form, either in the form of radio source catalogs or by other methods.

Relativistic Effects at Increased Accuracy

As the accuracies achievable increase, we can anticipate that relativistic effects are going to cause new and different constraints and requirements for the Astronomical Almanac. For example, the inclusion of gravitational light bending in the tabulation of the daily positions of the planets increases the accuracy of the position of the planet, but at the same time presents difficulties, in some cases, if someone attempts to interpolate between daily positions. This is similar to the problems presented by short-term nutation effects. I can anticipate that other such circumstances will arise and solutions will have to be formulated.

Your Ideas and Input

Anytime I talk about the Astronomical Almanac and the activities of the Nautical Almanac Office of the USNO, I feel I should emphasize that we do appreciate and solicit the suggestions, criticisms, and ideas of people who are--or might or should be--using our services with the hope that we might improve what we are doing. Therefore I certainly will welcome your ideas concerning either the requirements that the VLBA will put on the USNO or what the USNO should or could be doing to better serve the requirements of the VLBA.

REFERENCES

Johnston, K.J., P.K. Seidelmann, and C.M. Wade 1982. Observations of 1 Ceres and 2 Pallas at Centimeter Wavelengths. Astron. J. 87:1593-1599.

Kaplan, G.H. 1977. A Lunar Occulation of 3C446 Observed with VLBI. Unpublished Technical Report.

Kaplan, G.H. 1981. The IAU Resolutions on Astronomical Constants, Time Scales and the Fundamental Reference Frame. USNO Circular 163, Washington, D.C.

Kaplan, G.H. 1982. The Earth's Nutational Motion Determined from Radio Interferometry. Bull. Amer. Astron. Soc. 14:658.

Newhall, XX, E.M. Standish, and J.G. Williams 1983. DE102, A Numerically Integrated Ephemeris of the Moon and Planets Spanning Forty-Four Centuries. In press.

Williams, J.G., and W.G. Melbourne 1981. Comments on the Effect of Adopting New Precession and Equinox Corrections. Proceedings of IAU Colloquium 63: High Precision Earth Rotation and Earth-Moon Dynamics: Lunar Distances and Related Observations, O. Calame, ed., Reidel.

Zhu, S.-Y., and I.I. Mueller 1982. Effects of Adopting New Precession, Nutation and Equinox Corrections on Terrestrial Reference Frame. Bull. Geod. In press.

DISCUSSION

ROGERS: I wonder if it is really possible to do much in the way of observations of the planets without using either a radio transmitter or perhaps a radar signal to illuminate them?

SEIDELMANN: I can't think of a good way. That is why I said I needed the beacon, with the exception of the minor planets, for which we have demonstrated that it can be done with the VLA.

ROGERS: The resolution is much higher with the VLBA.

SIEDELMANN: That may be a problem.

BURKE: Until now there has been an impression that the ephemeris is slow to take in radio astronomical data as part of its regular body of information. Do you see this changing in the next few years?

SEIDELMANN: We are trying to change that. We have started listing astrometric positions of radio sources and the flux values for radio sources. If we can do something different or additional that would be useful to the community, we would certainly welcome the idea, as long as it wasn't publishing 600 pages of data each year.

SHAFFER: I have a comment on that latter point. The radio information that was published in the last couple of issues of the ephemeris has no indication of its quality. I am thinking specifically of some of the flux density sources that were given. Realizing how I go to the ephemeris if I want to get a position of a star, I assume that that position is just as given, and I am worried that an optical astronomer who wants to calibrate a radio telescope is going to pick some piece of information out of your ephemeris and take it as totally correct. I would advise more consultation before some of those numbers appear, because they might be misleading if they are used blindly.

SEIDELMANN: We are consulting with people to try to get the best values, but we do have a time lag that becomes a factor.

WESTERHOUT: Particularly with variable sources.

SEIDELMANN: Yes, the situation changes from year to year, unfortunately.

REID: If you are accepting complaints about the radio information in the ephemeris, the radio observatories are listed by their most obscure names, which are the small towns near where they are located. If they could be listed by location in country or state, or something like that, it would be easier to look up the information.

SIEDELMANN: Yes, we try to give an index, and maybe we can change this. We haven't yet found a uniform way to list everything that doesn't run into some problem. I welcome the comment, and we will try again.

SHAPIRO: Along the same lines, when you are modifying what you do as far as inclusion of radio observatories, the accuracy of the position of radio observatories, and in a frame that could be well-defined, might be useful, especially to new users of the VLBI who want to know where an observatory is, and what coordinates are used for it. You could use much more accurate coordinates and have a system that is consistent for all the observatories.

SEIDELMANN: We are doing this. The instruments are listed individually now on a rotating basis for the accuracy we have available from the observatory. We run into problems with what observatories send us, but to the extent we can get the information, we are trying to publish it.

NIELL: I think one of the points that Irwin was trying to make was that, with the accuracies that we have now, you have to worry even about the reference position for that; there seem to be several in existence now. Haystack and Goldstone, depending on which part of the country you come from, seem to be the reference positions, so there is some inconsistency. But there is some work that is being done to try to tie all of these together. For example, the position of McDonald Observatory is supposedly known from the lunar laser-ranging information relative to the geocenter of the earth to something on the order of 10 cm, and all the ties exist now to put everything on that frame via VLBI in some classical geodetic work.

BENDER: With respect to either this or the previous talk, are there plans for additional delta VLBI measurements with the Viking transmitter?

WESTERHOUT: The Viking transmitters and the landers are all dead.

NIELL: However, we do have measurements on the Pioneer Venus Orbiter. There are two made in the same way and reduced in the same way. In terms of the vu-graph that Jay Lieske showed earlier (Figure 15-9), the offset in right ascension agrees well within the scatter with the Viking data that were shown. There does seem to be a difference in declination, and the cause is not known.

17

GENERAL RELATIVITY AND THE VLBA

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INTRODUCTION

General relativity (GR) is a theory of gravitation first formulated by Einstein (1916). The classical theory of Newton, though sufficiently accurate for most ordinary phenomena, is not precise enough for some solar system applications and is grossly incorrect for most astrophysical phenomena associated with massive objects. Thus the continued verification of GR or other competing gravitational theories is extremely important.

The angular resolution of the Very Long Baseline Array (VLBA) offers a powerful technique for measuring the minute effects that differentiate gravitational theories in the solar neighborhood. The light deflection experiment is the most obvious but there are many others. The linear resolution of the VLBA in mapping galactic and extragalactic radio sources will probe the radio environment near the massive objects in which gravity plays an important role. The understanding of the physics associated with these objects must also include the validation and understanding of the law of gravity. This paper describes experiments--some well-documented and others very speculative--in which the VLBA could lead in our understanding of gravitation.

EXPERIMENTS IN THE SOLAR SYSTEM

In the weak gravitational field of the solar system, the differences between most theories of gravity are small, and their differences can be summarized in 10 post-Newtonian parameters (PPN). In the last decade the use of spacecraft and radio interferometric techniques have enabled accurate determinations of many of the PPN parameters.

Light Deflection Experiment

One of the classical tests of GR is the deflection of light caused by its passage near a massive object. At the limb of the sun the bending is 1.75 arc sec according to GR. Optical experiments made during solar eclipses have had relatively poor accuracy. In the last 10 years, conventional and very long baseline interferometry (VLBI) has measured the bending of radio waves to an accuracy of about 1 percent and is in agreement with GR (Fomalont and Sramek 1977).

There is little doubt that the VLBA can ultimately measure the bending of radio waves by the sun to an accuracy of about 0.1 percent by obtaining a positional accuracy of about 0.0001 arc sec. However, it will take a dedicated VLBA to reach this goal. Some experiences gained over the last decade in performing this experiment are as follows:

- Dual-frequency observations in order to remove the coronal refraction. Switching times between frequencies should be less than about a minute.
- Highest possible observing frequency to lessen coronal effects and to permit observations close to the sun.
- Observations of several sources as they pass near the sun in order to remove a large number of long-term instrumental effects. Three sources in an approximate straight line has worked well.
- Good atmospheric and ionospheric models at each site.
- At least 5 days of observations over a 20-day period near occultation and a few days of time a half-year later.

Radio Tracking of Spacecraft

Recently, the most accurate tests of GR have been obtained by precision radar tracking of interplanetary spacecraft (Cain et al. 1978, Reasenberg et al. 1979). Observations with the VLBA of spacecraft would add information about its transverse motion and complement the radial motion obtained by radar tracking. Limitations to fitting the spacecraft orbit are often caused by nondynamic forces; such as, solar radiation pressure, solar winds, internal spacecraft forces, and forces of unknown origin. All such effects would be better understood and evaluated with VLBA observations. Because of the high angular resolution of the VLBA, such observations would probably be limited to spacecraft and not to celestial bodies.

Monitoring the Earth

The use of the VLBA for geophysical problems, astrometric problems, and earth-moon dynamics has been outlined in previous chapters. A full and proper analysis of these problems requires a choice of gravitational theory and are thus tests of general relativity. Some examples are the following:

- Unexplained yearly variation of the rotation of the earth indicates that the gravitational laws are not independent of the Lorentz frame. The annual variation of the rate is about 4×10^{-9} and can be explained by seasonal variations of the atmospheric winds. Any deviation is less than 4×10^{-10} (Rochester and Smylie 1974).

- Variation of the gravitational constant G violates the Principle of Equivalence. The limit of variation can be measured in many experiments and $\dot{G}/G$ is found to be less than 10^{-10} per year. Such a variation would produce an increase in the radius of the earth of about 0.1 mm/yr, which would be within the sensitivity of the VLBA over a decade or less.

EXPERIMENTS OUTSIDE THE SOLAR SYSTEM

At the present time, experimental tests of gravity using slow moving objects in the relatively weak field of the solar system agree with general relativity in all of the 10 PPN parameters to an accuracy of 10^{-2} to 10^{-7}. Further testing of GR in strong fields must be done outside the solar system, and probably outside of the galaxy. However, clean tests of GR are not easily afforded because of the complexity and lack of understanding of most of the phenomena involving massive objects. Fortunately, the VLBA has sufficient resolution to probe these massive objects, and it should be one of the major observational tools in understanding them and, concomitantly, in understanding strong gravitational interactions.

Binary Objects

The binary pulsar is an exciting testing ground for gravitational theories. Using the pulsar period variations as it orbits an unseen companion, one can deduce the orbital parameters with great accuracy. Since its discovery in 1974, the advance of periastron and the decrease of the orbital period have been accurately determined. The advance of periastron is in good agreement with the amount predicted by GR, and the loss of orbital energy is consistent with energy lost by gravitational radiation (Weisberg et al. 1981). The separation of the binary is about 10^{-5} arc sec, so it cannot be resolved by very long baselines (VLB) limited to the earth.

However, other binaries in which one of the stars emits significant radio radiation may be accessible with VLB resolution. Depending on the mass of the stars, the orbital separation, and their interaction, these binaries may also be good testing grounds for gravitational theories. Only a sensitive VLBA is capable of detecting the expected faint radio emission from a reasonable sample of stars.

Gravitational Radiation

Gravitational radiation has yet to be detected, although its presence is predicted by many gravitational theories. Some of these theories predict different propagation velocities, polarization, and multipole type for this radiation. It is likely that the strongest such waves will be associated with cataclysmic events, such as a supernova or other energetic outbursts in a star or in the nucleus of a quasar.

Comparison of the arrival time of the gravity wave with that of any other electromagnetic wave associated with the same event would be important in understanding them.

Since cataclysmic events are rarely observed directly, their time of occurrence must be estimated by other methods. Often, the extrapolation back in time from the observed proper motion of ejecta can determine the time of the associated outburst very accurately. Since VLBI techniques do, in fact, observe proper motions in components associated with some stars and quasars, simultaneity of a cataclysmic event that produced the ejecta and possible gravitational waves could be established. Dedicated instruments like the VLBA are needed to monitor and observe these events that may produce gravitational radiation.

Distance Determinations

The Hubble relationship is the cornerstone of the application of GR to the structure of the universe. This relationship is not well-established beyond about 50 Mpc, a small distance compared with that of the observable universe. VLB techniques have the possibility of determining the distance to quasars.

VLB observations of superluminal sources can measure the angular velocity of material expelled from galaxies and quasars. If there were independent methods by which the linear velocities could also be inferred, then an approximate distance could be determined. The discovery of a radio spectral feature that could be detected above the continuous synchrotron emission would enable velocities to be determined. Such spectral features may be more likely at the highest planned frequencies for the VLBA and would require good instrumental stability and dynamic range. In the meantime, other indirect methods of estimating the velocity associated with VLB observations can be used. Marscher and Broderick (1981) have recently examined the ratio of the radio radiation and X-ray radiation emitted by the quasar NRAO140. Assuming that the radiation was emitted from the same volume, the unexpectedly small amount of X-ray radiation could be best explained if the material were moving with a Lorentz factor of 4 nearly in the line of sight. A linear velocity of material ejected from a galaxy can also be inferred by the Doppler brightening and dimming in intensity between the forward moving and backward moving ejecta. This assumes that the ejecta are intrinsically identical and that they move in opposite directions. When combined with the angular velocity from VLBI measurements, an approximate distance is then obtained.

If sufficient examples can be found where VLB observations can obtain the distance to objects with measured redshift, then better values of H_0 and q_0 can be estimated. The cosmological value would be enormous.

Evolution versus Cosmology

Various cosmological and gravitational theories predict significantly different behavior of objects at large redshift, and the dependence of various source parameters with redshift has been a useful test of these theories. However, there is significant evolution in many properties of extragalactic objects (galaxy formation rate, radio/optical luminosity), so it is difficult to separate evolutionary, cosmological, and gravitational effects.

Observations with the VLBA will be able to probe deeply the nucleus of quasars at large redshift. It may be possible that evolutionary effects will not be so large in this dense environment and that the redshift dependence of milliarc second phenomena mapped by the VLBA may be affected more by cosmological and gravitational laws than by evolutionary changes. Examples might be the determination of orbital parameters of a binary black hole in a quasar or the redshift dependence of the size of an accretion disk.

SUMMARY

It is expected that the VLBA will be one of the most useful tools in testing the various theories of gravitation and their cosmological implications. Although solar system experiments have produced the most accurate tests to date, the better understanding of massive objects and related astrophysics in which gravitation plays an important role may well be the new testing grounds for general relativity.

REFERENCES

Cain, D.L., J.D. Anderson, M.S.W. Keesey, T. Komarek, P.A. Laing, and E.L. Lau 1978. Bull. Amer. Astron. Soc. 10:396.

Einstein, A., 1916. Ann. Phys. 49:769.

Fomalont, E.B., and R.A. Sramek 1977. Comm. Astrophys. 7:19.

Marscher, A., and J. Broderick 1981. Extragalactic Radio Sources. IAU Symposium No. 97, edited by D.S. Heeschen and C.M. Wade, Reidel, Dordrecht, p. 359.

Reasenberg, R.D., I.I. Shapiro, P.E. MacNeil, R.B. Goldstein, J.C. Breidenthal, J.P. Brenkle, D.L. Cain, T.M. Kaufman, T. Komarek, and A.I. Zygielbaum 1979. Astrophys. J. 234:L219.

Rochester, M.G., and D.E. Smylie 1974. J. Geophys. Res. 79:4948.

Weisberg, J.M., J.H. Taylor, and L.A. Fowler 1981. Sci. Amer. 245(4):66.

IV. Other Users

18

GENERAL VLBA CONSIDERATIONS

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FREQUENCY BANDS

Ten frequency bands covering 0.3 to 43 GHz have been selected for the Very Long Baseline Array (VLBA). These bands are given in Table 18-1. While it will not be possible to switch rapidly between bands in less than a few seconds, it will be possible to receive simultaneously at S- and X-band. If additional dichroic reflectors are added, it will be possible to make simultaneous dual-band observations at 43 and 10 GHz and 22 and 5 GHz. Other combinations may also be possible.

The VLBA will be able to use up to 32 simultaneous receiving channels. Each of these channels can have one of the following bandwidths: 32, 24, 16, 12, 8, 4, 2, 1, 0.5, 0.25, 0.125 MHz. This ability to use more than the 4 simultaneous bands specified in the early National Radio Astronomy Observatory proposal ("A Program for the Very Long Baseline Array Radio Telescope," May 1982, National Radio Astronomy Observatory, Charlottesville, Virginia) is needed to better support bandwidth synthesis (BWS) observations in a manner fully compatible with the MARK III S/X system used for geodesy and astrometry.

Ten kilohertz is the finest increment available in the local oscillator system that defines the precise frequency range of the individual receiving channels within the ranges given in Table 18-1.

DIGITIZATION

The individual receiving channels will be digitized with either two- or four-level quantization. Four-level quantization provides an improved signal-to-noise ratio (SNR) for spectral-line observations, while two-level quantization is best for continuum observations and is compatible with present systems.

RECORDING

The average recording rate specified for the VLBA is 100 Mbps or 8.6 Tbits/day. At this rate the recording system should be able to run

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TABLE 18-1 VLBA Bands

312-342 MHz	
580-640 MHz	
1.35-1.75 GHz	
2.175-2.425 GHz	} → S/X
8.0-8.8 GHz	} → S/X
4.9-6.1 GHz	
10.2-11.2 GHz	
14.9-15.9 GHz	
21.3-25.6 GHz	
42.5-43.5 GHz	

TABLE 18-2 VLBA Recording Systems

System	MARK IIIA	VCR 16	VCR 40
No. of transports	3	16	40
Tape	18,400' x 1" reels	VHS T160 cassette	VHS T160 cassette
Operator attention required			
without changer	24 h	10 h	24 h
with changer		24 h	
"Burst" mode data rate	200 Mbps (600)[a] (2400)[b]	100 Mbps	500 Mbps
No. of tapes recorded each day/station	3	36	36
Weight/day/station	30 lb	22 lb	22 lb
No. of transports/ station at processor	1	8	8

NOTE: Average recording rate = 100 Mbps = 8.6 tera (10^{12}) bits/day.
[a]With three recorders running simultaneously.
[b]With three recorders running simultaneously and four headstack/recorders.

1. MARK III compatibility: What does this mean?

2. Geophysics proposals and scheduling:
   Full array
   Subarray
   Priority (earthquake)

3. Calibration:
   UT1 + polar motion: ½ - 1 h/day?
   Baselines: one 2-, 4-, 8-h session/day, week, month?
   Array requirements?

4. WVRs + GPA + gravimeter + meteorological sensor + monument + laser pad +?

5. Antenna slew rate and horizon limits?

6. Dichroic S/X bandwidth: Is it enough?

7. Alaska as an additional site?

8. Dual-band combinations: 43/10, 22/5, 43/22?

9. Six GHz excited OH, red-shifted lines: Does the VLBA have adequate frequency coverage?

10. Array configuration: four antennas

11. International connections

FIGURE 18-1 Issues for discussion raised during the workshop.

unattended for at least 24 h. Higher recording rates of 200 Mbps or more should be possible in a "burst mode." Two recording systems are being considered for the VLBA. One, described in detail in the NRAO proposal, is based on the commercial video cassette recorder (VCR). The other is an upgraded version of the longitudinal MK III recorder known as MARK IIIA, in which the bit packing density is increased by using narrow-track heads. Table 18-2 shows some of the key parameters of both systems.

A third system, of 40 VCRs, not mentioned in the NRAO proposal, is also shown in Table 18-2 for comparison. While this system uses a large number of cassette recorders, it could meet the VLBA requirements without a changer. Both the VCR and longitudinal recording systems will undergo further operational tests before a choice is made.

TYPES OF OBSERVATION

The following types of observing were carefully considered for the VLBA: continuum, spectral line, polarization, bandwidth synthesis (BWS), S/X geodesy, and pulsar.

The VLBA will be able to observe simultaneously with other antennas in a manner compatible with the S/X MARK III system currently being used by the POLARIS network and the Crustal Dynamics Project. The interface between the recording system and the digitization electronics or processor electronics will be designed to allow either longitudinal recorders or VCRs. If VCRs are chosen, MARK III compatibility can be achieved by having some longitudinal recorders at the processor.

Figure 18-1 gives a set of questions that were raised earlier. We may want to discuss them now, since I have mentioned recording systems and the MARK III compatibility question that was raised several times earlier, and what we really mean by that.

My interpretation is that we should be able to observe simultaneously with POLARIS or NASA geodesy stations. We may not use exactly the same recording system, but the processor could provide a similar recording system and so process those data without having to transcribe the tapes. So the real requirement is that the observing bands and the way the data will be recorded on the tape be compatible. Whether we use a video cassette or a large reel of 1-in.-wide tape recorded on a longitudinal recorder shouldn't be decided yet, because we do not have that experience with the systems. I would like to get some comments on that interpretation. Dr. Carter, would that satisfy the needs?

DISCUSSION

CARTER: Yes, I think that is right. My concern was originally that when I saw the proposal last, it had only four channels. What you presented this morning looks like it is compatible, and I agree with you that from the POLARIS point of view, or from the geodetic point of view, it appears to be compatible.

ROGERS: Yesterday Dr. Clark assured us that there is enough bandwidth in the S/X dichroic reflector, which allows a simultaneous S/X reception, but I think the people designing the VLBA equipment should be aware that there are dichroic designs in use that do not have adequate bandwidth. We have to be careful to look at that further.

To return to that list of frequencies, you will note that the VLBA plans to support an even wider bandwidth at S-band and X-band than is presently available from the NASA systems; it would be desirable, at minimum, that the dichroic work well over the NASA portions of those bands and, if possible, cover those entire ranges in the dichroic mode.

CARTER: How do those numbers match with the Japanese K3 system, which is said to have about twice the bandwidth in the X-band?

ROGERS: I am not sure.

SPENCER: In the normal operation, are things like the water-vapor radiometers and the Global Positioning System (GPS) going to be monitored and used? As I understand it, they are not fully necessary for doing self-calibration imaging. However, it would be valuable, if you have the historical data at each site when you do the geodetic work, to have that kind of information available. Is that envisioned?

ROGERS: The water-vapor radiometers are in the early NRAO proposal, and I would see no reason why they wouldn't be run all the time. I think we have a good chance at the lower lengths--say, 6 cm and longer--of phase-connecting the entire array. This certainly should be a goal. Many experiments may actually get full-phase information. In such experiments the atmosphere is very important, whereas in the closure analysis, it may not be. Extending integration times is also important. I think the answer on the water-vapor radiometry is yes, but the present NRAO proposal does not cover the GPS receiver. It sounds as if it would be a very good thing to have.

KELLERMANN: It would be. Of course, the current cost of the GPS receiver is about $100,000 apiece. In 5 years, perhaps they will come down.

ROGERS: I mentioned that there are other dual-band combinations. We had discussed in the VLBA study groups the combinations of 43 GHz with 10 GHz, and 22 GHz with 5 GHz, and I believe Irwin Shapiro mentioned yesterday that perhaps 43 and 22 would be good for relativity experiments.

KELLERMANN: Dr. Shapiro will have to design that one; nobody else knows how!

ROGERS: The systems so far developed typically have 3:1 or more ratio between. Does anyone have questions on the recording system, for example?

STRANGE: If they would work equally well, wouldn't a system that would provide 3 physical objects--such as tapes--a day automatically be better than one that is going to provide 30 physical objects a day per station? If you are talking about 3 per day per station, and you have eight or nine stations, that is some 30 per day. You are talking about hundreds and hundreds a day, and tens of thousands a year, which involves an awful physical problem of transporting, storing, and keeping track. It would seem to me that if the two systems were equally capable of recording, you would automatically pick the MARK III system.

ROGERS: You have to realize that those 36 tapes might well go in one canister; if that is done more or less automatically, I don't think it is such a problem.

WEILER: Could you say something about the gross properties of the Japanese K3 system?

ROGERS: It is a MARK III-compatible system, even at the tape level. We have exchanged MARK III tapes. The physical hardware, which is being developed at the Radio Research Labs in Japan, the so-called Kashima station, is different.

WEILER: How?

ROGERS: The diagram is very similar, but the layout of the electronics is different. For example, we use the RS232 type of communications link between various modules, using a device called a microprocessorized ASCII transceiver.

WEILER: I mean more in terms of tape densities, numbers of tapes, sizes of tapes.

ROGERS: Both systems use exactly the same.

SHAPIRO: Pursuing the K3, what do they do for calibration signals, and is that compatible with what MARK III is now using?

ROGERS: Yes, they use the same pulse-type injection calibration into the front end as the NASA POLARIS does--the standard S/X system.

CANNON: I just checked the numbers in the K3 X-band. It is 800 MHz wide, the same as your proposed figures, except it starts at 7.86 GHz. It is shifted down by 120 MHz.

ROGERS: 7.86?

CANNON: To 8.68.

ROGERS: Somebody asked a question about cost. A full cost analysis is in progress now as part of an updating, and will be more detailed than in the NRAO proposal. At present, the systems are much the same.

The basic video cassette recorders are very inexpensive, but there is some trade-off, because although the cassette recorders themselves are inexpensive, a fair amount of electronics has to go with those cassette recorders, a fair amount of buffering of the data. On a video cassette recorder you cannot really record a continuous stream, as you can on a longitudinal recorder. There is a head switch that switches the recorder over to the other head. It is a bit more complicated, and there is some extra cost associated with the electronics.

Otherwise the systems are quite comparable--it is a matter of whether one wants to use 40 cassette recorders without a changer, or 16 with. My feeling is that the changer will save money, but we haven't yet developed a changer. That would seem to be a straightforward project, but could be more difficult than we think. However, it is not absolutely essential that such a changer be developed. It has been suggested that we could perhaps use large reels of tape with cassette recorders, so there are several possibilities.

SHAPIRO: With the cassette scheme as presently envisioned, will there be any data gaps, and, if so, what would their lengths be?

ROGERS: It is a matter of sequencing those recorders. For example, if the tape is finishing on eight recorders that you are running simultaneously, then you can start up another eight recorders. There need not be a gap. They can be overlapped.

ROBERTS: I have a question about the flexibility of the frequency selections. I am confident that you have picked the important astrophysical frequencies at the moment, but I think it may be presumptuous of us to believe that we won't discover something new and important that lies somewhere in between those bands. How flexible is the feed and radio frequency situation, especially when no one is going to like having his favorite band pulled to put something new in. Has thought been given to leaving space in the feed circle for new bands?

ROGERS: I believe there is a plan for a so-called spare location, so that you could add another band. This is what a narrow-track head for an instrumentation recorder looks like. The head is roughly 1 in. long, and the individual tracks are 40 μm wide. The heads are spaced 762 μm apart. The whole head assembly moves between pauses on the tape. When it is mounted on the recorder, it really looks no different from the present MARK III. Of course, in the present MARK III, the heads are fixed and cannot be moved.

19

USES OF THE VLBA RELATED TO DEEP-SPACE NAVIGATION

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As I studied the newly discovered quasars and radio galaxies when I was a graduate student, it never occurred to me that these objects, and the new technique of very long baseline interferometry (VLBI), would ever have any practical application. And yet a knowledge of the celestial sphere has returned to the place of importance it once had in man's exploration of distant and unknown worlds, but now that knowledge is important for navigation through featureless space to other parts of the Solar System rather than across the featureless oceans to other continents. Deep-space navigation now relies heavily on an accurate celestial reference system composed of just these "useless" extragalactic radio sources to provide the reference frame for positioning a spacecraft. It is only through the development of that same new astronomical technique, very long baseline interferometry, that this is even possible. Thus it is reasonable to ask how the Very Long Baseline Array (VLBA), the next big advance in VLBI, might be of use for deep-space navigation.

In sending a spacecraft to some planet, or its satellites, or to any other object, two basic questions must be addressed: (1) Where is the spacecraft? and (2) Where is the target? The accuracy with which the second can be answered may have a significant effect on the amount of science done by the mission, since it determines what fraction of the spacecraft's mass resources must be allocated to adjusting the spacecraft trajectory as it approaches encounter. Use of the VLBA may contribute to answers to both of these questions.

The three types of measurements made for determining the state of a spacecraft are (1) range, which is obtained from the round-trip travel time of the telemetry signal; (2) range rate, obtained from the Doppler shift of the telemetry; and (3) Delta VLBI, which gives the angular position of the spacecraft relative to extragalactic radio sources (Renzetti et al. 1982). As the name suggests, Delta VLBI is a measurement of the differential position between the spacecraft and a radio source; the measurement is made using VLBI and treating the spacecraft as a radio source. As a result of astrometric programs, the positions of the natural radio sources are known with an accuracy of better than 0.01 arc sec, and the relative spacecraft coordinates are measurable with comparable accuracy. These two observables give the two radial components of the spacecraft-state vector--that is, velocity and distance away from earth--with great accuracy, but the tranverse components in the plane of the sky are not well determined. The use of Delta VLBI has only recently been added to the traditional navigation types, Doppler and range. Addition of Delta VLBI gives accurate values for the right ascension and declination of the spacecraft, and may eventually give the transverse velocities as well.

Five factors determine the accuracy of the navigation system. These are (1) geocentric station location, (2) earth orientation at the time of observations, (3) calibration of the media through which the radio waves of both the spacecraft and natural radio source pass, (4) the "absolute" time at all stations, and (5) a catalog of extragalactic radio sources with accurate positions. Use of the VLBA will most likely contribute to (1), (2), and (5) from the preceding list of factors, and will do so either directly or by increasing our general knowledge in those areas.

All of the navigation measurement types require a knowledge of the positions of stations on earth to determine the location of the spacecraft. For the National Aeronautics and Space Administration (NASA) Deep Space Network (DSN), the geocentric locations of the tracking antennas are known to within about 1 m through a combination of radar measurements of the inner planets (Mercury through Mars) and tracking of spacecraft. The relative positions of the antennas are known to within better than 0.3 m as a result of VLBI measurements that are being made for astrometric determination of a radio reference frame. In addition to the positions of the stations on the fixed earth, their positions relative to the celestial sphere must be known. This requires the earth orientation parameters UT1 and polar motion. The accuracy of these data from the time services gives uncertainties in the station locations comparable with those of the VLBI results.

The propagation time of the radio signals through the troposphere and ionosphere may be a limiting error source at a level of several centimeters for the Delta VLBI data (5 cm corresponds to 0.001 arc sec on a baseline between California and Australia). It is hoped that water-vapor radiometers will provide calibration of the wet component of the troposphere to better than 1 cm, and that the effect of the dry component can be calculated with similar accuracy from surface meteorology. Delays due to the ionosphere will be removed by dual-frequency observations.

The more sophisticated ranging techniques, such as two-station differenced range, require an accurate knowledge of the time-offset between two sites. Clock synchronization is now provided by VLBI measurements between the pairs of antennas with an accuracy of 0.1 μs.

Finally, for Delta VLBI an accurate radio source catalog is needed, since the navigation is no better than the source positions. Current radio astrometric measurements made by two independent groups agree to better than 0.01 arc sec for the positions of about 40 sources from the DSN astrometry program that have been measured over a relatively short span of time. Positions of this accuracy exist for more than a hundred sources, although most are not within 10° of the ecliptic, as desired for accurate navigation.

TABLE 19-1 Delta VLBI Navigation Accuracies

Spacecraft	Year	Spacecraft Location (arc sec)	Radio Source Position (arc sec)
Voyager	1983	0.02	0.01
Galileo	1987	0.01	0.004
?	1990s	0.003	0.001?

The current and projected accuracies from Delta VLBI are given in Table 19-1.

Since the Voyager encounter with Saturn, Delta VLBI has been a primary data type for navigation, and its value will increase as the spacecraft travels to Uranus (to arrive in 1986) and Neptune (to arrive in 1989).

Galileo will be launched in 1986 on a 2-year trip to Jupiter. On arrival it will eject a probe to sample Jupiter's atmosphere, and then continue on to orbit the planet and study its satellites. Since there is no direct communication between the probe and earth, the trajectory of the probe must be reconstructed in part from the change in the orbiter's path. The accuracy requirement on reconstructing the probe entry angle into the atmosphere of Jupiter sets the goal for Galileo navigation of 0.01 arc sec. Because of the other contributions to the error budget, the source position uncertainties need to be less than 3 or 4 milliarc sec.

Projecting into the 1990s suggests a goal of 3 milliarc sec for navigation, and source positions to 1 milliarc sec.

From this description of current and future deep-space navigation tasks and goals, some possible uses of the VLBA might be deduced. These may be divided into two areas: (1) results from the VLBA derived from nonspacecraft observations, and (2) direct observations of spacecraft. The latter may be either for navigation and telemetry or perhaps for science objectives.

The most obvious application of the VLBA is in the area of astronomy. As the requirements on source positions become more stringent, the extent to which even the milliarc second structure is not pointlike will become more important. Even more serious is the time variability of the compact radio structure. The Delta VLBI observations for navigation are made with only two antennas, as are the supporting astrometry measurements made by the Deep Space Network. From these data, source structure cannot be determined. Since the time on the VLBA will be devoted to observations of many of the same sources as those used for navigation, the results will be of direct interest.

As part of the calibration of the VLBA, it will be necessary to make accurate baseline measurements among all the antennas. This will produce two useful results--an independent astrometric catalog of radio sources for comparison with that of the DSN, and additional data for definition of a terrestrial reference frame. As accuracies improve, the tectonic changes of the earth will require a more complicated description of its surface, and all resources should be utilized for the best model.

One method of better understanding where the planets are is to determine if there is a rotation between the reference frame determined by radio sources and the frame defined by stars, from which the outer-planet ephemerides are determined. With the increased sensitivity of the VLBA, it should be possible to extend the current observations of radio stars and to include them directly into radio astrometric programs.

Passive radio observations of Solar System objects, such as asteroids and planetary satellites, are being made with the VLA to determine their dynamics. The improved sensitivity of the VLBA operating with the VLA as one element may permit similar measurements of smaller objects. A better understanding of solar system dynamics directly addresses the second of the questions posed above, that is, "Where is the target?"

In occasional situations it may be desirable to use the VLBA for tracking of spacecraft. Such situations would include the following three: (1) In the event that a spacecraft signal became "lost," or if a spacecraft exceeded its expected range, the opportunity would exist to obtain a significant increase in sensitivity by arraying the antennas of the VLBA with those of the DSN. (2) Shorter baselines than those of the intercontinental network may be needed for specific parts of a mission. An example might be the direct tracking of a spacecraft orbiting an object that is too resolved by the long baselines. (3) Multiple baselines--in particular, a pair of simultaneous orthogonal baselines--may be desirable for a mission of short duration in order to get the two components of position without waiting for the earth to turn. A balloon flight into the atmosphere of a planet for which the expected motions are large or of short duration may require the use of the north-south baseline of the VLBA.

Use of the VLBA for spacecraft tracking does not, however, imply significant changes in configuration beyond those being contemplated for other programs. The main requirements would be frequency compatibility at S- and X-band, water-vapor radiometers for troposphere calibration, and a system for phase calibration. The last two components, water-vapor radiometers and phase calibration, are probably needed by the VLBA to achieve the calibration and stability desired for the next big improvement in mapping, while the availability of simultaneous S/X reception will allow inclusion of the DSN antennas for very high sensitivity studies and for simultaneous dual-frequency mapping.

REFERENCE

Renzetti, N.A., J.F. Jordan, A.L. Berman, J.A. Wackley, and T.P. Yunck 1982. The Deep Space Network--An Instrument for Radio Navigation of Deep Space Probes. JPL Publ. 82-102, Dec. 15.

DISCUSSION

SHAFFER: You said you are tracking monochromatic signals from the spacecraft. You must be phase-tracking on the spacecraft. Do you then look for a source close enough that you can phase-connect the quasars to that?

NIELL: No, we do bandwidth synthesis on the spacecraft as well. On Voyager there are many tones because of the modulation of the signal, the differential delay between the spacecraft and the radio source. So we do bandwidth synthesis.

SHAFFER: How broad are the spacecraft signals?

NIELL: The harmonics go far out; I think they are currently using something like 18 MHz.

ROGERS: We haven't really discussed the phase-calibration tone spacing. Certainly 1 MHz, but it sounds like you might want to go down to 100 kHz?

NIELL: The spacing that will be needed is something that should be kept in mind.

ROGERS: I have another question. The proposed block diagram would not be able to actually Doppler-track the satellite. We would propose that fine Doppler tracking be done in the processor. Does that pose any special requirements for the spacecraft?

NIELL: I am really not the person to ask, but I will convey the question.

WALKER: I know that there are some plans to use the VLA for tracking Voyager when it gets to Neptune. There is a problem with that: every 50 ms there is 1 ms of signal going out to the telescopes, and the spacecraft telemetry can't accommodate such a break. If there is some thought of using VLBA for telemetry, we probably need some sort of specifications on what the recording system, or what the receiving system, can withstand in terms of what we might put in. For purposes of astronomy, there is no particular reason not to leave small bits of data out, but for telemetry such data would be important. Do you have any thoughts on that?

NIELL: I think the work that is being done in arraying and the work that is being done for the Uranus encounter will provide information on this and will certainly be available, but I don't know the answers now.

ROMAN: I have two questions. First, can you tell us something about your source catalog's characteristics--what minimum intensity, what sort of density, how wide a band around the ecliptic? And second, have you any estimate for the sort of time you are talking about for spacecraft navigation purposes with the VLBA?

NIELL: In regard to the first question, there are 110 sources in the catalog. We observe around 80 precession, which changed slightly. The declination range is -45 to +84 at the moment, so we cover the full sky that is visible by the DSN.

The coverage in the ecliptic within ±10° of the ecliptic is not sufficient at the moment for the requirements that we have set out for navigation, but there is a program under way, looking for sources down to roughly two-tenths of a Jansky-correlated flux density.

The surveys at S-band by Bob Preston, Dave Morbito, and Ann Worley have been completed, and the next stage is to look at these with VLBI at X-band to find out if they are satisfactory at X-band, and then to pick the ones that seem to be in the best locations for navigation. In fact, we will cover the entire ecliptic eventually and include those new sources found in the source catalog as well. About the amount of time for navigation on the VLBA, I can't estimate that right now.

SHAPIRO: Is it fair to say that there are no missions planned that would be relevant, as the VLBA won't be ready until 1989.

ROMAN: Pioneer Venus.

Audience participant: It is not developed for that.

NIELL: Delta VLBI will be used for all navigation for all of the upcoming spacecraft.

BURKE: What about the Neptune encounter?

SHAPIRO: I don't really think it would be necessary.

CHRISTIANSEN: I agree. We know where Neptune is. We are doing studies now, trying to bring the VLA in for Neptune array for telemetry purposes. For navigation, there wouldn't be any need.

NIELL: I don't think there are any current plans to use the VLBA for navigation. I was speculating. There are no direct plans.

HINTEREGGER: I would like to suggest that we look at the question in another way: that is, at what the DSN can do to enhance the sensitivity of the VLBA instead of what the VLBA can do for spacecraft tracking.

NIELL: One of the points I forgot to mention is that if short baselines are of interest, it might be useful to have some of the short spacings near the DSN antenna at Goldstone in order to take advantage of the sensitivity there. There is a plan for the 64-m antennas to be upgraded to 70 m in the 1987 time scale, and with the increased efficiency or with other changes, the efficiency at X-band will increase by 55 percent. The sensitivity will be 55 percent above what it is now, and there will be other upgrades.

KELLERMANN: Would you like to make any estimate of the availability of time on the DSN antennas? Perhaps comparable to the amount of time that the VLBA is used for geodesy? In the same spirit in which Drs. Clark and Coates spoke earlier about the changes and additions to the VLBA that might be needed for geodesy, would it be feasible to implement the radio astronomy bands on the DSN antennas instead of the bands NASA is using for transmitting, which make radio astronomy a little bit difficult?

NIELL: I can address only the question of frequencies. We just put 22 GHz on the 64-m antenna; unfortunately, it didn't become workable before the 64-m antenna went down for a year. But perhaps a better antenna will be there when it comes back up. This is DSS-14, and there has been a 22-GHz on DSS-43 in Australia as well. I think it is planned to put 22 GHz on Spain. There is a question about what the next priorities are. There will be possible 1.6 GHz system coming up as result of the DSN involvement and the French-Russian-American balloon flight in the Venus atmosphere. The 5-GHz has been discussed. I can't make any promises about observing time. There seems to be a lot of it coming up next month though. I can't make any promises about the future; I am fighting for that, too.

CARTER: Several people have discussed water-vapor radiometers. What is the VLBA planning with regard to water-vapor radiometers? And if you know how to build some that work and we can get the data, would you tell us?

KELLERMANN: That is just what I was going to ask you. We are planning them, but one hasn't yet been built that will do the job. There are three or four around that look promising. They will be essential for the VLBA work, extending the coherence time and doing phase-referencing, so we want to have them, and they are budgeted for. I just wish we knew how to build them.

20

A VLBI OBSERVATORY IN SPACE--AN ENHANCEMENT OF THE VLBA

R.A. Preston
Jet Propulsion Laboratory

The angular resolution of radio maps made by earth-based very long baseline interferometry (VLBI) observations can be exceeded by placing at least one element of a VLBI array into earth orbit. A VLBI observatory in space can offer the additional advantage of increased sky coverage, higher-density sampling of Fourier components, and rapid mapping of objects whose structure changes in less than a day. This chapter explores the possible addition of an orbiting antenna to the proposed Very Long Baseline Array (VLBA).

INTRODUCTION

The National Research Council recently formed a committee headed by George B. Field to chart the direction of U.S. astronomy for the 1980s. One of the recommendations of the committee was that a space-based very long baseline interferometry antenna be built in this decade (NRC 1982).

During the last 15 years, the development of the technique of very long baseline interferometry has effected a revolution in the imaging of celestial objects. VLBI has surpassed the angular resolving power of optical telescopes by three orders of magnitude. This extraordinary resolving power has led to a number of surprises, including apparent velocities in quasars that exceed the speed of light and ordered structures in radio galaxies on scales from one to one million parsecs. Virtually every radio quasar and active galactic nucleus has angular structure that is unresolved with the best VLBI observations currently available. Within our home galaxy, the powerful molecular masers, often associated with the star-formation process, have been shown to have complex spatial and velocity structure on very small scales.

Active binary systems, such as the mass-transfer binary X-ray objects, exhibit outbursts of radio noise. Even the nucleus of our galaxy is sufficiently compact to require study by VLBI techniques.

In nearly every case, there remains spatial structure that is unresolved with the best angular resolution achievable with antennas on earth. VLBI observatories in space will allow even smaller structural details to be explored by creating larger synthesized apertures, and hence will provide finer angular resolution than can arrays of ground antennas alone (Burke 1982, Morgan et al. 1982, Preston et al. 1982).

BASIC CONCEPT OF SPACE-BASED VLBI

Conceptually there is no difference between space-based VLBI and ground-based VLBI. A VLBI observatory in space could merely be considered an outrigger antenna of a ground-based array such as the future VLBA (NRAO 1982). To illustrate aperture synthesis with space-based VLBI, consider in Figure 20-1 the u-v plane coverage generated by a baseline between a single ground antenna and an antenna in a 400-km circular polar orbit. The observed source is chosen to be in the orbit plane at 30° declination. All possible observations during a 24-h period are shown. For clarity, reflection points through the origin have not been plotted in this example.

The resulting u-v coverage is rather uniform over roughly the dimensions of the orbit. The plot consists of a family of curves. Each individual curve is principally due to the rapid satellite motion during one orbit, while the appearance of a set of similar curves is due to the slower earth rotation causing slightly different east-west baseline projections on each orbital pass. The rapid motion of low-orbit satellites will limit coherent integration times to $\lesssim 2$ minutes to prevent excessive u-v plane smearing. The density of u-v coverage could be increased by observing on multiple days, assuming the orbital period is not commensurate with the earth's rotation period. For the low-orbit case, the quality of u-v coverage seems to be reasonably independent of source/orbit geometry as long as the ground antenna can see the source for several passes a day and the orbit inclination is $\lesssim 45°$. In actual practice, more than a single ground antenna would likely be used in order to obtain phase closure data in addition to fringe amplitude data and to effect more rapid filling of the u-v plane.

ADVANTAGES OF SPACE-BASED VLBI

Space-based VLBI offers several advantages over earth-bound VLBI, including the following:

1. Increased angular resolution--Space-based VLBI provides longer baselines and hence finer angular resolution than can ground-based VLBI at the same observing wavelength. The ultimate resolution achievable by VLBI in space may be limited by interstellar scattering. This limit is reached for baselines of about 10 to 10^3 earth diameters in length, depending on the wavelength.

2. Improved sky coverage--Current VLBI ground networks cannot make high-quality maps over the entire sky. At low declination, linear u-v tracks and the lack of large north-south antenna separations result in poorer aperture synthesis. Since half of the sky is located in the equatorial band ±30°, this is a severe problem. In addition, since

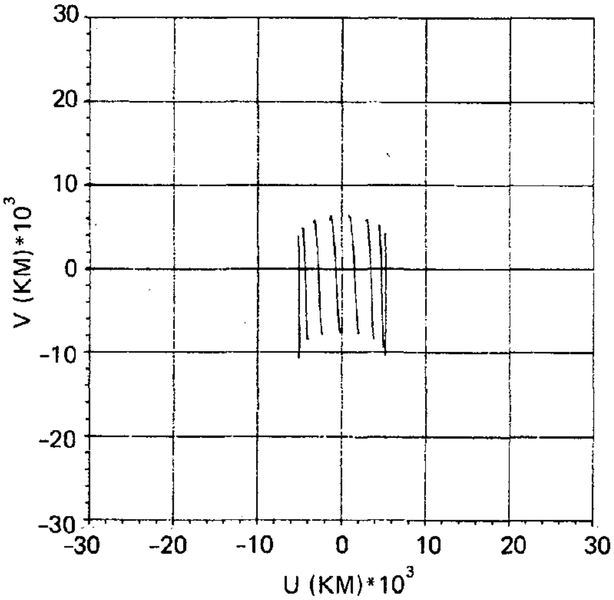

FIGURE 20-1 The u-v coverage for low-earth orbiter with single ground antenna.

most of the large astronomical telescopes are located in the Northern Hemisphere, the southern sky is presently poorly observed by VLBI. A space-based VLBI system operating with a current Northern Hemisphere ground array could provide excellent u-v coverage from the North Pole to perhaps -30° declination. Good u-v coverage could also be provided for the remainder of the Southern Hemisphere by only a few Southern Hemisphere observatories working with a space-based VLBI antenna.

3. More completely synthesized apertures--A space-based VLBI antenna working with a ground array would provide many more u-v tracks than would the ground array alone, and successive days of observation will yield even more tracks. Hence, space-based VLBI has the capability to totally "blacken" the u-v plane. This results in several potential advantages: (a) the smaller holes in the u-v coverage would increase the field of view over which a reliable map can be synthesized; (b) fine-scale detail would be more reliably reproduced (allowing smaller restoring beams); and (c) the lower sidelobe level of the synthesized beam would reduce the effects of calibration errors.

4. More rapid mapping--Since a single pass of a low-orbit VLBI antenna working with a ground array would result in fair u-v coverage, a crude map could be constructed from a single pass alone. This property might prove useful for monitoring the structural evolution of flaring active binary systems whose structure can vary significantly in time periods of less than a day.

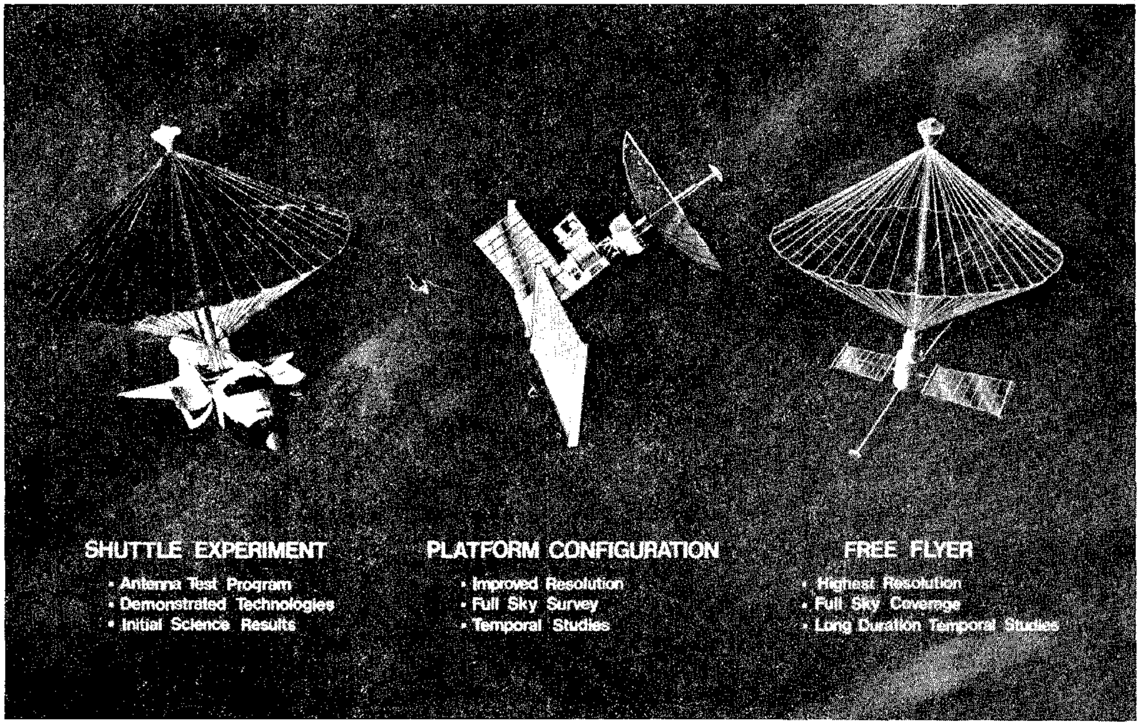

FIGURE 20-2 Possible space VLBI missions.

EXAMPLES OF SPACE-BASED VLBI SYSTEMS

The space-based VLBI concept may be implemented in several ways. Missions with maximum orbital altitudes of a few hundred kilometers can be achieved by three different spacecraft types (see Figure 20-2): (1) the Space Shuttle--for 1- or 2-week demonstration and test experiments; (2) a future space platform or space station--for a longer-duration facility, perhaps 6 months; or (3) a free-flier--for a long-lived (2 yr) observatory. Examples of the u-v plane coverage that can be obtained with such low-orbit missions are shown in Figures 20-3, 20-4, and 20-5. Figure 20-3 shows 10-h u-v coverage for a low orbiter and a proposed 10-antenna U.S. ground array (Cohen et al. 1980) observing a source at a declination of +60°. Also shown is the corresponding 24-h u-v coverage for the ground array alone. The aperture synthesized by the orbiter/ground array has an area roughly 4 times larger than that synthesized by the ground array alone. Hence, maps constructed with the orbiter/ground array observations should have at least 4 times as many picture elements per unit angular sky area as would maps made with the ground array. Figure 20-4 shows a similar example (but 16-h coverage) for a source at a declination of 0°. Figure 20-5 shows an example of a network of five existing Southern Hemisphere antennas working for 24 h with a low orbiter for a source at a declination of -60°. Note how poor u-v coverage with the ground array alone translates into excellent u-v coverage with the addition of the orbiter. Although this

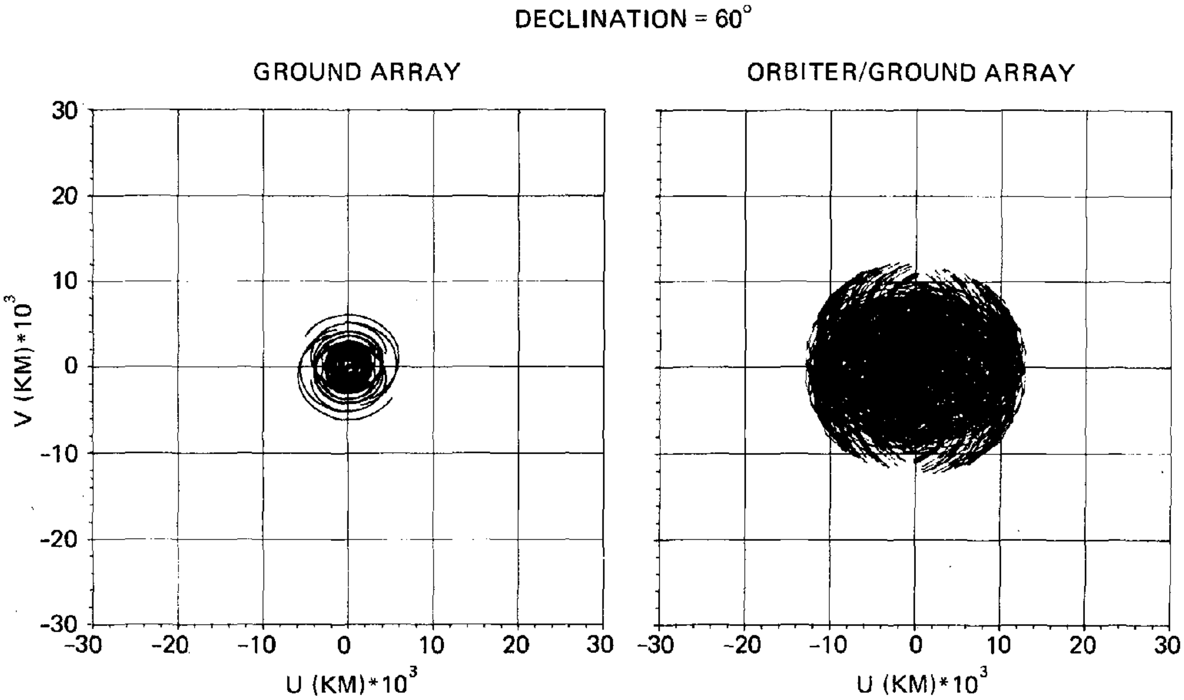

FIGURE 20-3 The u-v coverage for low-earth orbiter with ground array--declination = 60°.

example shows that useful maps could be made of Southern Hemisphere objects with only a few Southern Hemisphere antennas, the quality of the maps would not match those of Northern Hemisphere objects produced by a more powerful VLBA working with an orbiting antenna.

A free-flier spacecraft is the only possibility of obtaining a higher-orbit mission (>10^3 km altitude). At present, a high-orbit free-flier seems the most likely first step of VLBI into space. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have recently initiated a joint mission assessment study of an Explorer-class VLBI observatory named QUASAT (ESA 1982), with an apogee altitude of about 15 x 10^3 km, a maximum reception frequency of 22 GHz, and an antenna diameter of 10 to 20 m. Figure 20-6 shows examples of the u-v coverage that might be obtained with an eccentric satellite orbit with a perigee altitude of 4 x 10^3 km and an apogee altitude of 15 x 10^3 km. The left-hand plot shows the u-v coverage resulting from 24 h of observation with this satellite, the proposed 10-antenna U.S. ground array, and the Deep Space Network site at Madrid for a source declination of +60°. The coverage within a radius of about 8 x 10^3 km of the u-v plane origin results almost exclusively from the ground array alone, while the coverage outside that radius results almost exclusively from the baselines to the satellite. The right-hand plot shows the u-v coverage resulting from 24-h observations with the satellite and both the 10-antenna U.S. array and the 5-antenna Southern Hemisphere array for a source at a declination of 0°. The coverage generated by the ground arrays alone appears

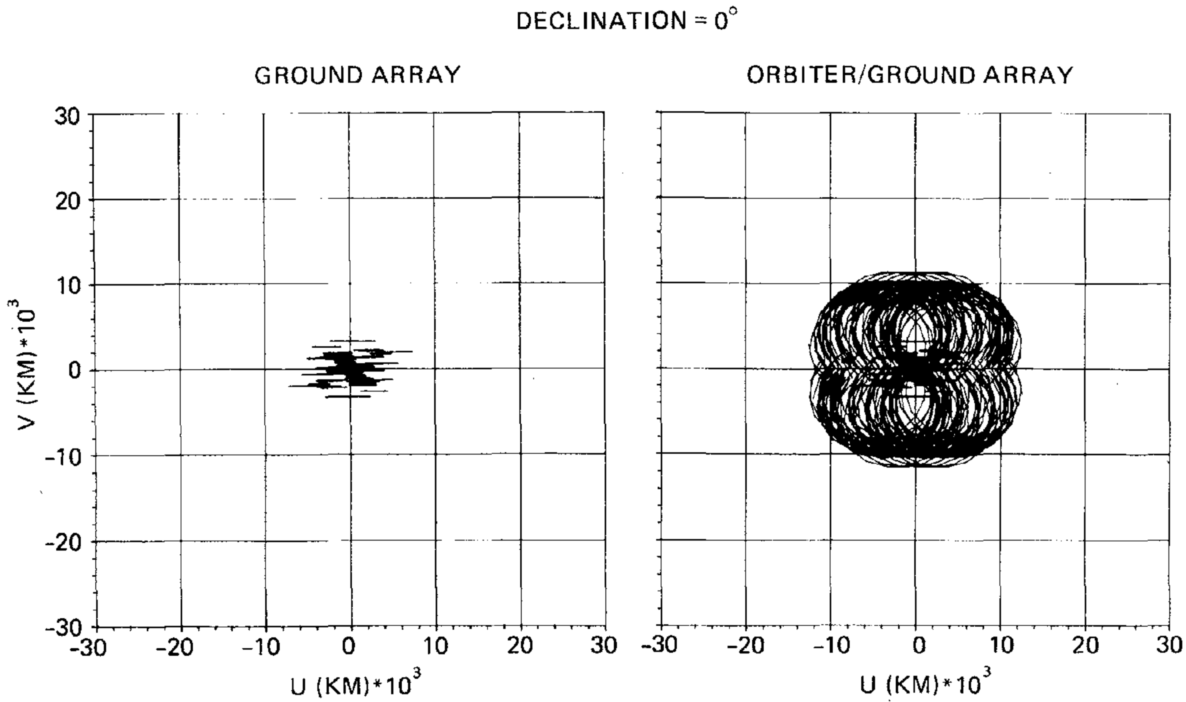

FIGURE 20-4 The u-v coverage for low-earth orbiter with ground array--declination = 0°.

as horizontal lines near the origin. In both plots of Figure 20-6, the aperture synthesized by the orbiter/ground array has an area roughly 8 times larger than that synthesized by the ground array alone.

Even higher-orbit free-fliers are possible, but the u-v coverage tends to develop holes or become elongated in the case of a single satellite. These problems can be overcome with multiple free-flying antennas. As an example, consider the case of two satellites in circular orbits with orthogonal orbital planes, semi-major axes of about 10 earth radii (6.4×10^4 km), and orbital periods that differ by 10 percent. Figure 20-7 shows the good u-v coverage that could be obtained by such a system. Only baselines between the two satellites are considered. Note that this two-satellite system scales to any orbit size. Many variations of the multiple-satellite scheme are possible, including systems with more than two satellites and the use of ground arrays.

TECHNOLOGICAL READINESS

Since there is no conceptual difference between ground-based and space-based VLBI, technological readiness reduces to our ability to produce space-based versions of the subsystems necessary to conduct a ground-based VLBI observation. The crucial subsystems are the antenna and its pointing system, receivers, frequency standards, intermediate

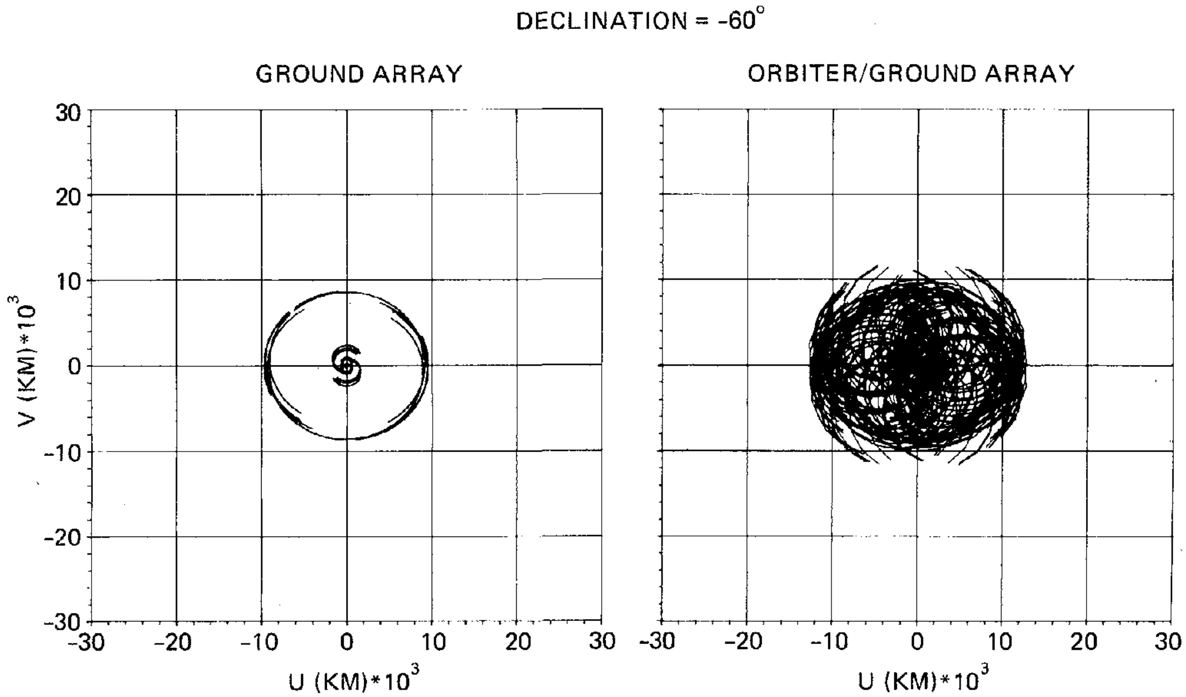

FIGURE 20-5 The u-v coverage for low-earth orbiter with ground array--declination = -60°.

frequency (IF) to digital electronics and data-recording mechanisms. The space-readiness of each critical subsystem is examined below for all mission types.

Antenna

If an orbiting VLBI system is to be applicable to the full set of astrophysics problems engaged in by ground-based VLBI, it should have an antenna diameter of 50 m. However, an important set of strong sources could be observed with an orbiting antenna diameter as small as 5 to 20 m, depending on other system parameters. Deployable mesh antennas of 10 m in diameter have been flown in space, and diameters as large as 50 m are possible. Other types of deployable antennas for space use (e.g., inflatable antennas) are under development. With current technology, the ratio of antenna diameter to root-mean-square (rms) surface irregularity is expected to be about 2 x 10^4 for a 50-m deployable mesh antenna and would allow good performance up to frequencies of about 10 GHz. For antenna diameters of up to about 20 m, 22-GHz performance should be achievable. A finite-element, dynamical computer simulation of a 50-m deployable antenna on the Space Shuttle has shown the antenna and its pointing system to perform well, even in the rather harsh environment of the thruster attitude-control system. Pointing of such deployable antennas in space is likely to be a

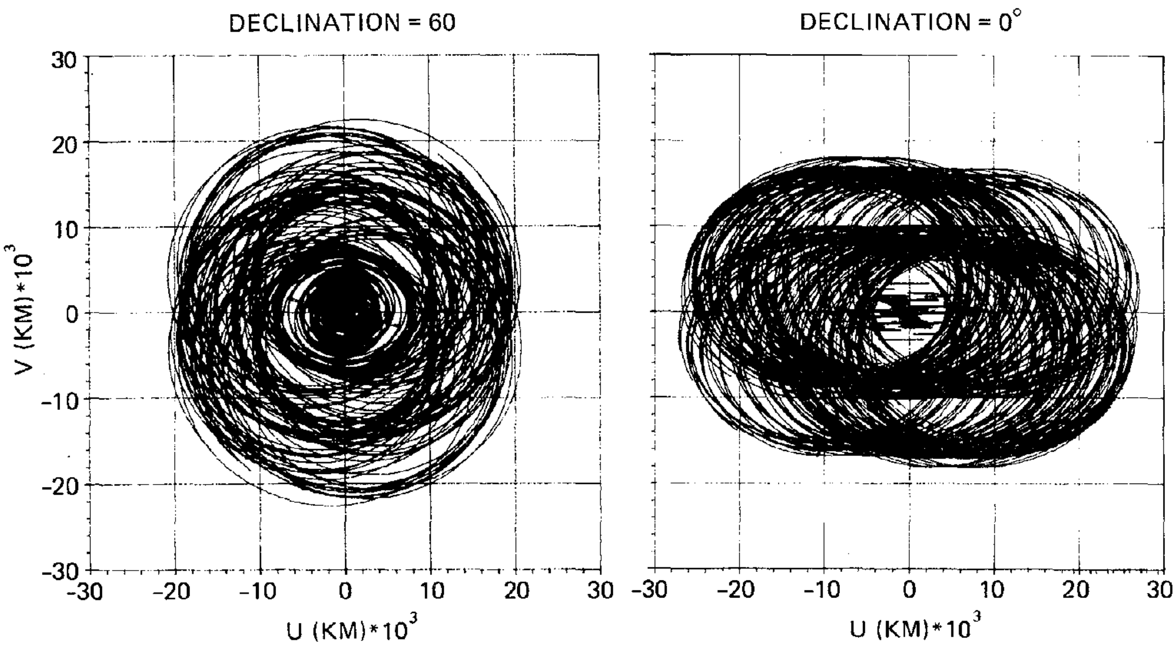

FIGURE 20-6 The u-v coverage for high-orbit free-flier and ground array.

two-stage procedure, with a three-axis or spin-stabilized (about the antenna axis) attitude-control system for crude pointing and a movable subreflector for fine adjustments.

Receivers

The recent development of gallium arsenide field effect transistor (GaAs FET) receivers has provided a very suitable technology for use in an orbital VLBI station. These small, reliable receivers should yield system temperatures in space of about 75 K at 2 GHz and 160 K at 8 GHz. At 22 GHz, GaAs FET receivers should soon be available for operational use.

Frequency Standards

A hydrogen maser of sufficient stability ($f/f \sim 3 \times 10^{-14}$ for $\gamma \sim 10^2$ sec) has been flown on a suborbital rocket flight in the Smithsonian Astrophysical Observatory (SAO) Gravity Probe-A (redshift) experiment in 1976. At frequencies below 5 GHz, flight-qualified crystal oscillators and cesium or rubidium frequency standards might suffice. For free-flier VLBI observatories that spend a significant portion of each orbit at altitudes ~5000 km, direct line-of-sight communication to Deep Space Network tracking sites is possible most of the time, allowing the frequency stability of a ground-based hydrogen maser to be

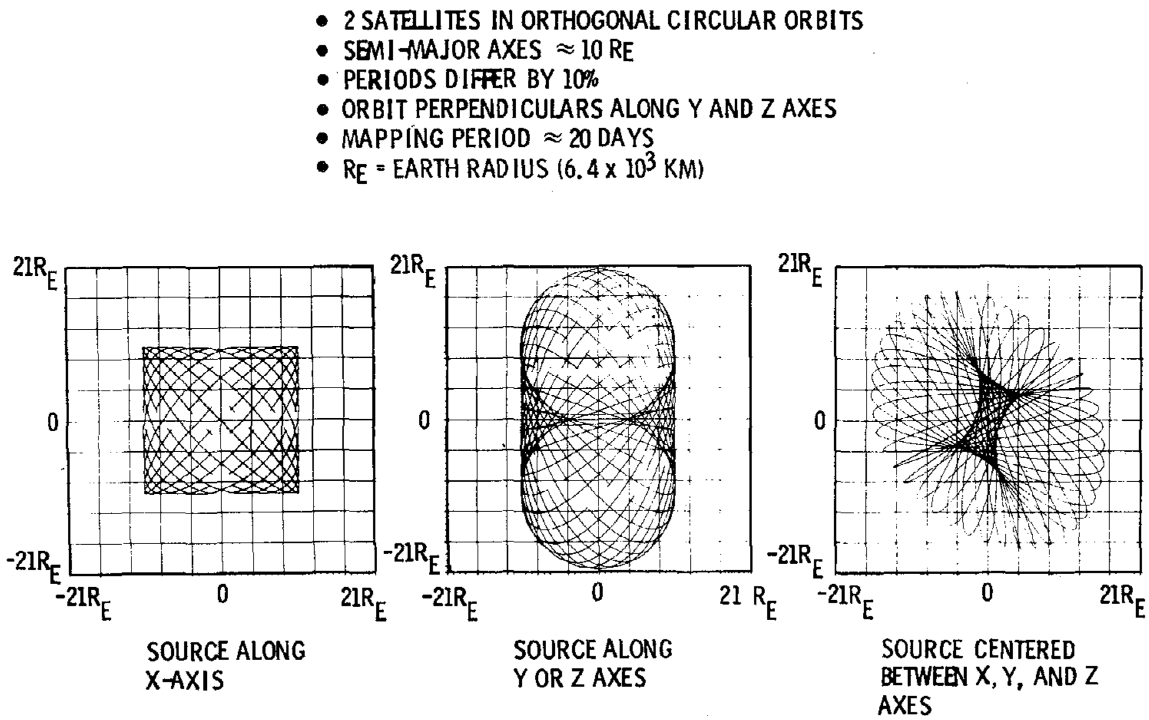

FIGURE 20-7 Aperture synthesis with high-orbit satellites.

transferred to the spacecraft via a self-correcting, two-way Doppler link.

IF to Digital Electronics

The MARK III system developed by Haystack Observatory has become a standard ground-based VLBI system. The electronic modules of this system (or future recording systems) could be repackaged and qualified for space use.

Data Recording

The MARK III system can presently record data at a rate of 112 Mbits/s on a modified Honeywell instrumentation tape recorder, preserving a bandwidth of 56 MHz in a set of 2 MHz channels. The number of channels included in a given orbiting VLBI system will depend on the data storage or transmission capability available. For the Space Shuttle, a set of cassette tape recorders should allow up to 8 MHz of bandwidth to be recorded. Low-orbit platforms, space stations, or free-fliers should provide bandwidths in excess of 12 MHz by combinations of recording systems and periodic dumping to the ground via the Tracking and Data by Relay Satellites System (TDRSS) communications satellites. Free-fliers such as QUASAT, which are high enough to have nearly continuous communication with the Deep Space Network tracking sites, will not require recording systems and could transmit data bandwidths of 20 MHz or more directly to the ground for subsequent recording, with the bandwidth limitation being imposed by international frequency bandwidth allocations.

CONCLUSION

The science to be gained by an orbiting VLBI observatory is exciting. There seem to be no technological barriers to building such an observatory. Preliminary design studies have been performed on both a Space Shuttle experiment with a 50-m diameter antenna and a free-flier with a 5- to 15-m diameter antenna. The estimated cost of the free-flier system was $50 million (U.S. 1982), excluding launch vehicle and operating costs. This is a low price compared with that of many astronomical space observatories. An orbiting VLBI observatory would prove a useful complement to a future ground array such as the VLBA. Since VLBI is already a discipline that demands international cooperation, it would be a natural evolution to consider an international development of an orbiting VLBI observatory.

ACKNOWLEDGMENTS

This chapter represents one aspect of coordinated efforts by many individuals to promote a VLBI observatory in space. Among those individuals are B. Anderson, A. van Ardenne, A. Boischot, R.S. Booth, B.F. Burke, T.A. Clark, M.H. Cohen, R. Doxsey, R. Fanti, G. Grueff, D. L. Jauncey, K. Johnston, J.F. Jordan, K.I. Kellermann, J.M. Moran, S.H. Morgan, I.I.K. Pauliny-Toth, R.A. Preston, E. Preuss, A.C.S. Readhead, D.H. Roberts, A.E.E. Rogers, B.O. Ronnang, R. T. Schilizzi, I.I. Shapiro, and P.N. Wilkinson.

REFERENCES

Burke, B.F. 1982. "Radio Telescopes Bigger than the Earth," Astronautics and Aeronautics, Oct. 1982, 44.

Cohen, M.H., et al. 1980. A Trans-continental Radio Telescope, report by California Institute of Technology, Pasadena, Calif.

ESA 1982. QUASAT, A VLBI Observatory in Space, a proposal to the European Space Agency, November 1982.

Morgan, S.H., M.E. Nein, B.G. Davis, E.C. Hamilton, D.H. Roberts, W.A. Traub 1982. "Concepts for Large Interferometers in Space," Proceedings of AIAA/SPIE/OSA, Conference on Technology for Space Astrophysics: The Next 30 Years, Oct. 1982, Amherst, Mass.

NRAO (National Radio Astronomy Observatory) 1982. Very Long Baseline Array Radio Telescope, a proposal to the NSF, May 1982.

National Research Council 1982. Astronomy and Astrophysics for the 1980's, report by the Astronomy Survey Committee, National Academy of Sciences, National Academy Press, Washington, D.C.

Preston, R.A., B.F. Burke, R. Doxsey, J.F. Jordan, S.H. Morgan, D.H. Roberts, and I.I. Shapiro 1982. "The Future of VLBI Observatories in Space," Proceedings of CNES Conference on VLBI Techniques, 31 Aug. to 2 Sept. 1982, Toulouse.

DISCUSSION

SHAFFER: There is already a 5-m antenna in space connected to a very broad band data system, which is the TDRSS, which, in fact, has two 5-m antennas on it. It might be worthwhile trying to see if we could get a little astronomical time on that satellite at some point.

Second, if you get two antennas in space, above the atmosphere, you should be able to do very good phase-linked interferometry, so you should consider some kind of a very precise navigation system on your two satellites, or at least a laser intercommunication system, so you can measure the baseline independent of your radio observations. Although it moves around, you should be able to get your radio source position grid down into the microarc second range.

PRESTON: To address the last point first, an additional advantage of having two antennas in space is to be able to go even higher in frequency and not have to worry about the atmosphere. To address the first point, there is a study at JPL now to try to use the TDRSS satellite as a demonstration of the technology for the link that would be needed for a free-flying orbiting VLBI satellite. If that works, the objective is to make some actual observations.

WALKER: Could you give us some idea of what the technical constraints on the VLBA would be, so that we could operate with a space-based system?

PRESTON: The important thing to consider is the processing system. You want to make sure that the fringe rates and delays that are needed for an orbiting system have been taken into account in that.

In addition, I would hope that before the positions of the antennas on the ground were poured in concrete, some thought would be given to where those developing a space-based system might prefer to have antennas.

KELLERMANN: I want to elaborate on that point, but I would like to turn it around, because you are in a much better position to do that than we are.

OTA: My name is Minoru Ota. I presided at a workshop in Japan on an essentially similar subject, that is, space VLBI. We have started a current workshop to discuss the future possibility of using Japanese spacecraft for an essentially similar purpose. I am not an expert, so these numbers may not be exact; however, at the moment we are discussing sending out the spacecraft at 30,000 km, the weight of the spacecraft being 130 kg, and the frequency would be some 20 GHz. The antenna is to be 5 to 10 m in diameter.

Actually, what we originally anticipated was that after the first workshop everybody would laugh, and that would be the end of the story. But at the first workshop, Morimoto and those people you know held a rather careful discussion, and we felt that we should go ahead for a while at least.

PRESTON: I think it would be very interesting to get the two groups together. VLBI, by its nature, is an international science, and I think an orbiting VLBI observatory would be no different. We are working with the Europeans now, and we are interested in wider collaboration.

BURKE: I believe you said earlier that the time frame would be the early 1990s?

OTA: We have been developing our own launching system, and right now we are launching about a 400-kg spacecraft in a 250-km orbit, normalizing to that. Beyond 1990 that will be 300 kg at 10,000 km, and at 30,000 km it would be 100 kg.

SHAPIRO: Are you talking about circular orbits?

OTA: No. Highly eccentric.

SHAPIRO: That is the apogee, then?

OTA: Yes, that is right.

BURKE: I just wanted to comment that for that class of orbit in particular, the use of a ground array rather than of a single antenna is truly essential, so that makes it, I think, very relevant to this workshop.

ROBERTS: In regard to the distinction between a low-earth-orbiting satellite as a station and one in a higher orbit, you obviously get better resolution with the higher orbit, but the low orbit does have one advantage, which is that it precesses rather rapidly three or four times a year. Since the orbital orientation affects the direction of sources that can be observed with good u-v coverage, having a low orbit means that you can observe a given source several times each year with optimal coverage. The higher orbits essentially don't precess, and it is difficult to get the same kind of coverage with a single satellite.

About the optimum group station configuration, since the satellite's inclination provides the north-south track, it is obvious that the optimum ground situation is a 500-km-spaced east-west array, which is not very interesting for the VLBA alone. It would not be terribly important to worry about the ground configuration with respect to the orbiting satellite, especially because of the noncommensurability of the orbits and the fact that, regardless of the ground configuration, if you are willing to observe for a week you will get a huge number of tracks, and you will fill the plane regardless of the ground situation. You can continue to gather points almost forever. This actually was studied by Kardashev quite a few years ago, published in Soviet Astronomy.

PRESTON: I would agree that there isn't a high sensitivity to the place for the ground stations, but I think it is something we should look at.

ROBERTS: I think there is a certain orthogonality between the ground alone and the requirements for space.

WESTERHOUT: Does anybody know the status of the USSR space-based VLBI?

BURKE: Private communications indicate that the Soviets are planning a mission approximately 2 years from now for a 10-m-class antenna, to be flown first in low-earth orbit. The antenna size may be larger than 10 m for the low-earth orbit.

In about 1985-1986, they are also planning a mission going out to a very large apogee. I have heard both 200,000 km and a million kilometers. The antenna size that they are planning is 10 m.

Audience participant: Frequency?

BURKE: Low.

Audience participant: Three hundred?

BURKE: Nine hundred thousand megahertz. Roughly 1 GHz.

Audience participant: Is that going to run into a scattering problem?

PRESTON: I might point out, for those who don't know, that the Soviets did try this a couple of years ago, and they had a tape recorder failure. I might also point out that they had told us 1 month before that mission that about 2 years downstream they would fly something, and it occurred 1 month later.

BURKE: The radio frequency worked, because they saw radio sources with the antenna. I don't think they can decide completely whether it was tape recorder failure or oscillator stability limitations, and nobody has told us which it was.

HINTEREGGER: It is not obvious to me that a tape recorder is needed in space at all. Why not just record on the ground?

PRESTON: I am not sure I understood the intent of your question. I had mentioned for high-earth-orbit satellites that we could have direct communication and transmittal of data to the ground. Is that what you meant?

HINTEREGGER: Why would the desirability to do that change in the low-earth orbits?

PRESTON: In a low-earth-orbit satellite there is the possibility of going upward to the TDRSS. But there we would be limited in terms of the availability of that satellite for a very wide bandwidth user.

ROGERS: I wonder if the question is, have you looked at the possibilities of relaying to one of the VLBA antennas, using the spacecraft as just a frequency translator, very simple electonics?

SHAPIRO: That would seriously compromise the orbiting capability, because you don't have common visibility between the orbiter and the VLBA stations, whereas you can maintain common visibility of the source.

21

PRECISE SATELLITE TRACKING

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Massachusetts Institute of Technology

Figure 21-1 attempts to answer the question: Why bother to track satellites? The first satellite tracking with very long baseline interferometry (VLBI) that I know of was by Robert Preston and others at MIT in 1969. They pointed out that satellites can provide better radio sources for many nonastronomical applications, such as geodesy, than can quasars. The advantage of a satellite is that the signal from it, as received on the ground--that is, the flux density--can be six orders of magnitude higher than that of a quasar. Therefore one does not have to transport a big dish, bandwidth recording systems, and a very stable frequency standard about if one is doing only geodesy.

Consequently, the first application of a satellite is for monitoring crustal deformation on various size scales. However, there is a problem with satellites that quasars either do not have or have at a much lower level. Satellites move in a random way, much more randomly than do quasars. Just as one must know quasar position to do geodesy, one must also know the satellite positions.

As you know, quasars do milliarc-second functions on time scales of months; satellites do many, many milliarc-second functions on time scales of hours. Therefore much more attention must be given to satellite tracking. The Very Long Baseline Array (VLBA) can help with this.

The current state of the art of determining earth satellite orbits does not compare well with that of determining the positions of quasars. The reason is the unknown nongravitational accelerations acting on satellites that push them about quite rapidly. It is easier to determine an earth satellite orbit in some cases than others, depending on whether the satellite is high or low, what kind of solar panels and attitude-control system it has, and so on.

We can observe a satellite and determine its position today. We can then extrapolate. Integrating the equations of motion and making certain assumptions about the forces acting on the satellite in the Global Positioning System, at an orbital altitude of 20,000 km, we might get about 10 m of orbital position uncertainty, which is at least two orders of magnitude less than is needed for some geodetic applications. For example, if one is looking at regional-size scales and trying to monitor the crustal deformation around the fault in California, the baseline lengths that one would be measuring would be

Improved ability to determine earth-satellite orbits is needed for

- Monitoring crustal deformation on regional and continental scales
- Mapping the earth's gravitational field
  - By observing satellite motion
  - By "gravimetry"
  - By "leveling"
- Mapping sea-surface topography
- Other applications requiring accurate knowledge of position on land, sea, air

Continuous tracking from multiple sites is necessary especially because of uncertainty about nongravitational forces acting on satellites.

Tracking-site positions (and clock synchronization differences) as functions of time and with respect to inertial frame should be known independently.

Ergo: Track satellites from VLBA sites!

FIGURE 21-1 Why bother to track satellites?

of the order of 100 km. We would like to know the satellite's position with an uncertainty that corresponds to about half a centimeter.

Using interferometry, radio astronomers can determine the positions of quasars within about 10 milliarc sec.

If one is trying to monitor crustal motion or deformation on continental rather than on regional scales, where the distances are greater, then even more precise determinations of satellite position are necessary. To do relative motions of continental plates, for example, one would like to get out to some 2000 km at, say, 2 cm, which would be about 2 milliarc sec. That is somewhat better than the state of the art in interferometry today, but not really out of reach.

Another way in which satellites are useful is in mapping the earth's gravitational field. All the large-scale information about the gravitational field results from tracking satellites. If we observe a satellite's motion, especially a drag-free satellite, we can see the acceleration of gravity more or less directly, and we can determine the gravity field.

In addition, satellites are useful in an indirect way for determining the small-scale structure of the gravity field. Small scale is used here to imply distances on the ground of less than 100 km. There are two ways to make such determinations. One is by means of a gravity meter, or gravimeter, of which there are many kinds. There are so-called absolute gravity meters that drop a mass in a vacuum; a laser interferometer is used to count the fringers as it falls and to measure the acceleration. Such instruments have a resolution equivalent to the amount that the acceleration of gravity changes just by moving oneself vertically by about 2 cm. There are also relative gravimeters, which are basically masses on springs. By watching the amount that the spring extends, you can measure the weight of the mass or the acceleration of gravity. These instruments have even better resolution.

However, having an instrument that can measure the acceleration of gravity at different places to which we go is not sufficient. We must know what those places are and know their positions very precisely if we are going to take advantage of the precision of the gravimeter. For example, I mentioned 2 cm for an absolute gravimeter. To determine those positions all over a grid one is mapping is a geodetic positioning problem, and one for which satellites are needed. The problem is the same as in monitoring crustal motion.

There is another technique. We can map the geoid without being able to measure the acceleration of gravity at all. We can use a level and follow an equipotential surface. But following it means that as we move, we determine the position of each point along it. And that brings us back to the position-measuring scheme.

Another function that requires highly accurate determination of each satellite's orbit is mapping the topography of the sea. The surface of the sea deviates significantly from the equipotential surface that I mentioned in the previous example. The reason for the deviation is that the fluid is not at rest. You have heard of SEASAT and of future missions such as TOPEX. An altimeter in the satellite will measure the distance between itself in orbit and the surface of the sea below. If we can determine the satellite's positions, we have mapped the topography of the sea. The information obtained is primarily of use to physical oceanographers who are trying to determine how the ocean circulates and what the turbulence is on various scales.

There are many other applications. Basically, wherever accurate knowlege of position, or time derivatives of position, is needed, on the land or sea or in the air, satellites provide a means of obtaining these measurements. For example, one might measure the spreading of the sea floor, if one could measure the difference in position between sonar transponders on the floor of the ocean and a barge on the surface. A recent report (NRC 1982) published by the National Research Council indicates that, with some additional research and development, such a determination should be possible to the few-centimeter level.

In regard to the barge, it would be moving up and down with the waves, and knowledge of its position relative to points on land would also be essential. A satellite would be required to provide these data. Using a quasar would be much more difficult, with the barge moving and the wind blowing. It would not be practical to take a large radio telescope out to the barge position. Further, it would be difficult to obtain a long enough, coherent integration because the platform would be accelerating. If an inertial navigation system were employed, with gyros and accelerometers, the entire system would become even more unwieldy.

These examples show why it is important to track satellites. The next problem is how. Continuous tracking is needed; it is not sufficient to observe one pass and then extrapolate from that, because the nongravitational accelerations on these satellites are large.

Not only does one have to track continuously, but one has to track from multiple sites. Multiple sites are required because the dynamics are complicated; that is to say, the unmodeled accelerations are significant. One would need to observe, in effect, distances from multiple points on the ground and then through geometry determine where the triangle is. One cannot depend on $F = MA$ to fill in what is not observed.

The problem with tracking from multiple sites is that one must know the relative positions of those sites and one must know them independently. In other words, one needs to know the baseline vectors between the sites. Because all those baseline vectors are changing with time as the earth rotates and wobbles, nutates and precesses, one must know them as functions of time and in relation to an inertial frame, because the equations of motion that the satellite follows describe the motion in relation to an inertial frame and not to some ground-fixed frame.

We have here the perfect "recipe" for a VLBA. What is needed is to track satellites from VLBA sites. The radio telescopes should continue to observe the quasars, then this information can be used on baseline vectors as functions of time with respect to an inertial frame, clock epoch, and rate, and the like. There would be data on differences between sites and on water-vapor radiometry, on all the things required to do astrometry and coherent arraying to map sources. And these are the same things that are needed to track satellites.

I mentioned that the radio telescopes would not be used--they would continue to observe the quasars. But what do we use?

Figure 21-2 shows an example of a real system that actually exists and has determined the orbits of satellites from the Haystack Observatory and other sites.

First, we need an omnidirectional antenna to receive the satellite's signals. This is placed outside in some clear place a few hundred feet away from a radio telescope. The receiver is in a waterproof box, with 500 ft of cable that comes to a rack inside the observatory. There is a box that is the satellite equivalent of the MARK III data-acquisition system. In this case, it is a Global Positioning System (GPS) tracking or interferometric data-acquisition component. It contains the same sorts of things that are in the MARK III: radio electronics, digital electronics, a microcomputer, a mass-storage device, an uninterruptible power supply (so that all your data are not lost when there is a thunderstorm), which entails a large collection of gel cells with chargers, and red and green signal lights, and a voltmeter on the front panel. This system will keep the clock running and the oscillator stable when there are outages. There is

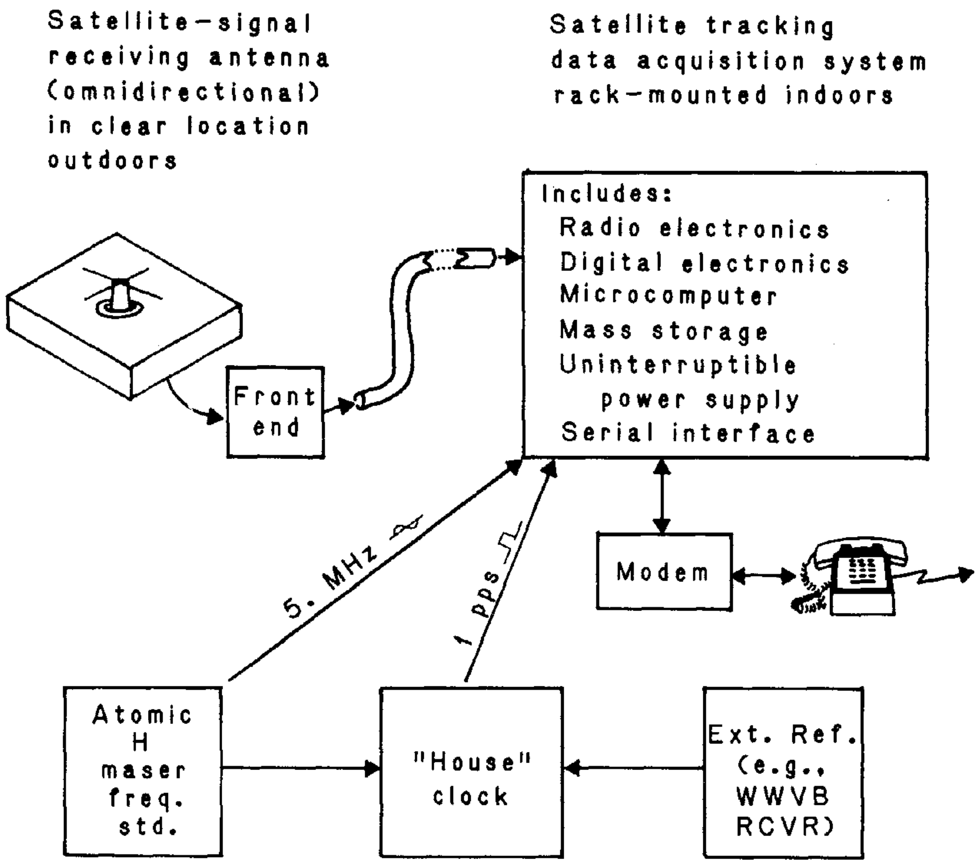

FIGURE 21-2 Global Positioning System satellite VLBI tracking equipment developed at MIT and being placed at Haystack Observatory, Richmond Station, etc.

also a serial interface, RS232. And there is a 1,200-band modem, connected to a telephone. In addition, we make use of the knowledge of site position that is obtained by the VLBA observing quasars. That is acquired by installing this antenna in a place where no one will move it. Then a survey is made, employing GPS, to determine the position of that antenna in relation to the radio telescope. This provides the geometric connection to the observatory. An epoch and rate connection to the observatory is also needed. One cable brings 5 MHz from the hydrogen maser frequency standard, and another brings 1 pulse per second from the house clock.

To get data to and from this system, no tapes are needed. The system operates completely unattended in a locked trailer. From our offices in Cambridge, we dial the number of the telephone through the modem. We get into the computer and read the files from the mass-storage device.

Everything is there: radio electronics, digital electronics, battery power supply, mass storage, serial interface, microcomputer. All of it is in that box. That is a 19-in.-wide rack.

There are now 16 units like the one I have shown you, and more are being produced. They have been used to measure vector baselines in Massachusetts, Maryland, Virginia, North and South Carolina, Georgia, Florida, Alabama, Texas, and Colorado. Measurements are currently being made in Columbus, Ohio. Vector baselines have also been measured at Wettzell, Lufling, and Muchin in West Germany.

The units typically obtain an accuracy of about a centimeter at a 10-km baseline. The accuracy is close to being limited by the uncertainty in the satellite orbits. To monitor crustal deformation, it is necessary to begin to use interferometric tracking.

Systems like the one I have shown you will be in Haystack and the George R. Agassy Station (GRAS) in West Texas. They have been used several times at Haystack on an experimental basis, and we expect to have them permanently in place there before the end of summer. Where the third one will be I do not yet know.

Eventually, when we get all the bugs out of the software, we should be able to do 2 milliarc sec, which corresponds to about 1 in 10^8, about a centimeter over some 1000 km, with this kind of system.

REFERENCE

National Research Council 1982. Seafloor Referenced Positioning: Needs and Opportunities, report by the Committee on Geodesy, National Academy of Sciences, National Academy Press, Washington, D.C.

DISCUSSION

SHAFFER: Do you really need to track the UT1 and polar motion if you monitor the satellites continuously? That really determines the satellite position in the ground-based system established by your antennas, and you need polar motion.

COUNSELMAN: Strictly speaking, if you determine the orbits of the satellites with respect to three points on the ground, for example, Haystack, Owens Valley, and GRAS, then for the geodetic applications you are just concerned with the position of some fourth unknown point with respect to those three reference points on the ground. That is all you need.

However, you do need some level of information about polar motion and UT1, because if you don't have those correct, then the coordinate system in relation to which you assume the satellites move is not inertial, and there are significant noninertial forces.

SHAFFER: But I am suggesting that you forget about the inertial system. You just say I know that X, Y, and Z are the satellite, so now I know X, Y, and Z.

COUNSELMAN: You can't do this thing entirely kinematically. The reason is that with an interferometer you are sensitive only to the difference in distance between the two observatories. In fact it is a little more complicated than that, because you have to allow for some unknown clock epoch difference between the system that is observing the satellites and the system that observes the quasars. You can usually get that by assuming that the rates are the same, but there is not perfect delay calibration between the two systems. So, you rely on the dynamics to some extent in order to solve for the position of the satellite.

COATES: How many stations do you need to get this 1-cm performance? In other words, how many VLBA stations or other kinds of VLBI stations do you need?

COUNSELMAN: To do a good solid determination of the orbit of the satellite, you need one nice triangle, three stations not in one line on the ground. Of course, in an operational system you would want to add a fourth.

COATES: But does that have to encompass the area of interest? How far can you go away from that? In other words, if you try to use these systems to "densify" California, is the triangle, Owens Valley to Fort Davis to Westford, a good one?

COUNSELMAN: I would think so, because, first, it is not a very big extrapolation to southern California from the perimeter of that triangle. Second, there is a qualitative difference between determining orbits of the GPS satellites, which are very high satellites--20,000 km--and the kind of satellites you are accustomed to thinking about, which are low-earth orbiters--even the Transit satellites are considered low.

The GPS satellites are so high that you can see any one satellite over a big patch of ground at one time, and that patch of ground moves rather slowly around the earth because the satellite only moves around once with respect to the ground per day. You can track one of those satellites; you have mutual visibility between, say, Massachusetts and Texas for many hours.

The sidereal period of the satellite's orbit is 12 h, so you are seeing 180° of arc around the orbit. When you do your orbit determination, you have a lot of leverage on the satellite's orbit, and you don't have the situation that you are accustomed to with some of the older, lower satellites, that, yes, the orbit is determined very well over the United States, but it is completely floppy around on the other side. You are actually getting to half the orbit.

22

DEFINITION OF THE U.S. GEODETIC GRID

William Strange
National Oceanic and Atmospheric Administration

The responsibility of the National Geodetic Survey is to provide reference systems of all kinds related to positions (vertical and horizontal) and gravity. These reference systems are of different types. In some cases you might have a set of monumented points on the ground for which you know the relative latitude and longitude, relative height, and values of gravity. In other cases you have the mathematical representation of the geometry of a surface such as the equipotential surface, which is called the geoid. Another geometric surface of interest is the ocean surface, which, as the previous chapter mentions, is not an equipotential surface. Ice is another type of surface.

Consider for a moment who uses reference systems and how they are used (Table 22-1). Two types of users are applications and scientific users. Applications users include those engaged in surveying, mapping, charting, civil engineering activities, land definition, and the like. They are interested in the relative positions of points that will enable them to carry on the pragmatic activities. They constitute our major user group, and their need is more for availability and accessibility than for high accuracy.

The second group--scientists--is becoming more important as we get higher accuracies through the use of space systems, obtain data on time variability, and provide information meeting various earth science needs.

There are a variety of needs for data on crustal motions, apart from determining tectonic activity. There are pragmatic problems and applications. For example, pumping of groundwater in Arizona, California, and elsewhere is causing the land to subside. There is a need to know how much subsidence is taking place.

In oceanography, there are also various applications. Very long baseline interferometry (VLBI) is useful when there is need to position tide gauges so that, when the elevation of the sea is measured, we can ensure that the land is not moving up and down rather than the sea.

In atmospheric sciences, interest in climatological activities is increasing, with needs for data related to wind, rotation rate of the earth, and determination of any overall rise in ocean surface and its possible realtionship to melting of ice and long-term climatic change.

Thus, many groups of users need reference systems. The National Geodetic Survey has hundreds of thousands of monumented stations in the

TABLE 22-1 Reference System Uses

Applications Uses
Surveying
Mapping
Charting
Engineering
Land Definition
Scientific Uses
Earth Science
Oceanography
Atmospheric Science

United States. They provide reference systems to both types of users. Many of these stations will remain, particularly for applications-oriented users who need to have ready access. But if we look to the future, we must consider the types of networks that will be needed both by applications-oriented and scientific users and how to go about developing the system that will meet their need.

The National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the U.S. Geological Survey, the Defense Mapping Agency, and several others are cooperating with us in an interagency program that envisions cooperative activities by the different groups. Under this program, there is a gradual transfer from NASA to the National Geodetic Survey of mobile VLBI activities. The transfer is to be completed by 1985. We will then operate mobile VLBI stations to support NASA's requirements and our own. In addition, we will have the POLARIS network, which we have put in place.

Our idea of basic control network here in the United States, serving both types of users, is a three-tiered operation. Table 22-2 shows what it might look like. First, POLARIS will comprise fixed VLBI stations. These would include the three POLARIS stations that were described in a previous chapter and possibly the Mojave Station in California, which is a four-station network for redundancy. These stations would provide the inertial reference frame used for determination of polar motion and earth rotation. We have planned connection of the network by use of mobile VLBI, that is, putting in 20 to 40 more stations around the United States so that we have a stable network related to this inertial system throughout the country. POLARIS will also be tying us to other continents so that our coordinate system will not be separate from the coordinate system in the rest of the world. We will need a common coordinate system and an understanding of how our coordinate system relates to that of the rest of the world. The idea is that, using the National Crustal Motion Network stations established by mobile VLBI, the extended control would be put in with the Global Positioning System (GPS) geodetic receivers. We are thinking in terms of some 30,000 stations, approximately 1 every 10 mi all around the United States. If

TABLE 22-2 Basis of Control Networks

POLARIS
Fixed VLBI
3 to 4 Stations
National Crustal Motion Network
Mobile VLBI
20 to 40 Stations
Extended Control Network
GPS Geodetic Receivers
30,000+ Stations

we get geodetic accuracy of, say, 2 cm and have 30,000 stations that we are monitoring at a given time period, the strains and deformations around the United States then become fairly well defined. We are working closely with NASA and moving forward on developing this National Crustal Motion Network.

Figure 22-1 is our first effort to depict what the National Crustal Motion Network will look like. You will notice that some of the

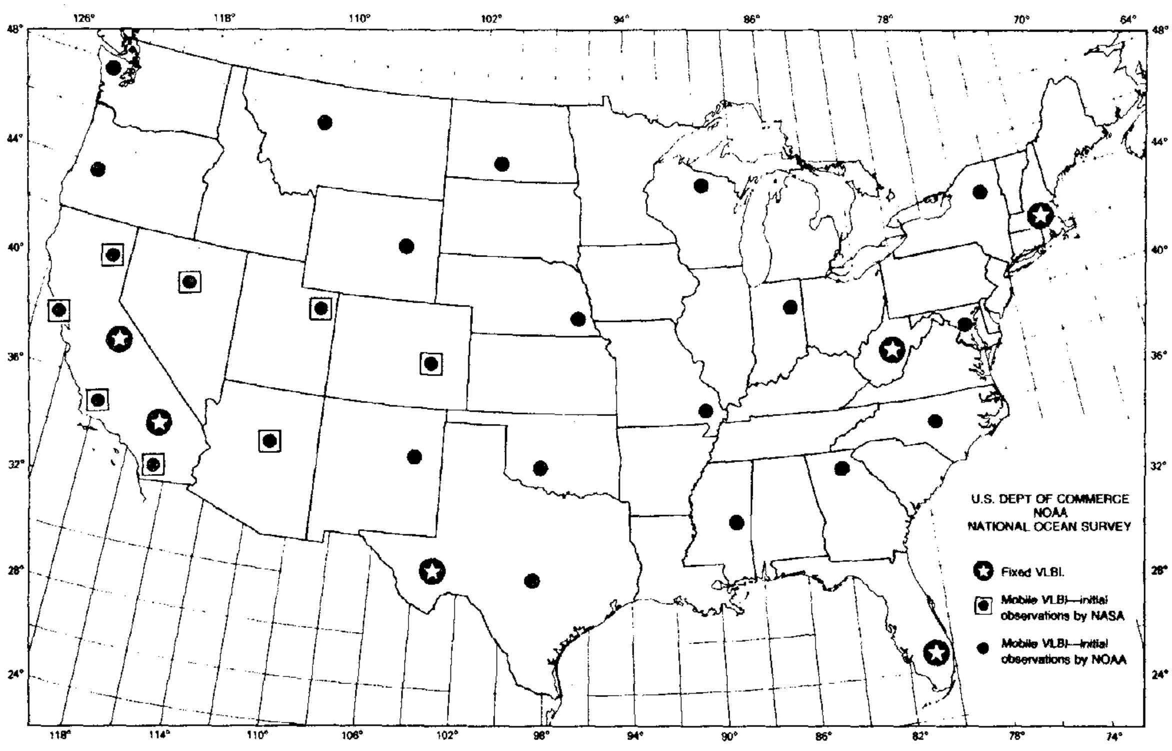

FIGURE 22-1 National Crustal Motion Network sites to be monitored by mobile very long baseline interferometry (VLBI).

TABLE 22-3 Constraints on the Use of VLBA

Capabilities	
	Compatible with POLARIS
Cost	
	Cost-effective
Availability	
	Operational Access

TABLE 22-4 Possible VLBA Applications

Coordinate systems
Polar motion/earth rotation
National Crustal Motion Network station
Base station for mobile VLBI
GPS orbit generation

stations listed are fixed VLBI stations. There are also mobile VLBI stations that NASA is observing now; we are cooperating with NASA on this. There are also stations shown that we would like to see as an extension to complete our network. The National Oceanographic and Atmospheric Administration (NOAA) will begin observations at these stations in 1985. We already have GPS geodetic receivers and are starting to test them. One place that these tests will be conducted is at the Very Large Array in New Mexico. Other receivers are on order, and we expect to begin observations on an operational basis later this year.

The National Geodetic Survey is also responsible for putting together a National Gravity Reference Network, which would be essentially coincident with the National Crustal Motion Network. We are moving forward on this project. We are purchasing an absolute instrument now and will be operating it within the next year or two.

Now let us consider the use of the Very Long Baseline Array (VLBA) and how it relates to these networks.

There are constraints on the use of VLBA (Table 22-3). First, there is capability: is it compatible with the VLBI instruments we are using? I believe that this question is being addressed and a problem may no longer exist. Further, to use the VLBA must be cost-effective; if we can accomplish the same thing more cheaply, there would be no point in incorporating the VLBA into our activities. Another constraint is availability. There must be operational access to the facility that makes it possible for a user to accomplish the required work.

Table 22-4 indicates ways in which the VLBA could contribute to geodesy. With regard to how the VLBA might fit in with our activities, we might first consider the establishment of a coordinate system.

Here, we would have a kind of symbiotic relationship. That is, in our activities we would be interconnecting geodetically with all the other continents. We would be developing a coodinate system that is in some way related around the world, and to the various plates and motions. We would be striving for a general coordinate system that was not tied to an individual tectonic plate. The VLBA could play an important part in terms of star coordinate improvements for our VLBI activities and could furnish much astrometric information, provided that the systems are interrelatable--that there is "a" coordinate system, not a number of different coordinate systems.

At the same time, if we are providing information on connections of North America to the rest of the world geodetic VLBI, the VLBA might help in sorting out the relationship between the actual rotation and polar motion of the earth and the motion of the North American tectonic plate.

Polar motion and earth rotation have been the subjects of other chapters. It was suggested that very accurate polar motion or earth rotation values might be obtained from a few hours of observation by the VLBA because of the large number of stations and the way in which the system was set up. Possibly, an interval could be selected, such as a period of one or two weeks, and 2-hour values obtained throughout that interval. Certain information on very short period variations might be acquired that would not be collected in any other way.

If the VLBI is compatible with the POLARIS network and with other geodetic VLBI stations, some of the VLBA stations could serve as stations of the National Crustal Motion Network without NOAA having to use a mobile system, provided that adequate observations were available. Particularly in the eastern part of the United States, that should not be a serious constraint; we would not need many determinations of the position of a station.

Another possible contribution of the VLBA relates to the need for a base station for the mobile VLBI activities. Not all VLBA stations but some subset of them might meet this need, provided it would be possible to schedule in a realistic way the use of the VLBA stations to support the mobile VLBI. This possibility should be explored. Again, in the eastern United States, there should not be a problem, as a reasonably long lead time would be involved and should make scheduling easier.

A final application is in GPS satellite orbit generation. It would be very valuable to have GPS receivers at the VLBA sites to provide accurate GPS orbit information that could be firmly tied to the inertial coordinate system established by VLBA observations of radio sources.

In summary, in determining crustal motions and developing geodetic networks in North America, the VLBA has the possibility of being of great value if it is compatible with geodetic VLBI instruments and if GPS geodetic receivers are placed at the VLBA stations. If it were not compatible, the VLBA might actually be a detriment to geodesy in the sense that funds appropriated for the VLBA might be seen as contributing to geodesy when, in fact, they were not.

DISCUSSION

WHITCOMB: In regard to coordinate systems, I don't see how we can avoid tying a coordinate system to a plate, because that is the only reference we have on earth. It has to be tied to at least one station, which has to be one plate.

STRANGE: You do have to relate to the surface of the earth. The possibility I was thinking of was that if you had all the plates tied together, you might try to look at some mean motion of all the total plates rather than that of any individual plate.

23

CLOCK SYNCHRONIZATION CAPABILITIES OF THE VLBA

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INTRODUCTION

The Very Long Baseline Array (VLBA) would be a valuable asset to metrology because it uses an ensemble of high-precision frequency standards, and it has the intrinsic capability to intercompare them with great precision (less than 1 ns).

Currently, the U.S. Naval Observatory (USNO) maintains a time scale that is based on an ensemble of 20 to 25 selected commercially available cesium-beam frequency standards. This time scale is stable to about 1 x 10^{-14}, which corresponds to a time stability of 1 to 2 ns/day. The time scale of the National Bureau of Standards (NBS) is currently compared to the USNO time scale via common-view, simultaneous observations of the Global Positioning System (GPS), a satellite-based navigation system, at the 3- to 6-ns level.

The USNO has embarked on a program to improve both the real-time realization of its time scale and its long-term stability. The first phase of the program will be the replacement of the cesium clock, which currently drives the master clock (MC) with a hydrogen maser frequency standard. The USNO MC is the physical realization of the USNO time scale. The vastly superior short-term performance of the hydrogen maser, coupled with an improved algorithm for modeling its short-term drift, should result in a master clock with the short-term performance of the hydrogen maser frequency standard, but locked to the long-term performance of the cesium ensemble.

In order to improve the long-term performance of the time scale, it is hoped that new frequency standards such as stored ion devices (Cutler 1982) can be incorporated into the time scale within the next 5 years. Currently, no such devices are commercially available. However, it seems that a prototype will be constructed and will be available within 2 years for test and evaluation. It is hoped that these devices will have an accuracy and a long-term stability better than 1 x 10^{-14}. Thus it may be possible to realize a time scale with a stability of 1 x 10^{-15}.

Undoubtedly, such developments will be forthcoming in other national time scales, and it will be highly desirable to intercompare them. At these unprecedented levels of precision and accuracy, the VLBA presents itself as a logical means to help with this intercomparison. Other than this most interesting area of metrology, the next most demanding requirements for known civilian systems--navigation and communications--are in the 50- to 100-ns range. While these requirements are rather modest by today's standards, it is anticipated that they will become more demanding within 5 to 7 years as industry incorporates advanced technology into their systems. The ability to occasionally compare clocks of the systems that monitor these navigation and communications systems, at the nanosecond level, could be useful in isolating the presence of systematic errors in the systems.

A survey of the present status of the use of very long baseline interferometry (VLBI) for time transfer or clock synchronization will be presented, followed by comments on the utilization of the VLBA for this purpose.

THE CURRENT STATUS OF VLBI TIME TRANSFER

One means of intercomparing clocks at two distant sites is by the use of a portable clock. One can measure the difference between some output signal of the portable clock (e.g., 1 pps) and one of the clocks, designated A, by means of a time-interval counter. The portable clock is then transported, as efficiently and carefully as possible, to the other clock, designated B, and a similar measure is made. The portable clock is then transported back to the original site, and the original measurement is repeated (closure) to measure the drift of the portable clock during the travel time from A to B back to A. After accounting for the drift, the difference between clock A and clock B is obtained by simple mathematics.

If clocks A and B are at the sites of radio telescopes being used in a VLBI experiment, the difference between clock A and clock B can be obtained as a resulting parameter of the VLBI experiment. However, it should be pointed out that what is really measured by the VLBI technique is the difference in time between system A and system B. Only after the two systems have been carefully calibrated, i.e., all delays throughout the telescope system are measured and accounted for, can the real physical difference between the clocks be obtained and be directly compared with the portable clock measurements.

Several successful time transfer experiments have been performed during VLBI experiments to compare and verify the results obtained for the difference between two clocks as determined by a VLBI experiment and as measured by portable clocks (Clark et al. 1979, Knowles et al. 1978). To date, the best results obtained have been a verification of the VLBI time transfer to the 3-ns level (Spencer et al. 1982). The result was obtained by using an ensemble of four portable clocks, not just one, to minimize the effects of portable clock errors.

However, up to this point, these experiments can only be looked on as an occasional effort to utilize a technique that has not yet matured into a fully reliable, continually operational system. The current series of VLBI experiments are not regularly scheduled, participating observatories vary from experiment to experiment, there still is a mixture of recording systems being used, and, finally, reports are only available considerably after the fact (J.M. Moran, private communication, 1981, 1982, 1983).

Because of these limitations, it is not possible to determine a meaningful history of any of the participating frequency standards through the VLBI process. Precise data covering only a rather limited period of time is obtained on them. This allows some useful analyses but in no way exploits the full potential of the system. By taking a few minimal, low-cost steps now, the VLBA could become an extremely valuable asset in the future for metrology.

THE ROLE OF THE VLBA FOR TIME TRANSFER

Since the VLBA will be using the MARK III wideband data-recording system, subnanosecond system synchronization is easily attainable (Rogers 1976). Since it is a dedicated system with observations made on a regular, continuing basis, the VLBA system appears to the metrologist even more attractive for clock synchronization. A long history on a set of hydrogen masers will be accumulated. No such set currently exists, although by 1988 the USNO should have a set of six to eight hydrogen masers, with access to several others in the Washington, D.C., area via a ground laser link. The statistical algorithms developed by the USNO to utilize and incorporate these hydrogen masers into a time scale should prove valuable to the operational efficiency of the VLBA. In order to relate the two sets of hydrogen masers, it would be necessary to intercompare them by expanded VLBI experiments on the VLBA, which would incorporate other stations, such as the Maryland Point Radio Observatory of the Naval Research Laboratory (NRL) and the Naval Observatory Time Service Substation (NOTSS), whose local frequency reference can be easily related to the USNO time scale. Also, such expanded VLBI experiments should include telescopes from other countries such as Japan, the Netherlands, Germany, and Australia to allow the international comparison of time scales.

To make the power of the VLBA available to the metrological community, two things are necessary. First, ease of access to a signal, such as 1 pps, from each station's local hydrogen maser frequency standard must be provided. Second, a program to verify frequently the calibration of each antenna system (all delays from focus to clock) must be instituted. This latter program should also prove valuable in assuring that each component of the VLBA network is functioning properly. In addition, it would be desirable to have the stations located in reasonably accessible geographic areas. There may be very little flexibility in locating the stations as this will be dictated by desired u-v plane coverage. Obviously, inaccessible sites would detract from practical usefulness.

Currently, the inability to maintain a uniform time scale at a telescope site and errors in the ephemerides of the earth's and other planets' motions are limitations to pulsar research. Over the next 10 years, if improvements in clocks develop as expected, the anticipated, improved time scales should prove valuable in providing a uniform standard against which observed changes in pulsar periods could be interpreted. This may be the greatest scientific benefit of tying the VLBA frequency standards to an external stable frequency reference as the USNO time scale.

REFERENCES

Clark, T.A., C.C. Counselman, P.G. Ford, L.B. Hanson, H.F. Hinteregger, W.J. Klepczynski, C.A. Knight, D.S. Robertson, A.E.E. Rogers, J.W. Ryan, I.I. Shapiro, and A.R. Whitney. 1979. "Synchronization of Clocks by Very Long Baseline Interferometry," IEEE Transactions on Instrumentation and Measurement, Vol. IM-28, No. 3, 184.

Cutler, L.S. 1982. "A Trapped Mercury 199 Ion Frequency Standard," Proceedings of the 13th Annual Precise Time and Time Interval (PTTI) Application and Planning Meeting, NASA Conference Publication 2220, 563.

Knowles, S.H., W.B. Waltman, W.J. Klepczynski, N.W. Broten, D.H. Fort, K.I. Kellermann, B. Rayhrer, G.W. Swenson, and J.L. Yen. 1978. "Real-Time Accurate Time Transfer and Frequency Standards Evaluation via Satellite Link Long Baseline Interferometry," Proceedings of the 9th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, NASA Technical Memorandum 78104, 135.

Rogers, A.E.E. 1976. "Theory of Two Element Interferometers," Methods of Experimental Physics, Vol. 12, Part C, 139.

Spencer, J.H., E.B. Waltman, K.J. Johnston, N.J. Santini, W.J. Klepczynski, D.N. Matsakis, P.E. Angerhofer, and G.H. Kaplan. 1982. "Comparison of VLBI, TV and Traveling Clock Techniques for Time Transfer," Proceedings of the 13th Annual Precise Time and Time Interval (PTTI) Application and Planning Meeting, NASA Conference Publication 2220, 231.

DISCUSSION

JOHNSTON: Are you saying that since at the Naval Observatory you use about 20 to 25 cesium standards to establish a master clock, by linking the 10 masers of the VLBI array together you can essentially synthesize an improved master clock?

KLEPCZYNSKI: That is one way to interpret it. We would be willing to try to work together on something like that. It wouldn't be absolutely necessary, but it could be of benefit to everybody.

SHAPIRO: Aside from astronomical uses, can you tell us what other scientific and practical applications you are aware of for which the world would need clock synchronization at 10 ns, 1 ns, a tenth of an ns, something like that? Can you give us an overview of that?

KLEPCZYNSKI: One aspect that comes to mind immediately is the Global Positioning System, which you heard about a little earlier. We have been monitoring the clocks as an integral part of the GPS. Each of the satellites in orbit has a rubidium clock and a cesium clock--

possibly hydrogen masers in the future. We have been monitoring the GPS satellites from the Observatory, and as the result of comparing the clocks in orbit with our laboratory clock or system, we found that there are errors in the transmitted ephemerides, which affect the navigational precision you get with it. They are easily discernible; we are talking about 10-ft precision, so you need checking of time to nanosecond precision.

COMSAT is interested in trying to increase the throughput of their communications satellites, SBS, with their high data-linked rates. Most of the networks are now timed to go in and transmit data through the network. COMSAT is looking forward to the day when it will probably require at least 10-, maybe 100-ns synchronization to maximize or utilize the communications satellites.

These are the two immediate, practical applications I see: monitoring navigation systems, and improving synchronization of communication networks.

SHAPIRO: I can't really think of any scientific uses aside from the nanosecond or subnanosecond, and I don't quite see why COMSAT would need nanosecond time synchronization. As far as GPS is concerned, I am not sure.

KLEPCZYNSKI: I think there are more practical technical applications.

SHAPIRO: I haven't seen any really practical technical applications, either.

KLEPCZYNSKI: In the navigation field, one of the interesting areas we have is Loran-C, where various users can use different Loran-C chain networks to get their position. If the clock is synchronized to the various networks, and they know the differences between the various networks, then they can navigate by picking up signals from different chains, one or two.

Right now, to navigate with Loran-C, you would need three signals. If you had a clock on board, you could then navigate with only two signals, and if you monitored the Loran-C chain properly and well, and you knew the offsets between the chains and their timing, then you could even navigate using one transmitter from another chain.

SHAPIRO: But you haven't established the need for nanoseconds.

KLEPCZYNSKI: In that area about 50 ns would be useful and practical. Today, with the communications network, the only thing I can say is that COMSAT is interested in doing this. They must have planned to synchronize their networks to take advantage of this throughput, to increase throughput loads.

CARTER: I understand, when you were doing the time transfer tests to see if you got agreement between carrying a clock and VLBI, why you needed to know the delays through the VLBI systems accurately. But I don't understand why, on a continuing basis, you would need to know those delays at the stations.

KLEPCZYNSKI: To make sure they don't change with time.

CARTER: You can compare the behavior of the clock, and from the VLBI you get the time difference between the clocks?

ROGERS: A comment: previous clock synchronization experiments have used dissimilar antennas and dissimilar receivers, so in order to get an absolute clock synchronization we have to know those instrumental delays. But in the VLBA we will have common systems, so the intrinsic accuracy should be a lot higher.

KLEPCZYNSKI: Every time you do a new experiment the antenna configuration is no longer the same as it was when you did it the last time. People change cables, put in these different receivers. The delays through the system change as a function of time. We hope that this won't happen with the VLBA, but we don't know that for a fact, and we do have to have some check on the system.

V. Conclusion

24

GENERAL DISCUSSION

SHAPIRO: I have made a list of things that have not been discussed in sufficient depth. I will introduce them, one at a time, for discussion. If anyone finds a topic I have overlooked, please feel free to mention it.

First, Carl Heiles wanted to know why the Very Long Baseline Array (VLBA) wasn't shaped like a Y, since the Very Long Array (VLA) was shaped like a Y, and many people studied it for a long time to decide on that shape. I thought perhaps it would be appropriate if Craig Walker could give a response to that question.

WALKER: The Y is optimal if you are trying to move antennas in and out, and if you are trying to run wave guides to the antennas; it minimizes the amount of track you need and the amount of wave guide you need. It is a good configuration for synthesis telescopes. But if you don't have those constraints, it is not necessarily better than others; in fact, in snapshop modes or low declinations, you have concentrations of baselines in certain directions, and it is not optimal for your beam.

The other reason is that if you try to put a Y centered near the VLA--we have tried to put short baselines near the VLA--one or another of the arms quickly winds up in the ocean. To a large degree, we are driven by geographic constraints.

HEILES: The real sense of my question was, has a study been done showing that the most economic arrangement of telescopes is similar to the one that you have? That is, if you threw out the constraint that you were going to use existing sites, could you get along with one fewer telescope, and thereby with more or less equivalent uv coverage? If you could do that you would be better off, even though you might have to spend a little more at the beginning.

WALKER: No. The only existing site that was a constraint from the start was the VLA. We wanted the short baselines near the VLA for reasons of getting mutual coverage, for the great collecting area of the VLA, and for eventual connection to the VLA.

In regard to other sites, you might think of it as placing a small potential well around each of the existing sites. In an optimal array, if we wanted something near one of these sites, we would put it at that site. It turns out that you can place about half the elements of the array randomly, then carefully place the rest, and come up with

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coverage that is approximately as good as you would get without such constraints.

If anyone has an optimal two-dimensional configuration that is mathematically defined, I would like to know about it.

Audience participant: Was there a study of a circle with an odd number of antennas?

WALKER: Yes, it was studied for the VLA. It turns out that if you want a 40-to-1 range of spacings with 10 elements, a circle doesn't work too well. Your maximum diameter is something like 3,000 km. I have studied circles of 7 elements plus 3 outriders, a circle placed in the United States, and it just doesn't work very well with that small number of elements.

SHAPIRO: The next topic I want to raise is scheduling. Scheduling desires, I am sure, are going to be complex, including a lot of subnetting, especially when you bring in Europe. When you have common visibility with some of the antennas for some sources and not for others, you will want to split the array up.

The software for all the scheduling and for the processor is a consideration. The implications are, of course, trivial in principle, but they should not be ignored or left to the last minute. They could provide many programs with many problems for many years. In addition to subnettings, there is also the question of interleafing observations: for example, for some programs you don't necessarily need continuous uv coverage; you want the snapshot mode, and then interleafing, that is, observation of different sources at different parts of the sky. For this you would want fast slewing, so that you don't waste valuable on-source time. In addition, for astrometry, you would want to connect phases by going back and forth over a large fraction of the sky, and for similar reasons one should consider seriously how fast you can make the antennas slew. Obviously, you don't want them to slew faster than 60-mph winds, but there should be some near that curve that should be examined more carefully.

Another consideration with antennas is the horizon view, especially using the VLBA as a base of very well known connected vectors for determining satellite orbits, as Charles Counselman said, and as the base for various sorts of continental and intercontinental geodesy. In addition to the primary astronomical purposes, you need to get good baselines for other functions. One of the problems is separating the signal of the atmosphere from the signal that gives you the baseline. The atmosphere separates out best at very low elevation angles. We haven't proven from our experiments to date just how much you can gain by going to low-elevation angles, but we ought to know in a couple of years. If it turns out that that is the best way to go, then it would be unfortunate if, by not thinking about it, VLBA antennas were sited where they didn't have low-elevation angle views.

WALKER: I have one question on the low-elevation angles that is relevant for the configuration: Do you need that over all azimuth angles?

SHAPIRO: Yes, you would want it over all azimuth angles; obviously, you will take what you can get. The point is to keep this in mind.

WALKER: There are sites like Owens Valley.

SHAPIRO: I know, there are certain sites where a certain part of the horizon is blacked out. I can't say, if you don't have 360° you are "dead in the water." But if you only have 6°. . . .

KELLERMANN: On the same point, we thought about this, but now we have to face the hard decision: How do we weigh this desire and the Owens Valley with the geometry? We decided to stay in the Owens Valley. Are you suggesting we were wrong?

SHAPIRO: There are many antennas in the array, and this. . . .

KELLERMANN: This is the one that is constrained by the horizon.

SHAPIRO: I don't understand. There may be one antenna that doesn't have very good view of the horizon in all directions, but that doesn't restrict the other antennas in the same way.

KELLERMANN: Absolutely.

Audience participant: What is the limit now for the VLBA?

WALKER: I don't think it has been specified as yet. I presume we will try to make it go down to the horizon.

BURKE: I want to interject a comment on the matter of horizon limits. Every major instrument that I have used generally has a horizon limit, and I have found that invariably, at some time, you want to get down through that horizon limit, or, rather, you want to get down from the elevation limit to as low as you can get. The reason is not always the same, but there is generally a good reason, a particular need.

SHAPIRO: But there is a trade-off.

BURKE: I think an antenna specification should read that you can reach the horizon.

SHAPIRO: The question we are arguing is, Where is the horizon at the different sites?

WALKER: This is a slightly different point, but it might be worth mentioning what we have in mind as the scheduling style for this telescope. We are used to thinking in terms of the VLA, or any of the other astronomical instruments, where the user has a particular block of time allotted, and that is when he does his observations. If it works, fine; if not, he can go to the director and try to get a repeat.

Here, we are thinking of following something more like the Westerbork style, where you propose an observation and give the constraints for what you need, and then at some later date you are told that your data are in hand. The operations staff schedules it at an appropriate moment, depending on weather conditions and conditions of the telescopes.

That mode gives us a lot of flexibility. If we lose a receiver at some site, we can shift the array to a different frequency; if the weather is bad, we can go to low frequencies; if the weather is good, we can go to high frequencies. I think that flexibility is really needed, but it also allows for certain things like inserting a short block of geodetic calibration observations in the middle of otherwise astronomical observations. It will be up to the staff to work out appropriate use of the telescope.

SHAPIRO: Yes, but I would argue that the software to allow this is nontrivial.

WALKER: Yes, we have already been thinking about that.

SHAPIRO: It is a very complicated situation.

WALKER: There is another problem. You need to have something, more or less in real time, so that if they suddenly discover they lose a 1-cm receiver. . . .

SHAPIRO: It takes too long. We are not set up properly in the VLBI network yet for that. All the things you want to do quickly in real time, when you are scheduling something to maximize the antenna on source, require a lot of software effort.

CLARK: I have two totally unconnected items, but will comment on both of them. First, I hope that not all of the time on the array is done in the Westerbork mode; while having these things just run as a service might serve many of the needs, I think there are needs for which a certain amount of hands-on use of the array is going to yield maximum progress.

SHAPIRO: Also, international cooperation is a factor to be considered.

CLARK: The second comment goes back to the antenna items. Since the total latitude range of the telescopes is about 25°, since ALTAZ telescopes are currently planned, and since you are going to have a fair number of sources that transit south on one set of telescopes, east on another set, west on another set, and north on yet another set, I think that a great deal of additional complication in the scheduling operation is likely. Special care must be taken: for example, which antenna is having to unwind its cables, at what time, and so on. Having been through the writing of some scheduling programs to handle this on smaller arrays, I know how difficult it can be.

Along those lines, there is one type of antenna mount that actually might be more efficient in avoiding having a hole in the zenith, and that would be to go to a XY-mount antenna. Were XY mounts with two horizontal axes considered in any way for the array?

KELLERMANN: They were considered and rejected. Unfortunately, I can't tell you why. Probably you know better than I do what the deficiencies of the XY mount are. We are allowing for 720° of cable wrap and looking over the Pole. So, for any reasonable length of time in any reasonably well-planned schedule, it shouldn't be necessary to keep going back and forth.

KUNDU: Several times you used the term "snapshot mode." What is the time scale we are talking about? Can one produce a map, for example, in 10 ms?

SHAPIRO: You are thinking of observing the sun?

KUNDU: I am thinking about observing stellar flares, for example. I think we have evidence that the more we observe, the more we will encounter those physics problems. It is an important thing to consider. For example, in the sun we observe what we call the synchrotron masers, and they have a time scale of milliseconds. That would have important bearings on the analogues in stellar flares, I think.

KELLERMANN: Dr. Walker, have you any snapshot uv diagrams?

WALKER: No, I don't.

KELLERMANN: It gives as good a snapshot mode as one might reasonably expect to get from any 10-element array. It is not very good; it is only 10 antennas. It is worse than the VLA, certainly.

KUNDU: Ten milliseconds?

KELLERMANN: Well, 10 ms, 5 min of arc; it is essentially the same.

SHAPIRO: That is really a correlator problem.

KUNDU: I am asking a different question.

SHAPIRO: He wants to know how fine a correlation of data you can obtain.

KUNDU: Right. I am talking about, for example, millisecond structures, time-scale structure that is seen; therefore, brightness temperatures of the order of 10^{15}°. Obviously, that kind of temperature isn't going to be produced by classical synchrotron radiation, so people are invoking, and quite successfully, gyro synchrotron masers. Probably they originate from structures of the order of milliarc seconds. I would like to know where they come from, and I think that this is probably a good instrument to address that question, so we should not forget about it.

SHAPIRO: The question is, do you have enough signal-to-noise to do anything at 10 ms of time?

KUNDU: I think these are very strong bursts.

SHAPIRO: But we could perhaps look at these and see if there is any good reason to make sure that the parameters of the VLBA do not preclude such fine time resolution.

KUNDU: Right.

WALKER: How frequently would you need. . . .

KUNDU: They last a few tens of milliseconds. Then they are over, and then you wait. That would be a good compromise. At least you would know where it is coming from, because that is what is the most important part.

ROGERS: I was going to comment on that point, that in the process there would be two ways of looking at short events. One is to use the pulsar-gating capability of the correlator, and, second, if there are a few very special events, like one in a whole observing session, one could in principle actually dump those data via the same system that is used for real-time fringers into the computer and do the analysis and software.

SHAFFER: Are you talking about the sun or about stars?

KUNDU: I am talking about the sun primarily. But I just heard that somebody showed some maps of HR1099, and HR1099 behaves in much the same manner as solar flares. That is the point I am trying to make.

SHAFFER: But I don't think you need any kind of time resolution, because at that distance things can't happen faster than the physics involved, and at 10 ms that distance is well below the angular resolution of the system, so you can accumulate data for some seconds before your source has moved far enough that you can even tell that it has moved in terms of making a map.

SHAPIRO: I am not sure what you are trying to do. Are you trying to get spatial resolution?

SHAFFER: Yes, if Dr. Kundu is thinking of spatial resolution as a function of time.

SHAPIRO: Following the flare along the surface of the star?

KUNDU: No, I was thinking in terms of the sun.

SHAFFER: For the sun, you would need the faster, angular resolution. But for flare stars, you don't need rapid response in terms of watching anything move.

JOHNSTON: Could I make one comment on Dr. Kundu's problem? Dr. Burke and I once looked for flares on the sun with VLBI between Maryland Point and Haystack. After observing the sun for 2 weeks, we saw a flare occur just when someone was changing a tape at Haystack. So, the time scale of variations that Dr. Kundu is talking about are very short. This problem underscores the need for redundancy in taking some of the observations.

SHAPIRO: Yes, you really have to have very rapid scheduling capabilities. If there are no further comments on that point, let us move on to the question of frequency coverage. There are two problems: one, perhaps, is easy to solve. That is to make sure we have broad enough coverage at low frequencies so that any opportunities for observing, for example, hydrogen line absorption from high red shift objects not be precluded, because there is no particular frequency at which they will appear. They will cover a broad band.

I presume that, with the development of receivers being as rapid as it is, there will be relatively little trouble in covering the major part, if not all, of the low-frequency range.

The second point concerns multiple-band simultaneous observations. Earlier I mentioned the relativity test. It seems to me that, more generally, at the very high frequency operation of the array, one will want to integrate to get as much sensitivity as possible, and the thing that will limit the integration at the high frequencies is, of course, the neutral atmosphere.

Now, you might say, we will just observe at a lower frequency and use that to tell us what the atmosphere is doing to guide the integration at the higher frequency. But that may not be good enough because of the ionosphere, which is going to affect the lower frequency and not the higher frequency. So, in principle, a better way to do it is to use three frequencies simultaneously; the two lower frequencies to get out the ionosphere and tell you what the atmosphere is doing, thus to guide the integration at the very high frequency.

KELLERMANN: When you start talking about three simultaneous frequencies it becomes difficult, and you have to define beforehand which three you want. We should remember that we will have the ability to change frequency in some 10 to 15 s; that is well within the coherence time. It is not quite as good, but I think it goes a long way toward that. So you can make any arrangements you want in software.

SHAPIRO: At some time the stability of the atmosphere does allow you to do that, probably down to 3 mm.

KELLERMANN: The frequency switching time for the VLA is approximately 40 seconds. This will be improved with the VLBA, which will be able to do this in 20 s.

SHAPIRO: But will we be able to do it for long periods of time, switching back and forth? What I am saying is, it should be designed not to do this every day in 15 s, but to do it every 15 s for a day.

KELLERMANN: A few days, anyway.

SHAPIRO: The question is, what are the time scales for the variation of the ionosphere? That is a hard question to answer, because the power spectrum of the ionosphere is so variable. But you can't assume it is negligible at X-band on the scale of a wavelength of even 7 mm.

REID: That may be what I was asking. I am surprised to hear that the ionosphere--when you want to do a dual-frequency observation to get rid of the atmosphere for 22 or 43 GHz. . . .

SHAPIRO: You don't get rid of the atmosphere with dual bands.

REID: You said you couldn't because the ionosphere corrupts the lower frequency, and I am surprised to hear that at the low frequencies of, say, 5 or 10 GHz, the ionosphere plays much of a role.

SHAPIRO: We found that it does. If you looked at night and saw the minimum, you could use X-band alone. But you want to use the VLBA all the time. You don't want to wait until it is only minimum and only nighttime.

REID: I don't think we are talking S/X-band. I thought we were talking something like, say, X-band to K-band.

SHAPIRO: Yes, but what I am saying is, X-band is not good enough to assume that the ionosphere is negligible on the scale of the wavelengths of 43 GHz.

REID: All we are talking about is getting it down to where you don't hurt your coherence, not to any measurement accuracy.

SHAPIRO: And you don't want to lose a wavelength.

REID: Obviously. My question is, how often at X-band can you get a half-a-wavelength from the ionosphere?

SHAPIRO: You mean how long a period of time?

REID: Yes.

Audience participant: Half-an-X-band wavelength?

REID: Yes.

CLARK: Very frequent.

REID: What is very frequent?

CLARK: You can always coherently integrate at X-band for 5 min. If you can follow a source in 5 min, and follow it to the next 5 min, you can. . . .

SHAPIRO: No, we are talking about inferring what the atmosphere is doing at the much higher frequency, which is not the same as saying the atmosphere is not presenting a wavelength problem at X-band. It is a question of the ionosphere causing a wavelength problem at 43 GHz.

FOMALONT: One problem is that you are mainly talking about point sources. Now, you can play this trick when you are observing extended sources. It is a little bit harder. I just wanted to make that point.

SHAPIRO: Would anyone else like to comment on the frequency problem?

ROGERS: It may be controversial, the subject of the ionosphere, but I think we know that the ionosphere at X-band is about a nanosecond, maybe a little more on occasion.

SHAPIRO: It depends on the part of the solar cycle and the time of day.

ROGERS: But of that general order. The fluctuations in it are of the order of a few percent. When we observed the very massive ionospheric deviations that resulted from the Mt. St. Helen's explosion, we saw about a 3 percent fluctuation in the total ionospheric effect, and the time scale was of the order of 10 min.

CLARK: However, the X-band delay at solar maximum can amount to closer to 10 ns total. If you then take 1 percent of that as fluctuation, that is a tenth of a nanosecond, which is approaching half-a-wavelength at X-band. So you can see those kinds of fluctuations.

SHAPIRO: But the point is, you have to worry about the higher frequency.

CLARK: I have a frequency-related question. We were told that for special things at lower frequencies, prime focus would be available. Is that true in general at any wavelength if some special receiver was needed?

KELLERMANN: I think the dish deviates from a parabola by 3 or 4 cm, so you should be able to use it at even 20 cm.

CLARK: The reason for my question is that with an instrument as powerful as this, some new discovery will come up, whether it is very red-shifted, excited OH that is finding itself down at 3 GHz, or whatever, from some extragalactic source, and we are going to find ourselves without the right frequency coverage to be able to do what is needed. I think it is useful to know that it is at least possible to be able to do something special if the scientific requirements for it are there.

SHAPIRO: What I am concerned about is that the VLBA be designed so that as receivers improve and we get greater spectral coverage, you won't have to redesign the whole VLBA to install them. Is any thought being given to some sort of modular arrangement, so that one can plug in new boxes and take out old ones?

KELLERMANN: The receivers are completely modular.

SHAPIRO: How much are the feeds built in to the structure?

KELLERMANN: You saw the picture of the feed ring.

SHAPIRO: So you should be able to do that.

KELLERMANN: Right. But the receivers are completely separate, quite different from the VLA concept. They can be removed and changed and substituted.

NIELL: Is the limitation on the band and the width of the bands that has been adopted set by the feeds?

KELLERMANN: That is correct.

CARTER: Maybe you can just clarify something. You said that it is quite different from what they have at VLA. I thought this was supposed to play with the VLA.

KELLERMANN: The frequencies are the same. The receivers are packaged differently, so they can be taken in and out separately without having to take apart the whole system.

SHAPIRO: The physical structure is arranged differently. The electrical properties are compatible.

CARTER: But if you come up with a new frequency, you want to look at what has not been anticipated?

KELLERMANN: We are not proposing to change the VLA.

SHAPIRO: Not more than one antenna of it, anyway.

KELLERMANN: For those particular new frequencies, that is right. The reason for this modularization was that if these telescopes are out in the field somewhere, we don't need a large staff of people to maintain them.

SHAPIRO: The next subject I want to discuss is the correlator. We really should seriously consider the correlator ahead of time, because there are so many things that people will want to do, and if decisions are made too early they may become awfully difficult to do. For example, you might want to be able to easily accommodate subnet processing, or easily accommodate the ability to map many sources in the field of view at the same time, like gravitational images. You might have three or five, and with the new sensitivity that we will get and with new discoveries, there may be many disjoint objects all in the field of view at the same time that you want to map simultaneously. You must think about how you want to best accomplish that, as well as considering the polarization quantities that you want to get from each of them. With pulsars, you might want to follow the subpulse as well as the main pulse, and do it in a dispersive way. In the future we might want more flexibility.

Then there is multiple-band processing. Suppose you have two or three frequencies simultaneously and you want to use the result from the lower frequencies to help you coherently integrate the higher frequencies. That should also be thought of so that it could be done in an efficient way, if it is desirable to do it. And we want to make sure that we don't eliminate the possibility of using an orbiting VLBI with the network at, say, 22 GHz; we would then have to worry about higher fringe rates than we might otherwise.

All these things should be considered early, and I suspect that you will find the correlator is going to be a lot more complicated and perhaps cost a larger fraction of the budget than expected. I think it might be a worthwhile investment.

HINTEREGGER: I agree. I think even a rather cursory analysis of the requirements for at least the two main uses, including the spectral-line case, shows that the fraction of the budget that is currently envisioned for the processor is much too small. At least 10 percent of the total budget should go for the processor to meet the requirements.

Audience participant: Is this a "guesstimate"?

HINTEREGGER: No, it was a calculation. I believe that the present estimate is far too low, given what we want to do.

SHAPIRO: We should think about what we want to do and how much it will cost, rather than say X percent of the budget.

HINTEREGGER: I guess I should phrase it differently. I calculated that the production cost of the basic correlator to meet the basic requirements is at least $5 million. I think it requires a careful review. I think $5 million is not conservative.

SHAPIRO: Next on my list is data archiving, not only the archiving of VLBA data but also archiving the VLBI network data along with the VLBA data. The array will come into being about 10 to 20 years after we began doing VLBI studies, and there are many things for which a long-time baseline of data would be useful to have.

At the moment, there is no coordinated national plan of archiving. One might consider starting the archive with data that already exist, and incorporating them into a scheme to continue with the VLBA. If you look in a journal, you will see a map of Source A, but you won't see anything else. You will always be left with a question. Was this really a proper representation of the data, or would anything else have fit just as well? You can't tell from the published literature.

It might be interesting to look at those questions in light of better mathematical methods, better knowledge of the source. You would want the more raw form of the data, I would guess.

What I am saying is that even though the VLBA won't come into being for many years, we should give some thought to how to preserve what we have now and turn it over in an appropriate format to the VLBA.

SHAFFER: On this matter of archival data, I have had fairly extended discussions with John Benson and Craig Walker on what actually is the output of the correlator. The current thinking is that it is different from the output, for instance, from the MARK III correlator, where you save raw delays, raw rates, which are totally independent of whatever model was put in the correlator. The model, in some sense, is blacked out instantly by the correlator itself, so what is archived are the delays in rates. You can then pick some reference frame of your own choosing or at an arbitrary time in the future, and go back and analyze the old data without having to worry about taking out whatever model was used to begin with. The National Radio Astronomy Observatory (NRAO) mode, and, I think, to some extent, the Caltech mode of processing the data, is to leave the model in the data and essentially output the residuals. This is a nuisance if you want to go back and reprocess those data with a new model, especially if you haven't done a very careful job of keeping track of the model.

SHAPIRO: I had an experience with NRAO, and I had to give up because I couldn't find anyone who knew what the model was.

SHAFFER: That is right. It is generally in assembly language by some programmer who is no longer around.

SHAPIRO: Haystack has a pretty good archival system. I don't know what is being done at Caltech, and I don't know what is being done at NRAO, but I thought somebody ought to give thought to doing things in a way that could be used later.

SHAFFER: This is fundamental, not quite to the design of the correlator, but to the next thing you do with the correlator. I am not sure it has been addressed adequately for archival purposes. It does make things a bit of a nuisance for processing for closure phase, where in some sense you want a slightly different output from the correlator, but it is easy to fix up this first-order data to get a closure phase from it.

SHAPIRO: You are saying that a lot more thought ought to go into what archival material will be produced for the VLBA. A point well taken.

REID: I would like to second that, and to note that if you archive things like delays in rates, you will miss things that you couldn't go back and get, because you have made an assumption of what the sources look like. For example, if you looked at a double quasar and our output delays in rates, you might never be able to reconstruct the second quasar because you looked at the first one.

SHAPIRO: And if you don't know which one you were looking at.

REID: Archiving is certainly of value because you can go back and say, Now we know something new about that. Even at the level Dave Shaffer was talking about, archiving is inadequate. The whole thing needs much more thought than just saving delays and rates. That is not enough.

WALKER: In the data flow that comes out the back of the correlator and goes on into the mapping, we would not just look at the raw observables. We will have the residual. I think each data set will have enough information to completely reconstruct the models that were applied. Now, if you wanted to come out of that data flow and go into an archive with the models removed, that capability should be there. But I think the straightforward data flow through to the astronomical mapping should be optimized for the astronomical mapping, as long as we don't compromise the other uses.

SHAPIRO: It wouldn't matter so much that the models were there and the residuals were printed out, provided the model was really archived in its entirety at the same time. If you are going to have numbers that vary a little, you want to take out the big number and only put down the little ones, but you had better archive the big number and not assume that everybody knows what the big number is and so fail to archive it.

WALKER: Exactly.

SHAPIRO: The last topic is recording systems. I was wondering whether it is a good idea to consider what the growth potentials are for the different recording systems, as opposed to simply the state of development at the time you are trying to make a decision. Because obviously we are going to keep the array for a long time, and we are going to improve it. Maybe you won't be able to predict too easily which has the better growth potential, but it is probably something to keep in mind.

WALKER: We are trying to isolate the record system from the IF collection and, then, later, the correlating system. So if a better recording system comes along later, it will be a reasonably straightforward problem to slip it in.

ROGERS: Amplifying on that a little bit, there are 2 Gbits available, 2 Gbits/s, provided the recording system can handle that, and the interface is being defined in a way that we could substitute a better system for upgrading of whichever system we choose. I think there is a fair amount of growth potential. As for right now, it is hard really to say which system has the better growth potential.

JOHNSTON: I look at the calibration of this instrument as sort of a national resource. My feeling is that this instrument should be well-calibrated approximately once a week, depending on how much time it will take.

It would not only benefit the geophysicists, but it could also benefit the astrophysicists. If the data were turned around quickly, and if in the source list of calibrators for the baselines one could monitor a group of quasars and see whether the amplitudes were changing quickly, this would give you a complete picture of 20 or 30 quasars on evolutionary scales of, say, weekly scales. This capability could be extremely useful to astrophysicists.

SHAPIRO: That is a good point on operation of the system. If you really had very good hydrogen masers, such that they weren't a limit, you could take just a few minutes a day, spread out, and get all your baseline information, UT1, polar motion information, quite well with all the redundancy you have in a 10-element array.

I am more concerned here in going into matters that will affect decisions that will be made now. What I am worried about is things that, if not considered now and the design is frozen, will then be too late to deal with.

KELLERMANN: Yes. It is not very useful now to discuss what kinds of observations we should be making in 5 or 7 years, but questions like the slew speed and the kind of hydrogen masers are quite relevant. And the correlator.

CLARK: The geophysics community seems to have a fair interest in including Alaska as a site, and that was in the earlier array configurations and has now been replaced by Puerto Rico, which the geophysicists would also like to have. It seems there is a quandary here. I don't have any answer; I just think this is a question that hasn't been settled yet.

KELLERMANN: To what extent does the existing National Oceanographic and Atmospheric Administration (NOAA) facility, provided it is given the necessary connections and made compatible, satisfy the requirements with just the S/X-band system that is there?

CLARK: It would probably be a fairly useful facility, and in fact there are some programs that are envisioning its use even into the 1990s, so that may be a possibility. I suspect for 7 mm you may find Alaska a better site than Puerto Rico, because it is very dry at Fairbanks.

KELLERMANN: We are aware of that.

FLYNN: I am a geophysicist, and I think that I can speak for at least the part of the geophysical community I know. The planned activities in the Crustal Dynamics Project using the NOAA antenna at Fairbanks are entirely adequate to answer the question of crustal movements over original scales in that part of the world, at least from now until 1989.

If I were you, I wouldn't deform the design of the array in any way to accommodate a possible need that could, in any case, be satisfied by relocation of mobile VLBI stations from the Crustal Dynamics Project or NOAA in that region.

WHITCOMB: The geodynamics program does have a station in Alaska, so if I had a choice between Alaska and Puerto Rico, I would choose Puerto Rico because there is no planned big antenna in that area right now except for the VLBA. I would opt for a station in Puerto Rico to support a planned geodynamics program using Global Positioning System (GPS) stations, and that would be a station right in the middle of the array that could be used as a long base to tie that smaller network in to more distant antennas. I think there is more action in the Caribbean than there is in Alaska, and Alaska is already covered.

SHAPIRO: All three sites can be tied in to the VLBA very nicely if, as is presently envisioned, some of the antennas being used in the Crustal Dynamics Program are very closely located to antennas in the VLBA. So by conventional survey one can tie the whole net together.

KLEMPERER: There does exist a two-dimensional arrangement of nine antennas that uniformly samples the uv plane instantaneously, not in synthesis mode but in one moment. It was discovered by Perk and Elmer, I think about 12 years ago, and I will be glad to put it into the record.

SHAPIRO: What do you mean by "perfectly"?

KLEMPERER: That it uniformly samples the uv plane for the spacings that are available.

SHAPIRO: It is scalable, is what you are saying. It is scalable in terms of spacing. There is one minimum spacing.

KELLERMANN: It doesn't cover a 40-to-1 range?

KLEMPERER: No, it doesn't.

CARTER: It seems to me that perhaps Alaska allows you more "intervisibility" to other stations in places like Japan and Europe. And, for the geophysics community, there will be the Richmond Observatory, so we will have something down in that part of the country. It is not quite true that there isn't anything near Puerto Rico.

SHAPIRO: It is a long way from Puerto Rico. It is also on the other side of the Puerto Rican trench.

CARTER: Nonetheless, the question of connecting to other places like Japan should be considered.

Audience participant: Puerto Rico is better for Europe.

SHAPIRO: It depends on the declination of the source you are going to look at.

WHITCOMB: Are there plans to do geodesy with Arecibo?

SHAPIRO: We have discussed that for many years. The difficulty of doing centimeter-level work with Arecibo in geodesy is manyfold. Perhaps the fatal problem is that the antenna doesn't work usefully at any higher frequency than S-band at the moment. It is not instrumented compatibly. We get out the ionosphere with S/X, but we can't do that with Arecibo. They also don't have a hydrogen maser, or much sky coverage, because it is limited in elevation to 20° from the zenith.

FLYNN: I would like to talk for a few minutes from the point of view of the Geodynamics Program Office at NASA. I have been taking notes for the last 2 days, and this is a summary of my reaction to the papers and discussion.

I am impressed by the way in which you are attempting to design the whole system to maximize the scientific returns from the investment of taxpayers' money, particularly by taking into account the geodetic and geophysical factors in planning the whole system. It would have been possible to design it in a vacuum, and in that case there would have been geodesists and geophysicists somewhat unhappy with a tool that was almost right for making an important contribution to both geodesy and geophysics. But as far as I can see, the desires that I was able to write down a few weeks ago from the point of view of geophysics and that Drs. Carter and Clark have expressed from the point of view of geodesy seem to have been taken into account almost entirely in your planning at this stage. That is very commendable, and NASA will be prepared to support officially the proposal for this project after an exchange of letters between our offices and Dr. Burke, or whoever is in charge of this project--

SHAPIRO: NRAO. Morton Roberts.

FLYNN: In the letters we would summarize the things that we think ought to be taken into account at various points and get a favorable reply back from you saying, yes, we will pay attention to that. Then we will do whatever we can to assist.

The cooperation between radio astronomy and geophysics and geodesy has been very fruitful in the past approximately 15 years, since we have been working together. From the point of view of geophysics, we have a system that has been developed entirely by radio astronomers to do high-accuracy point-position measurements. You, on the other hand, have had the benefit of about $25 million to $30 million that we have put into the groups that have developed the tools that geodesy needed, and I hope that we can continue that fruitful cooperation in the future.

You also have with you today Ivan Muhler, who is the president of IAG COSPAR Commission on International Cooperation in Space Techniques for Geodesy and Geophysics, and if it would be useful to you to have letters from such people as Ivan, I am sure that he could comment on the desirability of what you are trying to do from the point of view of geophysics.

I also wanted to make a comment on cost. The folk wisdom is that you always multiply everything by π, unless you are extremely efficient, in which case you need to multiply everything by e. In going over the cost figures in that early NRAO study for capital cost and operating cost with Tom Fischetti, our feeling was that you may be low, and you may be below by about a factor of $1 + 1/e$. You are talking about an expenditure that is comparable to a space flight, and whenever any office in NASA is putting together a plan for doing a space flight, we are always forced to have the costs reviewed by an independent team of people who are not professionally involved in trying to put it over. The purpose is to keep the people from "buying in" with ridiculous cost estimates, then later needing to spend 40 percent more.

It might be desirable to take that precaution at some reasonably early time, to have some hard-nosed people who are experienced and yet disconnected from your project go over the costs with you, so that when the National Science Foundation is told how much it is going to cost, you will be close to what the figures will actually be.

SHAPIRO: You mentioned that almost everything you thought of has been considered. I was wondering if you would tell us what the other things are that perhaps we should consider now and haven't yet.

FLYNN: I had to miss the morning session, so I don't know what the reaction was to what Dr. Counselman said about making provision for other agencies to operate GPS receivers.

SHAPIRO: No problem.

FLYNN: That was one thing. Also, the connecting with international observatories, the extent to which that is planned for in what you are doing: the Shanghai, Kashima, Wettzell.

SHAPIRO: The main thing is that everything is going to be MARK III-compatible, and the correlator is planned to be large enough to accommodate 14 stations simultaneously. But there are more stations than we could possibly afford correlated to process in one task. Fourteen is somewhat of an arbitrary number; I am not sure why it is 14, rather than 15.

KELLERMANN: It reduced bandwidth. Fourteen gives you the full polarization capability. If you don't do that, then you have 16 or 17.

SHAPIRO: It is another flexibility that will be built into the correlator.

FLYNN: I wasn't intending to imply that I was going to surprise you in the letter that we would write about the kinds of things that we are interested in and asking for your agreement to taking them into account. I think that Dr. Clark's list and the topics you mentioned will cover our interests adequately.

Dr. Carter might consider a similar letter relative to his agency's interests.

CARTER: I am sure that we can do that, if that is useful.

SHAPIRO: It is hard to know what letters will carry weight with whom. I'm not sure.

CARTER: I would like to "up the ante" a little bit on compatibility, actually, to the K3 system. You said that you would look into that and see what the problems are, but it looks as if the Japanese have already matched their system, but made it bigger and better. I am sure we are going to want to be bigger and better too before very long, so I think we ought to at least be thinking about the K3 system.

KELLERMANN: Radio frequency (RF)?

SHAPIRO: Yes, the RF bandwidth at X and S. It is roughly the same size, but it is shifted by 120 MHz.

CARTER: What was the S-band you were going to look at?

SHAPIRO: But how did it overlap? How much of a shift was there?

Audience participant: One hundred twenty megahertz.

SHAPIRO: Shifted in both X and in S?

Audience participant: No, their S is 2220 to 2320.

SHAPIRO: The S fits in, the X has shifted.

CARTER: Back to the question of the design of the dichroic, and those amplifiers that are involved at the front end: whether we actually can do both, I don't know.

KELLERMANN: It will be pushing it, but the answer is yes.

BURKE: It is my impression that most of the bands overlap still. So it is a very small loss.

WEILER: I think for a project of this magnitude the support from other agencies, other communities, is very important, and you are never sure where it will actually come in handy, but it often does. As the Congress, and the Office of Management and Budget (OMB), and the President's Science Adviser, and the Office of Science and Technology Policy (OSTP) begin to consider the project, the efforts that have been made by the community, by the NRAO, by everyone here, to make the project as scientifically useful to all different areas, is extremely valuable and much appreciated.

The end result, we all hope, will be an extremely powerful, interesting, and useful scientific instrument. The only other comment that I have is that the suggestion for outside review is very well taken, and we expect fully within the NSF to have many different types of review, such as ad hoc and standing review committees, engineering review, and cost analysis, as is done for any major project and, of course, following the experience in construction of the VLA.

FLYNN: At the division level?

WEILER: At the division level, yes. Are there any questions anyone would like to address to me?

SHAPIRO: What do you think is the major obstacle that will have to be overcome, if there is any one you can point to, in regard to getting this project as an approved project of the NSF?

WEILER: I think at the moment, optimistically, one could say there are none visible. That does not mean that none will arise. The project has broad support in the "Field Committee" report, and within the foundation and, apparently, also within the OSTP. The usual problems are, of course, that it is a great amount of money, even though not relative to some types of projects for astronomy, and no one can predict in advance what sorts of questions will arise within the OMB or the Congress. One will have to simply deal with any questions or problems as they arise, as we have done. The most important argument is that the project has a very strong scientific basis and justification. That puts us on firm ground to start with.

BURKE: There are two items on the agenda for which some response might be useful. First, I would like to come back to the question of array configuration and degree of flexibility in choosing stations. Some of the questions were answered, but not all.

In particular, the question was asked, how does the Canadian connection influence the array decisions, and how are the other national groups' plans being factored into the array design?

WALKER: I will start with the non-Canadian things. There we haven't factored in other plans in any special way. Certainly, the plans for dedicated telescopes in Italy are attractive. Our density of coverage on the longer spacings is improved significantly by interaction with Europe, but we haven't made any particular plans, and I am not sure I perceive a need to consider these other plans.

The Australian telescope is so far around the world that we don't expect to have much useful interaction, other than maybe an occasional use with the Hawaii telescope.

The Canadian connection is something much more complicated. If we can increase the number of telescopes, there is an attractive possibility of filling in the spacings between the VLA and the VLBA, and I think the Canadian scientists see that. If there is a collaborative effort with the Canadians, I think that we would like to move the antennas in our configuration that are in the northern United States, in the Northeast, up into Canada, but basically building the newer antennas in the Southwest. In the United States we would have essentially an expanded version of the VLA in the Southwest, plus the Puerto Rico and Hawaii sites. This means that we have to know about that collaboration before we get deep into the construction, because it does change our configuration seriously. It changes some of the sites that we might choose to build first. In a couple of weeks there is going to be a meeting between people from Canada and the United States on this collaborative project. As far as I perceive at the moment, the overall enthusiasm is not terribly high. The Canadians would like to go it alone. We are worried about delaying our project. But the ability to fill in the spacings is a very attractive possibility. We need to know that early, before we start putting down some of the sites.

BURKE: Is there any response from our Canadian participants?

YEN: I think any collaborative effort will take us away from our planned east-west array. In Canada we can only have an east-west line, we can't go north and south at all. If we go to the north we put one in Yellow Knife--we can't go farther north. We realize the importance of the non-east-west system. However, we also realize that our two proposals have been going on sort of in parallel since their inceptions, and at this time we would rather keep it that way. If the Canadian system comes together with the U.S. one, the system will always be compatible in certain ways, though not entirely. For instance, we may not have designed for as many frequencies; we may not plan to go into 40 GHz, and we may not use the MARK III system. But basically it would be compatible.

CANNON: I would like to indicate that there is some interest in Canada from the geophysical community, as well as the astronomers, in the technique of long-baseline interferometry. We would like to push very hard for a dedicated antenna site on the Canadian shield somewhere, with Yellow Knife, I guess, being our choice at this point, since it would be a very high latitude and have common visibility with Europe, Japan, and China.

We would like to push for this sort of development independently of the CLBA. Since this is largely a nonastrophysical meeting, I wanted to announce that we would like to collaborate geophysically with the efforts that are going on. In the scenario that Dr. Clark put on the board the other day, I was interested in the sorts of things that are scheduled for the 1990s. I think we would like to be part of that.

Whether the CLBA will be funded is uncertain. Of course, the geophysical people in Canada are hoping that it will be. We have had some interest from some provincial funding sources, as well as the federal ones, so our "roller coaster ride" of optimism to pessimism back to optimism continues.

BURKE: Another topic for discussion is institutional oversight. How do groups, other than the astrophysicists, have input to the project planning on a continuing and satisfying basis? Second, what will be the arrangements for proposal evaluation and scheduling?

ROBERTS: As far as designing the array is concerned, we have heard over the last 2 days expressions of the parameters that should be considered to ensure that we have a universal-type instrument. Therefore, there has been much input from this group. There is a more formal way of doing this. There are some 10 working groups that are meeting monthly by conference phone. There are roughly 50 different people who are members of these groups: about half are at various NRAO sites, and the other half are scattered around the North American continent. There are at least two people who wear several hats as far as geophysics and astrophysics are concerned. Dr. Carter has been asked to sit on the scientific group that ensures that the scientific opportunities are kept in mind. We can, of course, increase representation in that group.

It will be an astrophysical instrument, but it would be absolutely foolish to say that we will not consider experiments from other disciplines. If one can solve the problem of the external referees for such disparate areas, I think the usage should be judged on the science.

We have a lesser problem, but somewhat similar, in VLA. There are very few astronomers who know much about the sun--we have one of the world's experts here, he is probably 25 percent of the solar radio astronomers--yet we get a variety of proposals on the sun. In addition to our regular referees, we have solar referees, and we do the same for the solar system, for galactic or stellar proposals, and so on.

Ultimately, it comes back to the observatory, and although there will be a bias toward astronomy, we are indeed open and welcome proposals from other areas. The point that came up yesterday about a target of opportunity after an earthquake--that would be a very high priority type of experiment.

So, I want to speak in a very encouraging and welcoming fashion to the geophysicists, the astrometrists, part of astronomy, to look on this as indeed a national instrument. The mechanism will be to turn in a proposal. We will have to face how we do the refereeing. All our telescopes have external anonymous referees, and all our decisions are based almost wholly on the advice we get from them. When a proposal is rejected, the referee's comments are returned with it to show the reasons for rejection.

Let me go on to a theme that has come up continuously over the last 2 days, and that is compatibility. There may not be compatibility in terms of the actual recording medium, but there will be full compatibility otherwise, at least with MARK III. As for the Japanese system, I don't think we need worry about the differences, but Alan Rogers said that he would look into this. It would be silly to build in a lack of compatibility, so we are fully aware of the need. Again, these working groups that I have mentioned, in addition to a workshop like this, provide the best way of getting information on needs into VLBA planning.

In regard to the Canadian connection, for several years the Canadians asked us not to raise the issue of possible collaboration because they were concerned, and I suspect rightly so, that a U.S. presence could do nothing but slow down their project, or even hurt it.

The situation changed dramatically toward the end of last year, when I was asked to address the Canadian National Research Council at a meeting in Ottawa about the U.S. plans. They became aware that there were two parallel projects. At that point, there was concern about the Canadian project because of its high cost, $70 million Canadian dollars, which, by the way, is within 10 percent of the U.S. cost once you allow for the exchange rate.

The situation now is that we have been talking at various lower levels about a possible collaborative effort. Later on this month there will be a meeting, with five representatives from Canada, in Charlottesville; we will have people from the general community, as well as from NRAO, to discuss those areas we can live with and those we might not be able to live with. Regardless of what happens, if two arrays are built we want as much compatibility as possible, and of course the ideal situation would be if the Canadians could build their array and we build ours, assuming there would be compatibility at least in recording data, if not in all the frequencies.

So that is an ongoing effort, and there is nothing specific to say at this point. There has been concern about cost, and this is perhaps the most difficult aspect for me to discuss. We heard a specific concern about the processor. We heard a general concern, and advice to be careful, about pricing. I can assure you we are worried about this. Perhaps the greatest danger we face is that we have had such success in the past with pricing a small system and a large system that we may have lulled ourselves into thinking that we can always do it right. Most recently, we allotted $450,000 for redoing the 36-ft telescope into a 12-m, and it amounted to $440,000!

In regard to the VLA, I would like to change a common story. It is said that it came in on time and on budget. It came in on time, but we went over budget by 2 percent. It took 8 years of construction, with fantastic inflation and throwing things out as a result of that, buying used railroad ties instead of new ones. It turned out to be a $78 million budget, when the figure was $76 million. That doesn't mean we will be right the next time, but many of the same people who helped us in pricing the VLA were involved in the early NRAO study prices. We continually worry about things that we may have left out, or things that may have changed. But we think in 1982 dollars, and it is indeed $51 million. It will cost more by the time you start, when you include inflation and pace it out. If you could have put $51 million into the bank last year, we feel we could build the array as described in the early NRAO study for that price.

There was some mention of long time scales for construction. If we can get optimum funding, our construction plans are such that I invite you to the dedication on March 8, 1988, in the morning!

<u>BURKE</u>: Let me add that if somebody wants to communicate to the project, they can easily do so by contacting you or Dr. Kellermann, depending on who seems to be the more appropriate person to contact.

<u>ROBERTS</u>: And we urge such input. If it doesn't get into the proceedings and somebody comes up with an idea, please contact one of us.

<u>BURKE</u>: Are there any further subjects that people would like to raise at this stage?

<u>COATES</u>: Usually when budgets get approved, they have to be spread out over years. I wondered if there was any thinking about the sequence of implementation of this array. In other words, would it be built one station at a time, if you have to stretch it out, or just how would that be handled?

What I am thinking of is optimization. If you got only half the money now, you could build part of it and have some elements working before the full array is finished.

KELLERMANN: That is described in sort of a block-diagram-way in the proposal, but very roughly. We anticipate doing it over a 3-year period, 1985 through 1987. In 1986 the antennas start becoming available two at a time.

ROBERTS: There are even more specifics. With 3-year funding, the first year we would like to be able to commit $29 million. We have 10 different scenarios responding to requests from the National Science Foundation. One close to the optimum would give us $29 million of commitment authority in the first year, so we could get rid of the antenna contract and certainly other long-lead items. You would be building the first antennas two at a time. You would put up two at a time and train your erection crews. If we could get the monies, $29 million the first year, then spread out the rest of the $57.5 million over the last 2 years, we should have at least a semi-optimum array across the country.

CANNON: In your array proposal, do you have a central site where you will have the correlator and receiver development and such things, or are they to be spread around?

KELLERMANN: There is a control center from which all the antennas are operated. There is a data analysis center where you have the processor, postprocessing computers. There is a maintenance center. These three centers can be co-located or not, and we are looking into the various possibilities now: which ones should be where, and what the cost-benefit trade-offs are in having them together or having them separately at places to be more effective. It is a very difficult question, because you are weighing a lot of subjective things.

25

SUMMARY AND CONCLUSIONS

Bernard F. Burke
Workshop Chairman

The Very Long Baseline Array (VLBA) was originally conceived as an astrophysical facility, but it has been clear as planning proceeds that there are many other areas of scientific activity that can profitably use the facility. Some of these uses will take the form of short experiments proposed through normal channels. Others, of a more programmatic nature, may require advance planning so that the objectives can be properly met.

There are classes of investigation that can be carried out by making use of calibration data, although consultation about calibration strategy will be desirable.

Geophysical investigations received major attention at the workshop. Determinations of large-scale plate motions and deformation will surely be an important component of VLBA activity. Even where there will be dedicated very long baseline interferometry (VLBI) networks, such as those for polar motion and earth rotation studies, the VLBA will have the ability to provide accurate, independent measurements that serve as control values for UT1 and polar motion.

With proper choice of VLBA station locations, and by combining the national programs with VLBI observations from foreign stations and foreign very long baseline arrays now being planned and built, highly interesting measurements of plate motions will result. In addition, the VLBA will probably be the instrument of choice for the development of source catalogs for the geophysical programs and for the determination of structural changes in the fundamental sources that would otherwise degrade the quality of the dedicated geophysical network observations.

It is likely that the VLBA stations can be used as base stations for Global Positioning System (GPS) geodetic systems. Geodetic uses of the VLBA can be identified. The combination of VLBA and foreign arrays give a network that can lead to the definition of an earth-based coordinate system that is not tied to a single plate. The stations of the array can provide some of the reference points for the National Crustal Motion Network. They will also serve as base stations for the mobile VLBI crustal dynamics. The stations of the VLBA plus the dedicated geodetic network will provide the United States with a fundamental coordinate reference system far more accurate than any currently in existence or contemplated.

The VLBA will be used for fundamental astrometry in several different ways. The quasar reference system should be a better approximation to an inertial reference system than any other. The use of interplanetary spacecraft referred to the quasar system allows intercomparison between coordinate systems. These many capabilities make the VLBA an astrometric instrument par excellence. Stability of instrumentation and of observing and reduction procedures will be essential. The VLBA can give an independent measurement of the precession and nutation constants, determine the earth-based frame, and measure the relationship between the quasar-based and earth-based frame.

Numerous specialized uses were noted. One is that the system of masers in the VLBA will have the capability of synthesizing an improved master clock for the United States, and the worldwide network can provide universal clock synchronization. Second, possibilities for spacecraft navigation through differential VLBI will be enhanced by the availability of the VLBA, both for increased sensitivity when needed, and for provision of simultaneous orthogonal baselines or shorter baselines when these are needed.

Third, precision satellite orbit determinations and studies of the earth's gravitational field for geodetic purposes will be greatly aided by the ability of the VLBA to make measurements with respect to an inertial frame.

Fourth, the existence of the ground-based VLBA makes possible the extension into space of very long baseline techniques, allowing both near-earth-orbit and eccentric-earth-orbit concepts that will ultimately lead to far greater angular resolution than can be obtained from the surface of the earth.

A number of concerns raised at the workshop relate to the effective realization of these goals. Others will doubtless come up as the project proceeds. Some of these concerns are as follows: The first relates to the geophysics input to the project. We have been assured that augmentation of the scientific steering group will be examined by Dr. Roberts, who will then report on the actions taken. There is a general invitation to all of the community to communicate their concerns to the director of the National Radio Astronomy Observatory or to the project scientist, Ken Kellermann.

A second concern involves array configurations. My impression of our conclusion is that the antenna placement for best geodesy should be accomplished without compromising the astrophysical mapping capabilities. The workshop concluded that both Hawaii and Puerto Rico are especially appropriate locations for stations.

Third, regarding proposals in scheduling, we will have to take note of the complexity of scheduling, the possibility of making observations with subarrays, and interleafing observations. We will need sufficient lead time to undertake the required planning.

Fourth, regarding calibrations, the array requirements and other program requirements may often be similar. Preparation for mutual use of the calibration data by different program interests should be initiated at an early stage and should include the examination of the best calibration procedures to optimize such joint use.

A fifth concern involves auxiliary instrumentation. Here I think the point was made by several speakers that water-vapor radiometers, GPS receivers, gravimeters, meteorological sensors, geodetic monuments, and laser pads are all pieces of equipment that may well be co-located at the various stations, and there seems to be no objection to any one of them. They could well be operated by different agencies when that is appropriate. We are sure that such arrangements can be worked out.

Sixth, with regard to MARK III compatibility, our conclusion is that the project is aware of the need to maintain compatibility with the MARK III system. Further, over a decade the physical type of recorder may well change. As the systems develop, proper notice and consultation well in advance should be part of the adoption of new systems and of the orderly maintenance of the old systems, when long-term programs require it.

Seventh, in terms of performance specifications, concerns include horizon-to-horizon coverage, high slew rate, frequency compatibility with dedicated geodetic arrays, high time-resolution ability, provision for extra frequencies, low-frequency capability--that is, flexible low-frequency capability--ability to make multiband relativity observations, and, above all, for all of the instrumentation, it is essential to retain good quality control. The project planning group is well aware of this requirement.

The eighth concern has to do with the international interface. Here I think we can see that the systems are being designed to be compatible with foreign systems, and in fact there is a great deal of communication with the various foreign users to ensure that it continues.

I also noted that the Yellow Knife station is a particularly interesting one among the possible Canadian locations. We should make it clear that we look forward to collaboration between the Canadian and American arrays, and we are confident that this will work out in a mutually satisfactory way.

A ninth item, which Irwin Shapiro brought up, is that archiving should be seriously considered at early stages in the project, and it is particularly important if the data are to be used for astrometry and geodesy.

Appendixes

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APPENDIX A: AGENDA FOR THE WORKSHOP ON MULTIDISCIPLINARY USES OF THE VERY LONG BASELINE ARRAY

April 8-9, 1983
Auditorium
National Research Council
2101 Constitution Avenue
Washington, DC 20418

APRIL 8

0900 CONVENE

INTRODUCTION

Background and Purpose of the Workshop - Bernard F. Burke, Workshop Chairman

I. The Proposed Very-Long-Baseline Array

0915 Summary of the VLBA Program:
Scientific, Technical, and Planning Overview - Kenneth Kellermann, NRAO

1000 VLBA Scientific Program - Mark Reid, SAO

1030 COFFEE BREAK

1045 RECONVENE

1045 Astrophysical Objectives - Marshall Cohen, Caltech

II. Geodesy

1115 Overview of the Geophysical Problems - Peter Bender, JILA

1200 LUNCH - Refectory

1300 RECONVENE

1300 1. Methods for Obtaining Earth Rotation Parameters

1300 -Present VLBI Program-Polaris - William Carter, NGS

1330 Special Topic - COMMENTS AND DISCUSSION ON VLBA
George Keyworth, Director, OSTP

II. Geodesy (continued)

1400 -Using the Proposed VLB Array - John Spencer, NRL

1430 2. Use of the VLBA for Study of Crustal Motions

1430 -The Crustal Dynamics Project - Robert Coates, NASA Goddard

1500 -Measurements of Crustal Motions - Thomas Clark, NASA Goddard

1530 COFFEE BREAK

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1545	RECONVENE
	III. Astrometry
1545	Overview of Astrometric Problems - Gart Westerhout, Naval Observatory
1615	1. Definition of an Inertial Reference Frame - Kenneth Johnston, NRL
1645	2. Improved Astronomical Constants - Jay Lieske, JPL
1715	3. Implications of VLBA Measurements for Ephemerides - Kenneth Seidelmann, U.S. Naval Observatory
1745	4. General Relativity Measurements - Edward Fomalont, NRAO
1815	ADJOURN
	RECEPTION - Great Hall
	APRIL 9
0900	CONVENE
	IV. Other Users
0900	General VLBA Considerations - Alan E. E. Rogers, Haystack
0945	1. Tracking Deep Space Mission - Arthur Niell, JPL
1015	COFFEE BREAK
1030	RECONVENE
1030	2. Orbiting VLBI - Robert Preston, JPL
1100	3. Precise Satellite Tracking - Charles Counselman, MIT
1130	4. Definition of U.S. Geodetic Grid - William Strange, NGS
1200	5. Precise Time Transfer - William Klepczynski, Naval Observatory
1230	LUNCH - Refectory
1330	RECONVENE
	Other Users (Continued)
1330	Extended Discussion - Irwin Shapiro, SAO
1500	Summary - Bernard Burke, MIT
1545	CONCLUSION OF WORKSHOP
1550	Organizing Committee Convenes in Executive Session (Room 180)

APPENDIX B: LIST OF INVITEES TO THE WORKSHOP ON MULTIDISCIPLINARY USES OF THE VLBA

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