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An overview of reconnaissance activities using satellite imagery following Hurricane Charley

FIELD REPORT:

COLLECTION OF SATELLITE-REFERENCED BUILDING DAMAGE INFORMATION IN THE AFTERMATH OF HURRICANE CHARLEY

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This field campaign, undertaken in the aftermath of Hurricane Charley, was funded by the National Science Foundation, the Natural Hazards Research and Applications Information Center, and the Multidisciplinary Center for Earthquake Engineering Research (MCEER). It presented the research team with a unique opportunity to collect perishable damage survey data that will support subsequent research aimed at improving the effectiveness of disaster response activities using satellite remote sensing technology.

Hurricane Charley was the most severe wind storm to strike the US since 1992. Making landfall on August 13, 2004 at 4 p.m. ET, 145 mph winds devastated the Florida coastal cities of Port Charlotte and Punta Gorda, and 10 ft. high waves wreaked havoc on nearby barrier islands. In the hours following, a Presidential disaster declaration was issued for twenty-five counties in the impacted region. The event resulted in the loss of at least 27 lives, and caused more than $15.4 billion of damage.

This event is the first Category 4 hurricane for which 'before' and 'after' satellite imagery is available from very high-resolution systems, such as Quickbird and IKONOS. From a scientific perspective, it therefore offers a unique opportunity to investigate the use of remote sensing for post-disaster urban damage assessment, technology which has the potential for improving the effectiveness of disaster response activities.

In order to validate building damage characteristics identified on the satellite imagery, corresponding ground-based observations are required. There is a narrow time window for documenting the building and infrastructure damage from extreme windstorm events, as clean-up operations are typically initiated as soon as possible. Through funding from the National Science Foundation Small Grants for Exploratory Research (SGER) program and the Natural Hazards Research and Applications Information Center Quick Response program, two field reconnaissance trips have been conducted by ImageCat in conjunction with the Wind Science Research and Engineering (WISE) Research Center at Texas Tech, to collect perishable damage data using the VIEWS (Visualizing Impacts of Earthquakes With satellites) system, which was developed by ImageCat through funding from MCEER (Multidisciplinary Center for Earthquake Engineering Research). It is envisioned that the data collected will ultimately form the basis of research activities extending the application of post-disaster damage assessment methodologies and algorithms developed for earthquakes to multiple hazards. This research will result in significant advances for windstorm engineering.

This preliminary report begins with a brief overview of the field study sites, together with satellite imagery that was available. It goes on to document damage survey activities that were conducted, together with the methodologies and sampling strategies employed for data collection. A summary is given of the resulting data sets, and a selection of illustrative examples presented, which were extracted using the MCEER-funded D-VRS (Virtual Reconnaissance System) system. The report concludes with a list of key findings and lessons learned.

Study Sites

The post-hurricane damage assessment was conducted during two separate deployments spanning August 18-21 and August 24-27, 2004. In terms of study site selection, field data collection was undertaken throughout impacted areas for which satellite imagery was also available. Efforts focused on the towns of Port Charlotte and Punta Gorda (Fig.1), which as shown in Table 1, were covered by Quickbird imagery collected both before and in the immediate aftermath of the hurricane. Although news reports suggested that other inland regions such Arcadia, and the barrier islands of Fort Myers Beach, Pine Island and Sanibel Island had also sustained damage, these locations were not included in this study either because satellite coverage was unavailable, or cursory field observations suggested that wind-induced damage was limited.

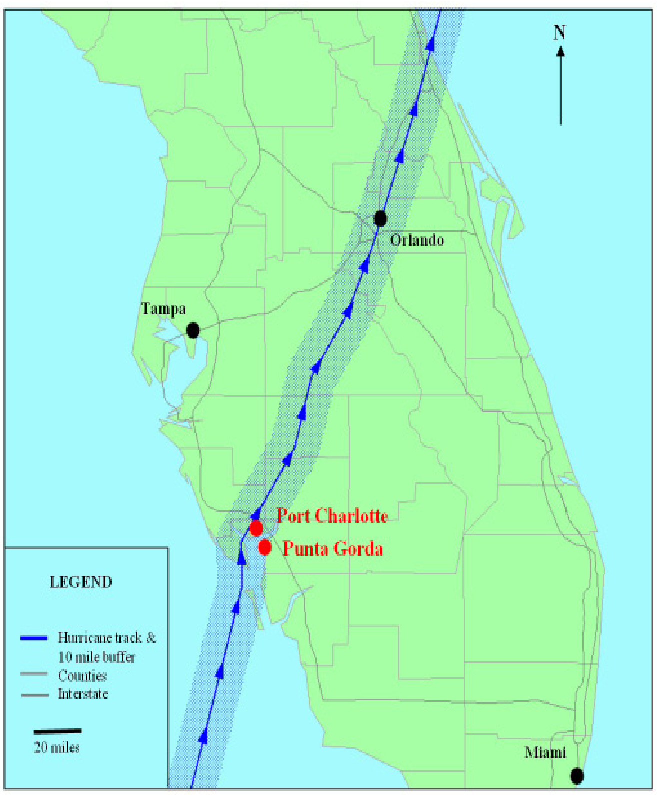

Figure 1. Field study regions of Port Charlotte and Punta Gorda, Florida, which sustained extreme damage during Hurricane Charley.

Table 1. Summary of Quickbird datasets employed during post-hurricane field-based damage assessment using the VIEWS reconnaissance system.

Date	Timeframe	Area covered
3-23-2004	Before	Punta Gorda
HURRICANE CHARLEY 8-13-04		
8-14-2004	After	Punta Gorda
8-19-2004	After After	Punta Gorda Port Charlotte

Field-based Damage Survey

Data Collection

The aim of these field deployments was to collect perishable information about the damage characteristics of buildings and infrastructure, which afterwards can be used to validate features distinguishable on the satellite imagery. Traditional methods of post-hurricane damage assessment involve walking surveys, where damage indicators together with the overall damage state (see Table 2), are logged on a spreadsheet. Commonly used indicators, such as those employed by the Wind module of the FEMA (Federal Emergency Management Agency) HAZUS-MH loss estimation software, include: roof cover failure, roof structure failure, window/door failure, roof deck failure, wall failure and the occurrence of missile impacts on walls.

For the present study, an alternative technology-driven approach was adopted for field data collection. The VIEWS (Visualizing Impacts of Earthquakes With Satellites) field reconnaissance system was deployed to accelerate and streamline the collection of these key measures, and produce a permanent visual record of damage sustained by individual structures. VIEWS is a notebook-based system, originally developed for earthquake with funding from MCEER. It integrates satellite imagery with real-time Global Positioning System (GPS) readings and map layers (see Figure 2a), and operates in conjunction with a digital camera and digital video recorder. It can be deployed either from a moving vehicle (Figure 2b), or on foot during a walking tour (Figure 2c).

The screen-grab of the VIEWS User interface in Figure 3 demonstrates how the 'before' and 'after' satellite images serve as the mapping base layer, and are available for use 'on-the-fly' to visualize damage and assess the degree of change. Through the real-time GPS feed, routes taken around the damaged areas were logged and overlaid on a vector-based street map. Georeferenced building damage observations, together with the location of road obstructions and broken power lines, were recorded using the GPS-linked digital video recorder (see Figure 2b). A georeferenced photographic record was also collected, illustrating in detail, characteristics relating to the damage states in Table 2.

Figure 4 depicts the routes throughout Punta Gorda and Port Charlotte along which GPS readings, georeferenced video coverage and a photographic record were recorded. Effort was made to include the following occupancy classes:

- Residential
- Commercial and industrial
- Government

Within these respective categories, the survey spanned all major structural types. For example, residential structures ranged from single family dwellings, to mobile homes and apartment blocks.

A purposive sampling strategy was employed when selecting neighborhoods to survey. Several days after the hurricane, FEMA published the damage map in Figure 5. The survey was designed to include a range of areas delineated on this map, including samples from each of the following damage states:

- LD – limited damage
- MD – moderate damage
- ED – extensive damage
- CD – catastrophic damage

Interestingly, these categories are different to the damage states employed by loss estimation programs such as HAZUS (see Table 2). The survey avoided areas of eastern Punta Gorda that were obscured on the satellite coverage by dense cloud or cloud-related shadowing. In each neighborhood, observations were also made of damage to the power system.

Access to selected study areas did not prove to be an issue, although several gate keepers asked to see letters of authorization detailing the purpose of data collection and the personnel involved. Accessibility was problematic in some locations where routes were obstructed by fallen power lines, or where repair teams were operating. Judging from the widespread evidence of clearance, obstruction by fallen trees was a significant problem in the immediate aftermath of the storm. Residents were generally interested in the research activities and keen to recount their experience of the hurricane. This proved to be a useful source of information about the onset and progress of the storm, together with the sequence in which different types of damage were sustained.

(a) VIEWS field reconnaissance system in operation

(b) VIEWS deployment from vehicle

(c) VIEWS deployment on foot

Figure 2. (a) Field deployment of the VIEWS system following Hurricane Charley, (b) from a moving vehicle and (c) through close-up visual inspection on foot.

Table 2. Indicators used in the aftermath of hurricanes and windstorms to asses the damage state of residential buildings.

Damage State	Qualitative Damage Description	Roof Cover Failure	Window Door Failures	Roof Deck	Missile Impacts on Walls	Roof Structure Failure	Wall Structure Failure
0	**No Damage or Very Minor Damage** Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof over, with no or very limited water penetration.	≤2%	No	No	No	No	No
1	**Minor Damage** Maximum of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	>2% and ≤15%	One window, door, or garage door failure	No	<5 impacts	No	No
2	**Moderate Damage** Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to interior of building from water.	>15% and ≤50%	> one and ≤ the larger of 20% & 3	1 to 3 panels	Typically 5 to 10 impacts	No	No
3	**Severe Damage** Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.	>50%	> the larger of 20% & 3 and ≤50%	>3 and ≤25%	Typically 10 to 20 impacts	No	No
4	**Destruction** Complete roof failure and/or, failure of wall frame. Loss of more than 50% of roof sheathing.	Typically > 50%	>50%	>25%	Typically >20 impacts	Yes	Yes

HAZUS Hurricane Model Technical Manual, FEMA 2003

The field survey was principally conducted from a moving vehicle. An SUV was selected, since the increased elevation above street level, compared with a regular vehicle, provided better coverage by avoiding obstructions in the foreground. The vehicle was driven at 10-15 mph, as this was found to optimize the video coverage and stills obtained by avoiding aberration, while enabling a large geographic extent to be covered. Using VIEWS, 21 hours of digital video footage was recorded during the field deployments. Practical experience suggested that the data collection process could be further streamlined through the deployment of duel cameras that simultaneously capture footage for both sides of the street. A library of 930 digital photographs was also collected. More in-depth damage assessments were conducted on foot at a subset of approximately 15 buildings. In these cases, the team spent a prolonged duration documenting the nature of damage, its likely causes, interviewing residents, and obtaining a detailed photographic record.

Residents were generally interested in the research activities and keen to recount their experience of the hurricane.

In terms of efficiency, traditional survey techniques previously employed by WISE researchers at Texas Tech typically enabled 20 – 100 buildings to be surveyed per day (depending on the level of detail involved in the survey). In comparison, the 4-day VIEWS-based survey covered 324.3 km of surface streets, capturing coverage of an estimated 10,000 buildings. This equates to some 2,500 buildings per day.

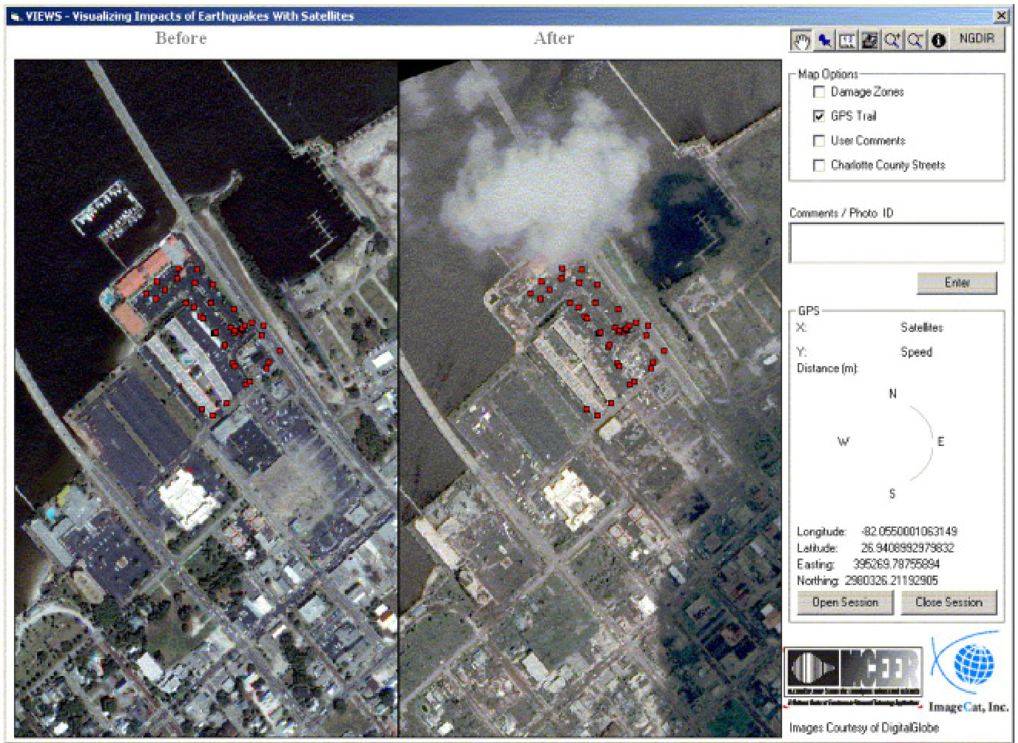

Figure 3. User interface for the VIEWS system, deployed to collect building damage data in Punta Gorda and Port Charlotte after Hurricane Charley. Quickbird satellite images acquired 'before' and 'after' the hurricane form the base layer, which is overlaid here with GPS readings for one of the routes taken.

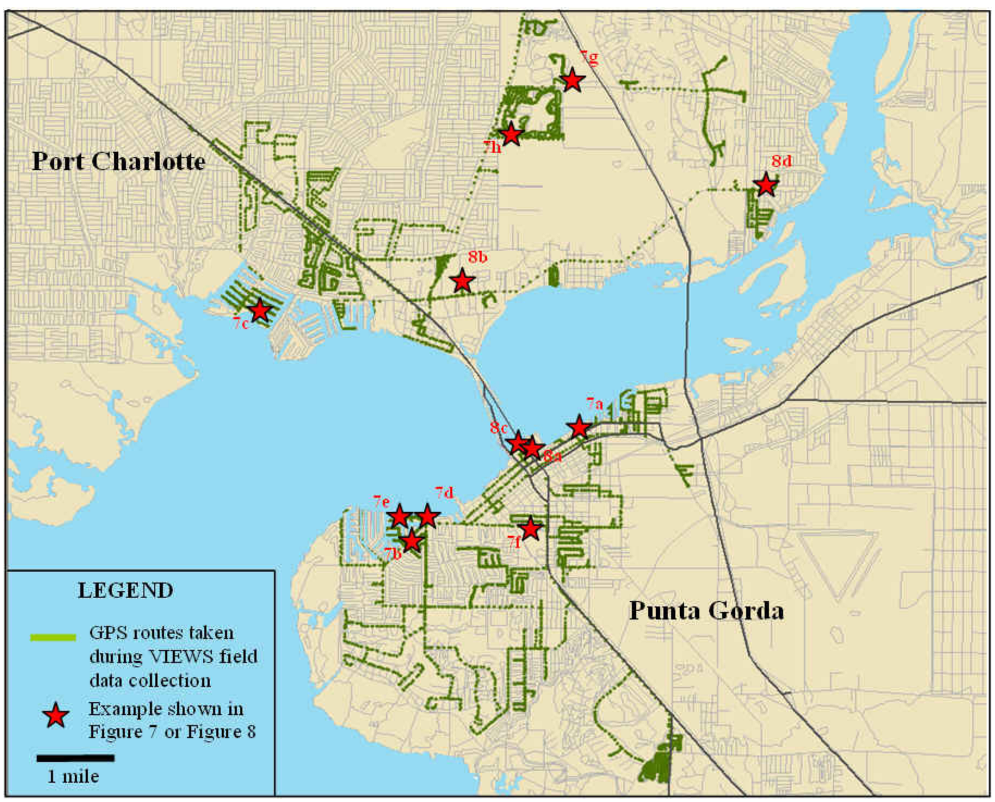

Figure 4. GPS-logged routes in Port Charlotte and Punta Gorda along which VIEWS was deployed, recording geo-referenced digital video and digital photographs. The annotated points relate to the examples of damage visualized in Figure 7 and Figure 8.

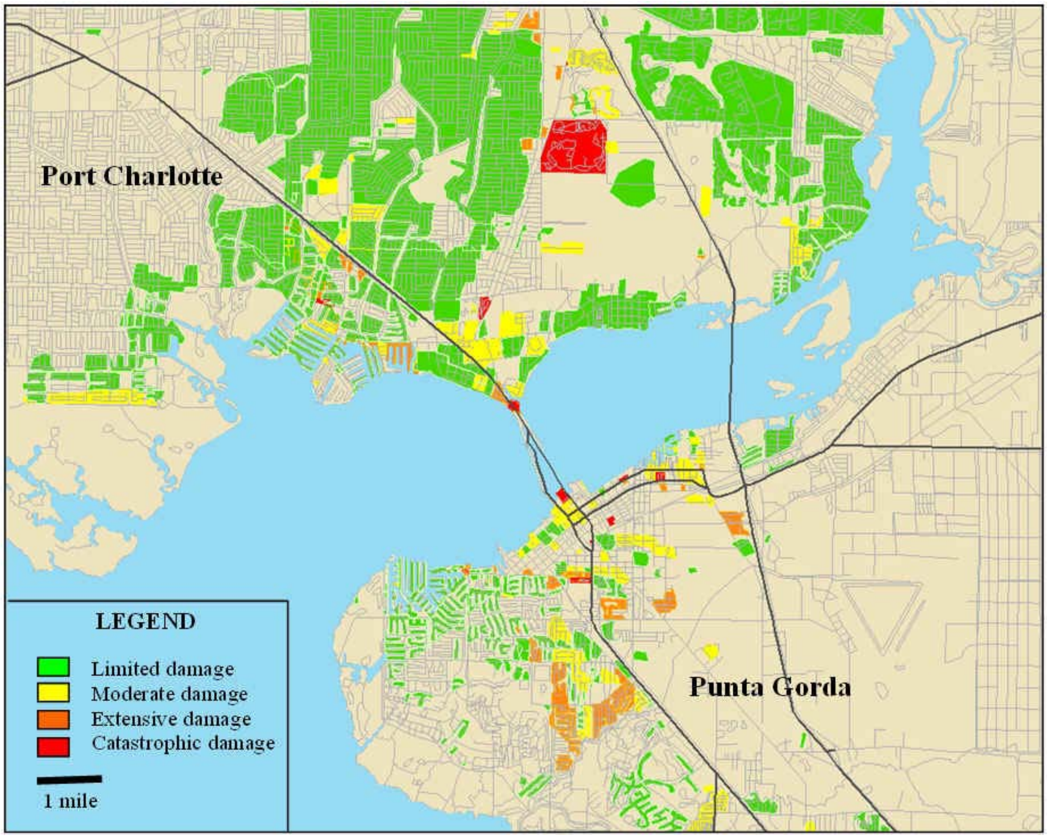

Figure 5. Post-hurricane damage zones in Charlotte County published by FEMA on August 20, 2004.

Damage Visualization

In order to integrate, share, visualize, and ultimately analyze post-disaster reconnaissance field data collected using VIEWS, MCEER is sponsoring the development of tandem internet- and desktop-based ‘virtual reconnaissance systems’, referred to as VRS and D-VRS. Figure 6 shows a screen grab from D-VRS, which provides researchers at ImageCat and Texas Tech with easy access to the satellite imagery, GPS readings and georeferenced video and photographic records for Port Charlotte and Punta Gorda. The user has an option to toggle between multitemporal and multi-source satellite images, and to explore these images in detail using zoom and pan functions. These images are overlaid with GPS routes collected during the survey. By selecting a GPS point, the user can view corresponding video footage and, in the adjacent window, scroll through the archive of nearby photographs. The photographic library can be augmented with stills captured directly from the video as it plays, each of which is output to a new georeferenced file.

Figure 7 and Figure 8 respectively show examples of the hurricane damage sustained by residential structures and commercial/industrial/government buildings in Port Charlotte and Punta Gorda. Where available, pre- and post-event satellite images are shown, together with corresponding ground-based photographs captured by digital camera, or as video-derived stills.

Three main types of residential structure were studied during the survey: (i) single family houses; (ii) apartment complexes; and (iii) mobile homes. For family houses, all levels of damage (see Table 2) were observed, ranging from complete failure of the roof structure (Figure 7a), through partial loss of the roof cover (e.g., tiles and asphalt shingles) and the wooden roof deck below (Figure 7b), to minimal removal of roof coverings (Figure 7c). Figure 7c also illustrates how looting was a major concern in the immediate aftermath of the event. Graffiti-style notices such as this were common throughout all neighborhoods, although in most cases this method was used to convey the resident's insurance company and claim number. Although difficult to detect from the satellite imagery, damage to garage doors was prevalent and numerous cases of window failure were observed. Where present, wall failure was principally sustained by car ports and pool covers.

Apartment complexes also exhibited mixed performance during the hurricane. As was the case for family dwellings, damage ranged from failure of the roof structure (Figure 7d and Figure 7e) to cosmetic losses of roof covering. Residents' car shelters fared poorly during the storm, with many examples of mangled metal sheeting scattered across apartment parking lots. In many locations, scattered debris comprising roofing materials and building contents was also widespread.

Of the three residential categories, mobile homes sustained by far the highest degree of damage. The field team witnessed numerous examples where mobile homes had been turned into mangled piles of debris (Figure 7f). In some instances, mobile homes had been thrown onto adjacent structures, crushing them both (Figure 7g). Roof cover failure was commonly observed, together with the collapse of attached car ports. Debris from the mobile homes was often scattered across a wide geographic area, extending up to one kilometer from the source. In Figure 7h, highly reflective metallic debris from the

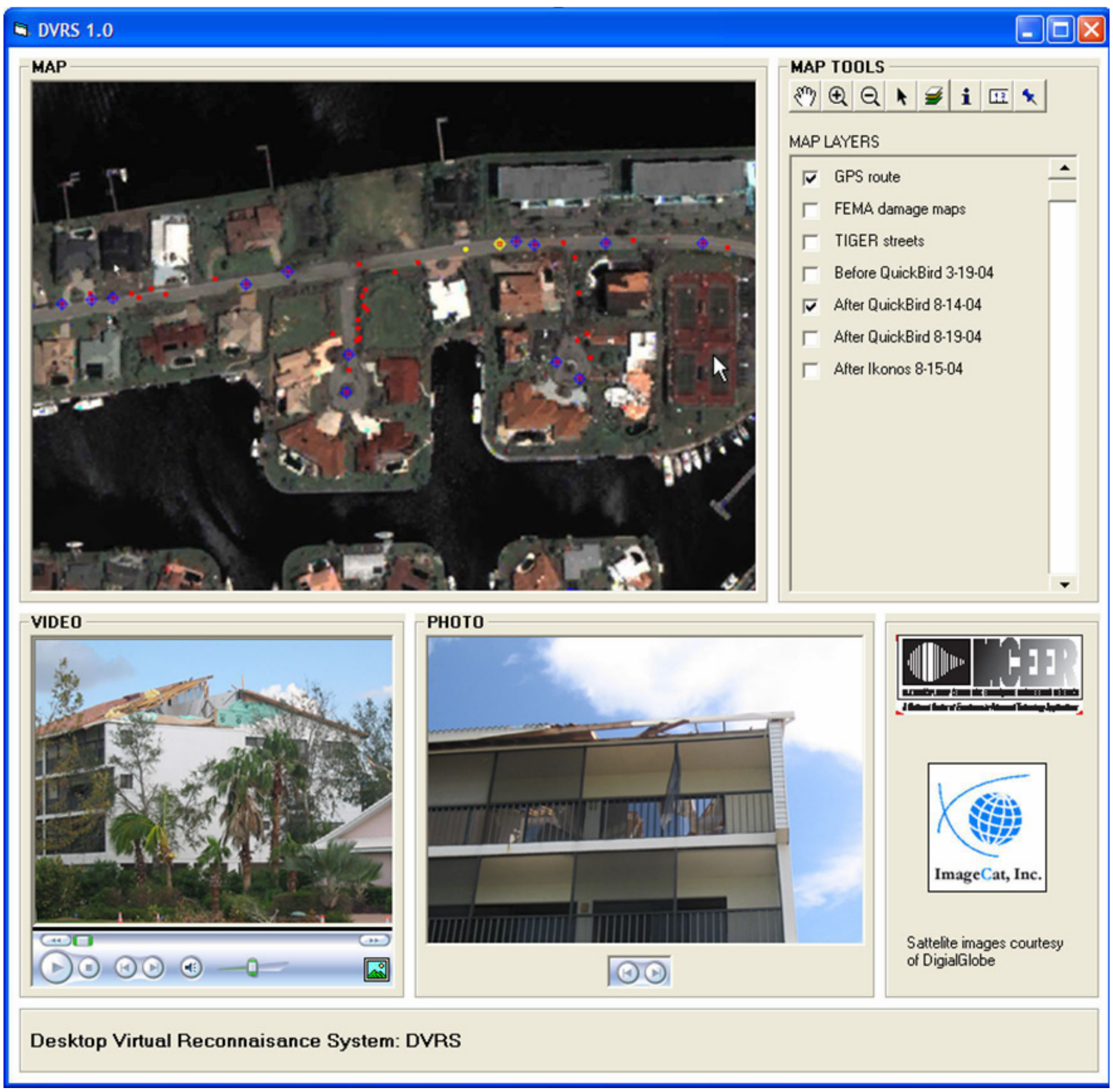

Figure 6. Screen grab from the D-VRS virtual reconnaissance system, showing satellite imagery, GPS readings, video footage and digital photographs collected in Punta Gorda after Hurricane Charley.

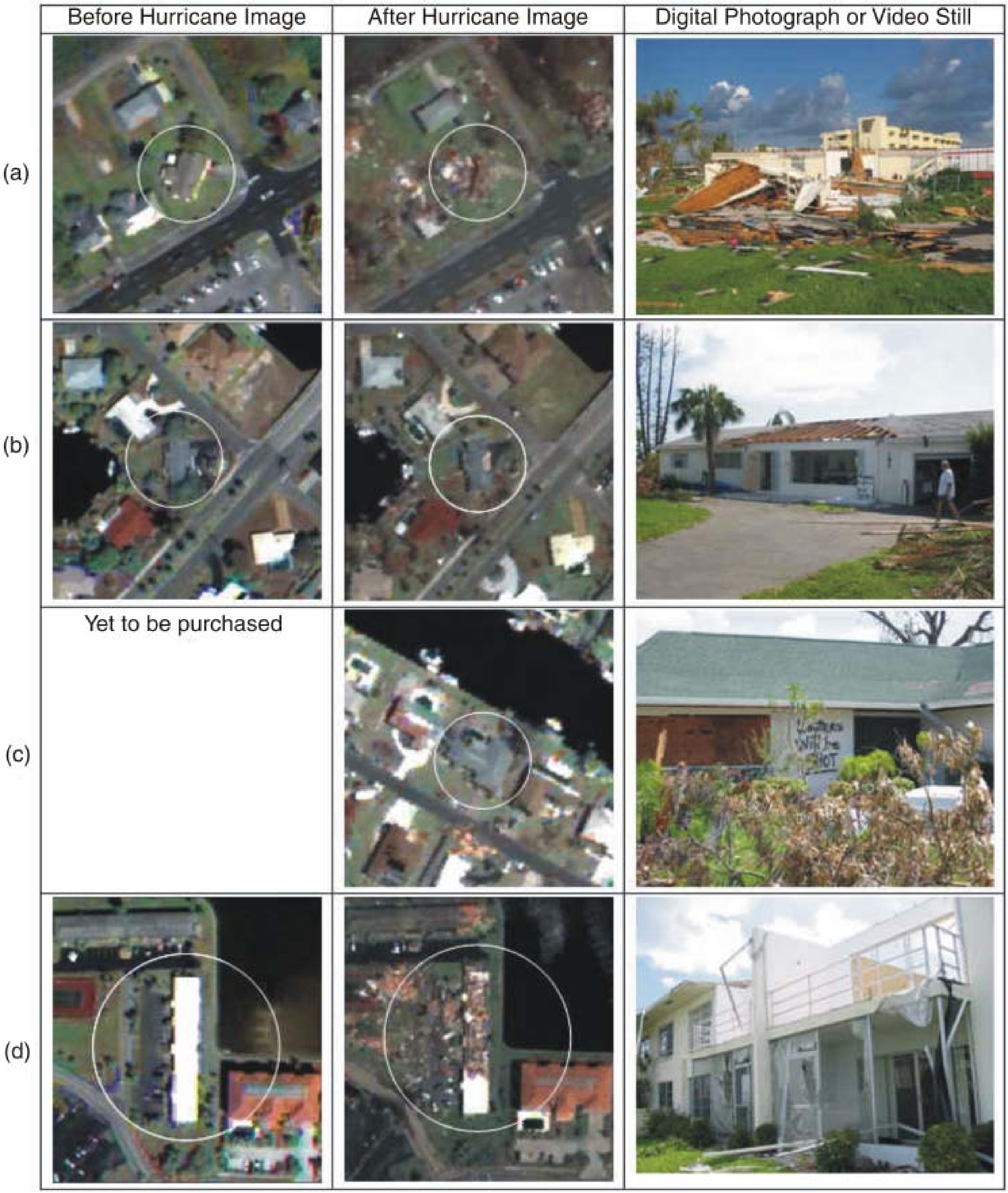

Figure 7. Photo mosaic of damage to residential structures in Port Charlotte and Punta Gorda. For family dwellings: (a) complete roof failure; (b) partial roof cover and roof deck failure; and (c) limited roof damage. For apartment blocks: (d-e) roof structure failure. For mobile homes: (f-g) catastrophic destruction; and (h) scattering of debris across an extended geographic area. For image/photo locations, see Figure 4.

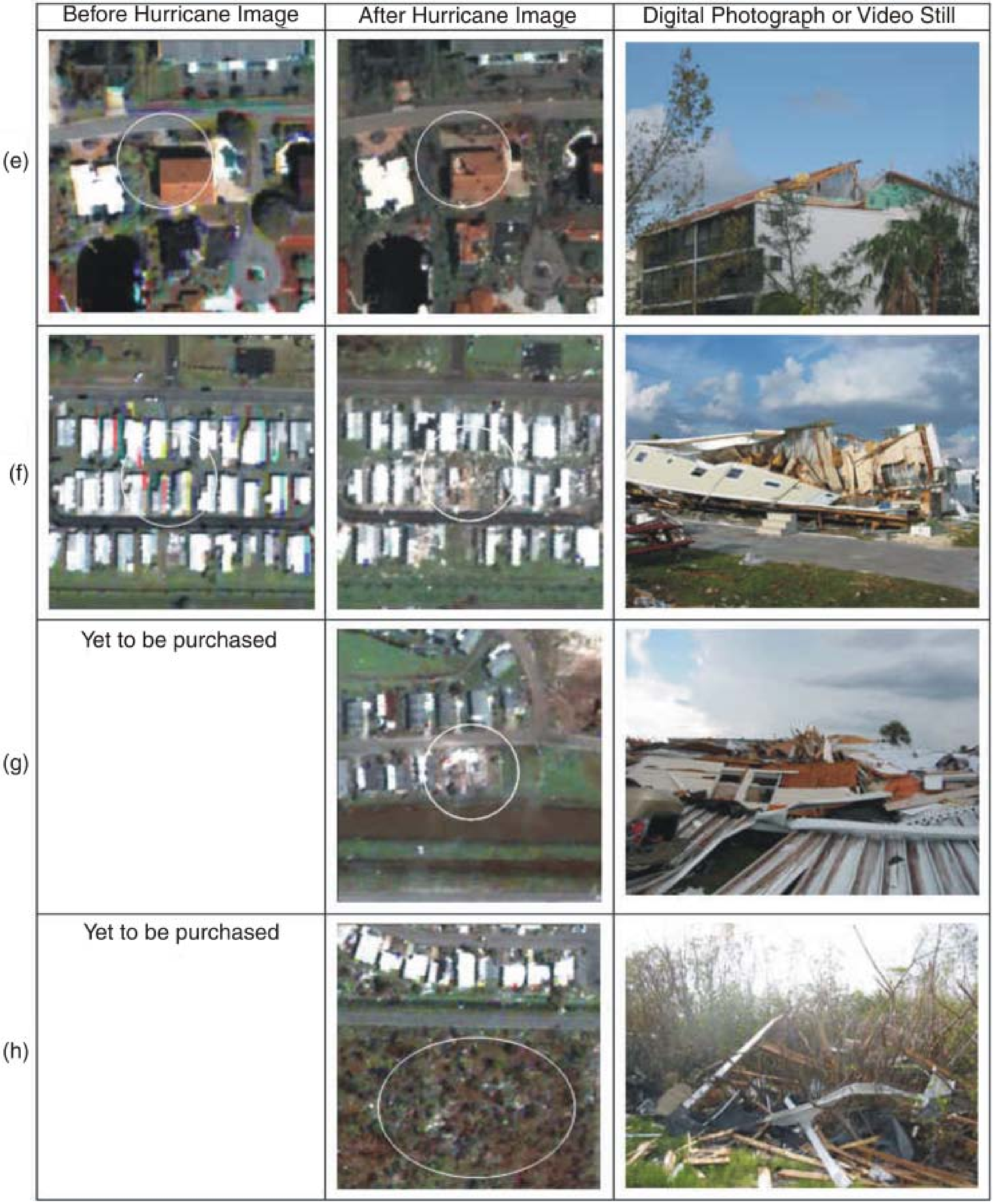

Figure 7 (continued). Photo mosaic of damage to residential structures in Port Charlotte and Punta Gorda. For family dwellings: (a) complete roof failure; (b) partial roof cover and roof deck failure; and (c) limited roof damage. For apartment blocks: (d-e) roof structure failure. For mobile homes: (f-g) catastrophic destruction; and (h) scattering of debris across an extended geographic area. For image/photo locations, see Figure 4.

Figure 8. Photo mosaic of damage to commercial/industrial and government structures in Port Charlotte and Punta Gorda: (a) the roof and walls of a steel framed auto shop collapse, only the hydraulic lift is left standing; (b) wall and roof failure at an industrial park warehouse; (c) roof failure at the Punta Gorda Holiday Inn; and (d) loss of roof cover at a Port Charlotte middle school. For image/photo locations, see Figure 4.

mobile home park to the north of Van Buren Avenue in Port Charlotte, can be detected in nearby hedgerows and spread across fields to the south.

Satellite Imagery of Hurricane Charley offers a unique opportunity to investigate the use of remote sensing for post-disaster urban damage assessment.

From a remote sensing perspective, Figure 7f and Figure 7g also illustrate the importance of acquiring both pre- and post-event satellite imagery; it is easier to determine the extent of damage in terms of change with respect to the non-damage scenario. When before imagery is unavailable (as for Figure 7g), interpretation relies on comparison with the appearance of surrounding structures. In the given example this method is also successful, since the degree of damage is high and the mobile homes no longer exhibit a ‘normal’ rectangular form. However, this approach may prove limited for lesser damage states.

Commercial structures sustained varying levels of damage. The field team witnessed many examples where the roof of steel framed warehouse structures had been ripped off and the walls had fallen in (see, for example the auto shop in Figure 8a and the warehouse in a Port Charlotte industrial park in Figure 8b). Some commercial buildings, such as hotels, responded similarly to apartment blocks. Figure 8c shows roof structure failure at the Punta Gorda Holiday Inn. Interestingly, from a remote sensing perspective, this commercial structure is indistinguishable from similar shaped and sized apartment blocks, and would probably be categorized as such if ground truth data were unavailable. The team also assessed damage to a number of publicly owned buildings. Several schools were hard hit, with a Port Charlotte middle school (Figure 8d) and the Punta Gorda high school respectively sustaining loss of roof cover and roof failure.

The perishable nature of post-disaster building damage data is borne out by differences to residential properties observed between the two field deployments and between the temporal sequence of ‘after’ satellite images (see Table 2). In the days immediately following the disaster, many damaged roofs remained exposed to the elements. During the initial field deployment, comparatively few were tarped, and there was little evidence of repair. At this stage, residents appeared to be focusing on securing of personal effects and building contents and on the clearance of debris and vegetation. Temporary roof-covering materials may have also been in short supply in the local area immediately following the hurricane. During the second deployment, there was a substantial increase in the presence of tarps and plastic covers. This trend is apparent from the Quickbird satellite scenes in Figure 9, which were acquired 1- and 6-days after the hurricane struck. During the second field visit, workers were observed making permanent repairs to the roofs of family dwellings. However, recovery efforts were progressing far more slowly in the mobile homes, where in many cases, debris clearance was only just commencing. Many of the mobile home in these parks are apparently used as winter vacation homes by people living elsewhere, and thus many residents may not have been in the area at the time of the storm to make temporary repairs to their properties.

These observations suggest that although post-windstorm building damage data is perishable by nature, for a hurricane of this magnitude, valuable information may be collected throughout the following days and weeks. However, the nature of available data clearly varies over this timespan. In residential neighborhoods with single family dwellings, early access is vital for observing the debris distribution, since it is cleared in generally 1-3 days after the event. In many cases, roof damage state may be evident for up to one week. After this time, an increasing number of roofs will be obscured. Experience from Hurricane Charley suggests that in mobile home parks (particularly those with a high percentage of vacation homes), debris distribution and roof damage is in evidence for considerably longer.

These observations suggest that although post-windstorm building damage data is perishable by nature, for a hurricane of this magnitude, valuable information may be collected throughout the following days and weeks.

The power system sustained significant damage during Hurricane Charley. On arrival in Port Charlotte on August 20, 2004 for the first day of field data collection, the team encountered lengthy delays

Figure 9. The perishable nature of building roof damage data is evident by comparing the Quickbird scenes acquired on: (a) August 14, 2004,1 day after; and (b) August 19, 2004, 6 days after Hurricane Charley. In the latter case, a number of roofs are now tarped.

because stop lights were not working and the police were directing traffic. Damage to the supply system was severe (Figure 11a). Residential neighborhoods were hard hit, with power lines lying cross people's front yards (Figure 11b), several occurrences of power poles impacting roofs, and evidence of severed connections (Figure 11c). Most businesses in Port Charlotte and Punta Gorda were closed at this time (Figure 11d), since there was no power supply. When the field team returned on August 25, some businesses had re-opened along the major highways I75 and SR41. During the initial reconnaissance trip, a number of routes were obstructed by fallen power poles and power lines. For the second visit, roads instead were closed by repair teams (Figure 11e-f). At the present time, the manifestation of windstorm-related damage to the power system on high-resolution remote sensing imagery has yet to be explored. This remains a topic for future research.

Overview of the VIEWS and D-VRS Systems

Post-Charley damage survey activities were accelerated and streamlined using the VIEWS field reconnaissance system. VIEWS (Visualizing Impacts of Earthquakes With Satellites) is a notebook-based system, which integrates GPS-registered digital video footage, digital photographs and observations with high-resolution satellite images of the event (see Figure 10). Research teams are currently sharing, visualizing and analyzing these datasets using a desktop version (D-VRS) of the 'Virtual Reconnaissance System'. These tools were originally developed for earthquake through MCEER (Multidisciplinary Center for Earthquake Engineering Research) funding.

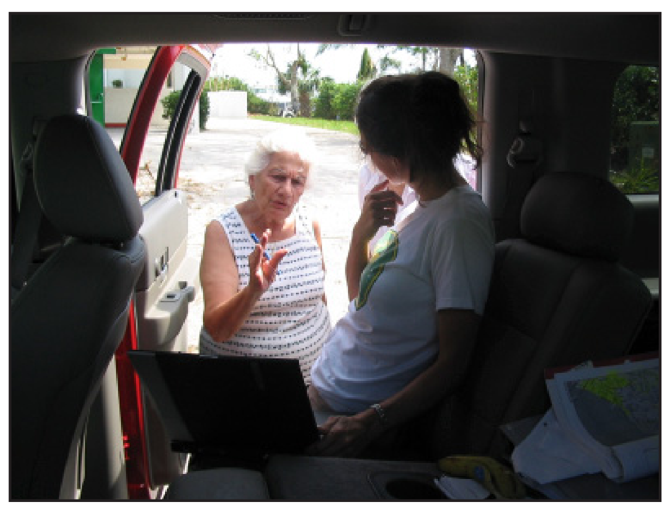

Figure 10. Many residents of Punta Gorda and Port Charlotte were interested in seeing how the VIEWS System was used following the hurricane.

Figure 11. Damage to the power system in Port Charlotte and Punta Gorda. Residential and commercial properties experienced loss of supply as power poles were toppled and lines severed. During the second field deployment, repairs were ongoing.

Future Work

The data collected during this field campaign constitute a valuable resource for future collaborative research activities by ImageCat Inc. and Texas Tech University, which aim to improve the effectiveness of disaster response activities through the use of satellite remote sensing technology. Funding will be sought from the National Science Foundation to support these activities. The August 2004 field deployments to Florida also provide valuable feedback for augmenting and improving the VIEWS field reconnaissance and D-VRS data integration and visualization systems. These refinements, and their associated benefits for future multi-hazard field reconnaissance, will be supported by MCEER funding.

Key Findings

- The acquisition of field damage data is significantly accelerated and streamlined using the MCEER-funded VIEWS (Visualizing Impacts of Earthquakes with Satellites) reconnaissance system. Whereas traditional surveys on foot cover approximately 20-100 structures per day, the vehicle-based VIEWS survey captured a GPS-linked photographic record, together with detailed video footage of building damage for ~2,500 structures per day.

- High-resolution optical satellite imagery collected by commercial systems such as Quickbird provides a detailed overview of building damage caused by Hurricane Charley. Exploratory visualization using the MCEER-funded D-VRS (Desktop Virtual Reconnaissance System) system suggests that different types and extremes of damage can be detected to residential, commercial/industrial and government structures. This information will support subsequent research activities that aim to improve the effectiveness of disaster response activities using remote sensing technology.

- A time window spanning several weeks was available for perishable field data collection in the aftermath of this category 4 hurricane. However, the type of damage that could be viewed varied as time progressed. For neighborhoods of single family dwellings, fallen trees and scattered debris was cleared within the initial 1-3 days following the storm. After 4-5 days, roof damage to some of these properties was obscured by tarps. By the second week, there was a significant increase in the number of covered roofs, for which damage characteristics could no longer be recorded. Roof repairs were also underway at this time. When compared with the remote sensing imagery, these roofs will now exhibit fundamentally different visual characteristics. Clean-up operations proceeded far more slowly in mobile home parks. Scattered debris was still evident in the second week, and few properties were either tarped or undergoing repair.

- Extensive damage was sustained by the power system. In the week following the hurricane, few stop lights were working and few businesses operating. Roads remained blocked by fallen power lines and broken poles. During the second week, progress was clearly being made with the repairs. Roads were instead obstructed by repair crews and some businesses had reopened. The signature of power system damage on remote sensing imagery is a topic for future research.

Figure 12. The field team, (from left to right) John Turner, Michael Mio, Beverley Adams and Arn Womble, outside one of the heavily damaged apartment blocks.

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