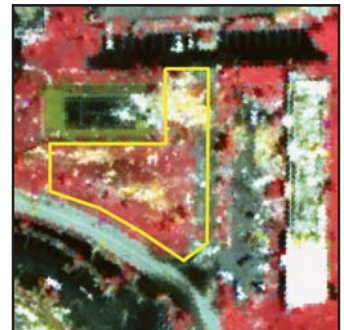


# Remote Sensing for Resilient Multi-Hazard Disaster Response

## Volume V: Integration of Remote Sensing Imagery and VIEWS™ Field Data for Post-Hurricane Charley Building Damage Assessment

by  
**J. Arn Womble, Kishor Mehta and Beverley J. Adams**



Technical Report MCEER-08-0024

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by

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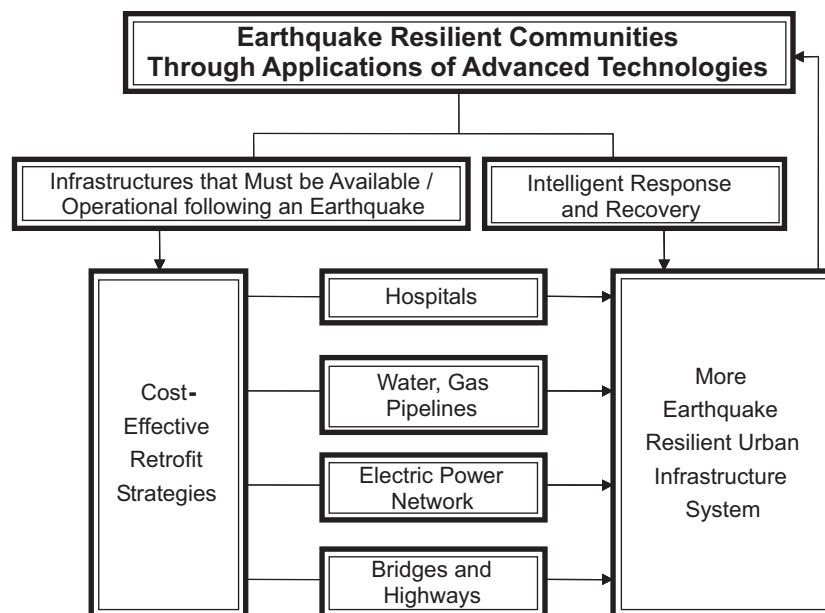
## Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

*This report investigates the use of remote sensing and advanced field data collection technologies to improve response to extreme windstorm events. Perishable field data collected by the VIEWSTM system in the aftermath of Hurricanes Charley and Ivan were analyzed, resulting in the development of a HAZUS-compatible remote sensing-based damage scale for wind. Then, quantitative characteristics of windstorm damage to buildings, debris surrounding buildings, and surrogate indicators of damage such as the presence of blue tarpaulins or roof covers, were investigated. The study found that while remote sensing and advanced field survey techniques do not replace detailed forensic studies of building damage, they provide complementary information about the overall damage conditions of buildings as well as the spatial distribution of perishable damage characteristics throughout a region. This report is Volume V of a five part series that investigates the use of remote sensing techniques for resilient multi-hazard disaster response.*

## PREFACE

This preface introduces a five volume series, documenting scientific research conducted by MCEER researchers at ImageCat, Inc., investigating remote sensing techniques for resilient disaster response.

Volume I: INTRODUCTION TO DAMAGE ASSESSMENT METHODOLOGIES

Volume II: COUNTING THE NUMBER OF COLLAPSED BUILDINGS USING AN OBJECT-ORIENTED ANALYSIS: CASE STUDY OF THE 2003 BAM EARTHQUAKE

Volume III: MULTI-SENSOR IMAGE FUSION TECHNIQUES FOR ROBUST NEIGHBORHOOD-SCALE URBAN DAMAGE ASSESSMENT

Volume IV: A STUDY OF MULTI-TEMPORAL AND MULTI-RESOLUTION SAR IMAGERY FOR POST-KATRINA FLOOD MONITORING IN NEW ORLEANS

Volume V: INTEGRATION OF REMOTE SENSING IMAGERY AND VIEWS™ FIELD DATA FOR POST-HURRICANE CHARLEY BUILDING DAMAGE ASSESSMENT

The report series embraces MCEER's stated mission of pursuing *the discovery and development of new knowledge, tools and technologies that equip communities to become more disaster resilient in the face of earthquakes and other extreme events*. Accordingly, the research documented here is multi-hazard in nature, spanning international earthquake, flood and hurricane events. In all cases, the research is undertaken with the underlying goal of improving resilience, in particular the *rapidity* and *resourcefulness* of disaster response activities. Further, it is aimed at meeting stated user needs in the immediate aftermath of disasters, such as a rapid estimate of the number of collapsed/damaged structures, and the delineation of flood inundation zones.

These volumes represent a significant milestone in post-disaster damage assessment, constituting the culmination of seven years' research activities. During this time, we have witnessed the 'Coming of Age' of remote sensing technologies and analytical techniques within the disaster response arena. *Technology push* in the form of new sources of high-resolution imagery and increasingly advanced and analytical techniques has driven the development of new capabilities attuned to meet the needs of responders. This has been coupled with heightened *User pull* from sectors including the re-insurance industry, and with the onset of recent catastrophes such as hurricane Katrina, opportunities for operational implementation.

Research collaborations established by ImageCat, Inc. with multi-hazard researchers from the US, Italy and UK, underpin this report series. Through sharing and exchanging a wealth of experience and expertise, the teams of scientists and engineers have advanced the knowledge boundaries of remote sensing damage detection. Particular highlights include:

- ✓ The ability to rapidly count the number of collapsed buildings, where a building is treated as an ‘object’ within the digital image, rather than a group of pixels (Volume II in collaboration with the University of Bologna)
- ✓ The fusion of pre- and post-disaster imagery captured by different high resolution sensors to facilitate flexible damage mapping irrespective of which sensor passes first over the disaster zone (Volume III)
- ✓ The use of cloud-penetrating to assess flooding extent throughout storm-ridden areas (Volume IV in collaboration with University College London)
- ✓ HAZUS-compatible post-hurricane damage assessment based on remote sensing imagery, when access to the disaster zone is precluded (Volume V in collaboration with Texas Tech University).

In June 2006, MCEER launched its Remote Sensing Institute (RSI), which will *serve as a platform for developing and operationally implementing innovative multi-hazard techniques, strategies and products for rapidly assessing post-disaster impacts, modeling and quantifying the built environment, and monitoring recovery*. The RSI will continue to embrace fundamental and applied research activities to develop innovative new approaches to short- and long-term disaster management. Commercial products and services developed by MCEER researchers and available through RSI include: near real-time flood, surge, hurricane, earthquake and tsunami damage assessment through remote sensing-based damage scales and advanced image analysis techniques; and forensic GPS-registered damage assessment using the in-field VIEWS™ data collection and visualization system.

## ABSTRACT

Volume V of this five volume damage detection report series investigates the use of remote sensing and advanced field data collection technologies for improving response to extreme windstorm events, using perishable field data and supporting satellite imagery collected in the aftermath of Hurricanes Charley and Ivan.

It documents research conducted through a collaboration between MCEER researchers at ImageCat and the Wind Science and Engineering (WISE) Research Center at Texas Tech University. The work was funded in part by the US National Science Foundation through SGER grant 0454564 and the Natural Hazards Research and Applications Information Center, through their Quick response program.

First, advanced techniques for streamlining and accelerating in-data collection using the VIEWS™ field data collection and visualization system are described. These resulted in a georeferenced archive of more than 2000 photographs and 30 hours of video capturing perishable damage characteristics throughout affected neighborhoods.

Research using the VIEWS data and satellite imagery captured before and immediately after the hurricanes struck was undertaken in two major phases. First, qualitative characteristics of damage were explored through visual inspection of a large sample of structures sustaining different damage levels throughout Port Charlotte and Punta Gorda. The characteristics are used to develop a *remote sensing-based damage scale for wind*, which is HAZUS compatible.

Building on these qualitative findings, the second phase investigated quantitative characteristics of windstorm damage. Three different aspects of the post-hurricane scene are explored comprising: (a) building windstorm damage to buildings; (b) debris surrounding buildings; and (c) surrogate indicators of damage such as the presence of blue tarpaulins or roof covers. The quantitative analysis demonstrates that *damage profiles* serve to correlate damage metrics with actual damage states and form the critical link for making automated assessments of building damage based on changes in remote-sensing imagery. The study of debris remains a critical research emphasis for wind engineers. As debris is quickly removed from the scene following a windstorm, the detailed study of debris is extremely time-critical. Remote sensing provides a method for rapidly preserving the post-disaster scene including debris characteristics. The remote sensing-based damage scale developed from the qualitative analysis has the potential to be expanded to include debris measures and surrogate indices.

Overall, satellite remote-sensing imagery provides a means for systematically and uniformly assessing damage conditions across an entire windstorm-affected region. While remote sensing and advanced field survey techniques do not replace detailed forensic studies of building damage, they do provide complementary information about the overall damage conditions of buildings as well as the spatial distribution of perishable damage characteristics throughout a region.



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## SECTION 1 INTRODUCTION

Volume V of this five volume damage detection report series documents research conducted through a collaboration between MCEER researchers at ImageCat and the Wind Science and Engineering (WISE) Research Center at Texas Tech University (see also Adams et al., 2004c). The work was funded in part by the US National Science Foundation through SGER grant 0454564 and the Natural Hazards Research and Applications Information Center, through their Quick response program.

Hurricane Charley was the most severe windstorm to strike the United States since 1992, and the first Category 4 hurricane for which high-resolution before-and-after satellite imagery was available. Hurricane Ivan followed just one month later. Although Hurricane Ivan was a less-intense storm (Category 3) than Hurricane Charley, it provided opportunities to acquire before-and-after satellite images for additional types of buildings (especially metal warehouses and commercial/industrial buildings) in the Pensacola area, and to thereby augment the building inventory examined. It also provided examples of flood damage caused by an accompanying tidal surge.

This research modifies and applies post-disaster remote sensing damage assessment techniques developed for earthquake to windstorm hazard. As shown by the logistical framework diagram in table 1-1, the objective of this research is: *to investigate the use of remote sensing technology for improving response to extreme windstorm events, using perishable field data and supporting satellite imagery collected in the aftermath of Hurricanes Charley and Ivan.*

For more than 35 years, wind engineers have made detailed investigations of the failures of select buildings and other infrastructure elements following major windstorms (i.e., hurricanes, tornadoes, and severe thunderstorms). These investigations yield significant information about the interaction of severe winds with the built environment. Such knowledge is used to strengthen the *resilience* of the built environment against the effects of severe windstorms, by influencing building codes, improving mitigation measures, and identifying life-saving construction practices (such as shelters and safe rooms). The enhanced understanding of windstorm effects and the effective application of mitigation measures can ultimately help to reduce windstorms from major disasters to a mere perturbation in our daily lives.

“Traditional” building-by-building windstorm damage surveys, which correspond with Tier 3 of the Tiered Reconnaissance Framework (see Volume I figure 1-3), are generally unable to fully characterize the effect of windstorms, as limits on time, human resources, and access to affected areas have precluded the documenting of damage extent to all buildings within an affected region. Several barriers to conducting complete damage surveys have emerged (Womble et al., 2005), most notably:

**Table 1-1 Logistical Framework Diagram, Summarizing the Research Objectives and Methodological Approaches Used to Undertake Specific Activities for Post-Hurricane Damage Assessment Using Remote Sensing Imagery and VIEWS™ Data**

<b>OBJECTIVE</b>	<b>To investigate the use of remote sensing technology for improving response to extreme windstorm events using perishable field data and supporting satellite imagery collected in the aftermath of Hurricanes Charley and Ivan.</b>			
<b>ACTIVITY</b>	1. Deployment of satellite imagery and the VIEWS™ field-reconnaissance system to streamline the collection of perishable post-windstorm damage data	2. Develop a qualitative remote sensing-based residential building damage scale for hurricane	3. Investigate the quantitative characteristics of windstorm building damage in remote sensing imagery	4. Qualitatively and quantitatively investigate the use of surrogate indicators for detecting windstorm damage
<b>LEVEL OF TRS</b>	Tier 3 (per-building)			
<b>STUDY LOCALE</b>	Punta Gorda and Port Charlotte, Florida			
<b>GENERAL APPROACH</b>	After hurricanes Charley and Ivan deploy VIEWS™ field data collection system from moving vehicle and on-foot to capture georeferenced photographs and video of the post-disaster scene.	Assess visual characteristics of damage within remote sensing imagery. Develop demonstration damage scale for residential wood framed structures.	Using before and after satellite images for hurricane Charley, quantitatively assess spectral signatures of: a) collapsed buildings b) debris	Analyze satellite and aerial imagery to demonstrate the occurrence of (a) missile impacts; (b) internal pressurization (c) blue tarpaulins (temporary roof covers) and (d) roof cover replacement.
<b>DATASETS &amp; SOURCE</b>	Pre- and post-hurricane Quickbird and Landsat satellite imagery (see Table 2-1 through Table 2-2)	Pre- and post-hurricane Quickbird and NOAA imagery. VIEWS™ field data collected following hurricanes Charley and Ivan.	Pre- and post-hurricane Quickbird imagery.	Pre- and post-hurricane Quickbird imagery.
<b>HOW TO ADDRESS OBJECTIVE</b>	Acquire pre- and post-disaster satellite imagery of affected areas and load into VIEWS™. Deploy to hurricane affected communities and acquire VIEWS™ GPS-referenced video of the scene. Post-process VIEWS™ data in preparation for analytical activities.	Visually assess characteristics for a range of building damage states by comparing pre- and post-hurricane imagery. Confirm characteristics using VIEWS™ in-field footage. For residential structures, relate remote sensing damage scale to existing HAZUS engineering-oriented damage assessment scale.	Delineate building and roof facet outlines to mask out other ground surface features. Apply image processing techniques and classification to the before and after images to assess the spectral characteristics and distinguishing features of building collapse, and debris.	Visually inspect features in imagery to assess whether they have a distinctive spectral signature. Where present, develop initial spectral generalizations.
<b>OUTPUT/ PRODUCT</b>	Georeferenced VIEWS™ footage and digital photographs for damage caused by hurricanes Charley and Ivan.	Descriptive remote sensing-based damage scale for visual damage assessment to residential structures. Scale is HAZUS compatible.	Damage metrics summarizing the statistical characteristics of wind damage to the roofs of residential structures	Qualitative and/or quantitative assessment of indicator performance for windstorm damage detection

- The inability to document the damage states of all buildings in large areas both rapidly and in detail before cleanup efforts have commenced;
- The inability to examine and document the “pristine” spread of windborne debris, which is frequently moved before investigators can arrive at the damage scene;
- The inability to access damaged areas isolated by either law-enforcement agencies or by natural causes (e.g. fallen trees, washed-out roadways and bridges);
- The inability to rapidly screen large areas for relative levels of damage, for use in the strategic planning of statistically sampled damage surveys, especially in unfamiliar areas;
- A lack of consistent (uniform) damage measures stemming from natural biases found to exist between investigators in assigning damaging-state rankings to damaged structures.

Such barriers can lead to costly time delays in the assessment of damage across a wide area and in the strategic deployment of emergency-response personnel and supplies. ‘Perishable’ information is also lost that may underpin longer-term research leading to improved understanding of severe wind effects on the built environment.

The recent availability (since 1999) of commercial, high-resolution imaging satellites presents opportunities for the enhancement of post-windstorm studies through the *rapid* and *resourceful* collection of damage data immediately following severe windstorms. Rapid acquisition of post-windstorm satellite imagery assists in preserving the perishable disaster scene (containing important clues for understanding widespread damage, such as debris spread), provides a basis for area-wide (synoptic) damage assessment, and facilitates the resourceful assessment of damage (enabling effective allocation of emergency resources) before teams depart into the field. It is envisioned that remote sensing damage assessments will complement (rather than replace) more-detailed surveys by providing a rapid and resourceful initial perspective, especially when access is limited, as well as a holistic view of the damage situation throughout the affected area.

From an analytical standpoint, initial insights into the potential of high-resolution imagery for post-disaster damage assessment have been obtained through research conducted in the aftermath of the 2001 Bhuj, 2003 Boumerdes, and 2004 Bam earthquakes (see, Volume II and Volume III, also Eguchi et al., 2003; Adams, 2004; Adams et al., 2004a). Change detection studies comparing before-and-after images have successfully identified cases of extreme damage, and visual characteristics of building collapse (Adams et al., 2004a; Gusella et al., 2004, 2005). As windstorm damage exhibits markedly different visual signatures from earthquake damage, their qualitative characterization requires a separate and focused investigation.

In the case of windstorm damage, prior use of remote sensing imagery in the 1970s and 1980s (limited to aerial/helicopter photography) has shown promise for the location of damage areas. As chronicled by Womble (2005), this prior use has primarily been restricted to non-systematic visual inspections of aerial photos. Opportunities to explore the quantitative characterization of major windstorm damage using high-resolution digital satellite imagery have largely been absent since the 1999 availability of sub-meter satellite imagery.

Learning from post-earthquake studies, digital remote sensing images are well-suited to systematic and objective change-detection analysis, promising that assessments of windstorm-related building damage could ultimately be performed automatically by comparing pre- and post-storm imagery. Operationally, such automation offers the advantage of speed and consistency (i.e., the elimination of the natural biases of human investigators), but requires an in-depth understanding of the appearance of damage from qualitative and quantitative remote sensing perspectives, together with the correlation of numerical damage measures with actual field observations and their alignment with existing damage assessment protocols that are employed operationally (for example, HAZUS-Hurricane damage scales).

These initial steps have yet to be undertaken and as such form the basis of the research documented in this Volume. The research documented in this report represents the first event for which damage detection and field data capture techniques developed for earthquake have been applied to wind hazard. In particular, the transferability of qualitative and quantitative damage assessment approaches employed for earthquake is investigated for hurricane.

In addition to the direct observation of damage using remote sensing imagery, it also has a secondary role to play through its integration into field survey techniques. The VIEWS™ data collection and visualization system, which was originally developed for post-earthquake damage assessment (Adams et al., 2005) was also applied in a multi-hazard context, to collect a detailed record of perishable hurricane damage information to support subsequent research and validation activities. VIEWS™ represents an important technological advancement that has streamlined and accelerated the data acquisition and archiving process. Described fully in Section 1.2.2, VIEWS™ enables wind engineers to rapidly and accurately document damage information for up to 2,500 buildings per day, rather than the 20-100 structures that were previously covered using traditional clipboard techniques.

The following sections describe how the overarching research objective of investigating the use of remote sensing technology for improving response to extreme windstorm events, was achieved. Following initial data collection using the VIEWS™ field data collection and visualization system, the research was undertaken in two major phases. First, qualitative characteristics of damage were explored through visual inspection of a large sample of structures sustaining different damage levels throughout Port Charlotte and Punta Gorda. Building on these qualitative findings, the second phase investigated quantitative characteristics of windstorm damage. Three different aspects of the post-hurricane scene are explored in the following sections, comprising: (a) building windstorm damage to buildings; (b) debris surrounding buildings; and (c) surrogate indicators of damage such as the presence of blue tarpaulins (tarps). As such the following Sections address:

- (1) Deploying satellite imagery and the VIEWS™ field-reconnaissance system to streamline the collection of perishable post-windstorm damage data (Section 2)
- (2) A qualitative remote sensing-based building damage scale for hurricane (Section 3)
- (3) Quantitative building windstorm damage profiles (Section 4)
- (4) Mapping hurricane debris (Section 5)

(5) The performance of remote sensing as a surrogate damage indicator by detecting missile impacts, internal pressurization, blue tarpaulins and temporary roof covers and roof cover replacement (Section 6)

The logistical framework diagram in table 1-1 summarizes the methodological approaches employed for each of these activities.



## SECTION 2 POST-HURRICANE DATA COLLECTION

Data collection activities were conducted in the aftermath of Hurricane Charley through a collaboration between MCEER researchers at ImageCat and the WISE Center at Texas Tech University. The goals were to obtain:

- (1) A set of pre-and-post-hurricane satellite imagery
- (2) Ground-based field observations of windstorm damage to buildings corresponding with the satellite imagery.

This effort emphasizes rapid and widespread data collection to preserve the initial damage scene as much as possible. Streamlining and accelerating data collection activities were also deemed important, in order to the greatest extent possible, preserve an accurate record of the event for future research activities.

Since 1970, researchers have methodically examined and documented wind-induced building damage from an engineering perspective (Minor and Mehta, 1979; Minor et al. 1977, 1993). For instance, the Wind Science and Engineering Research Center of Texas Tech University (TTU) has documented damage to buildings from over 120 windstorms. Information collected through detailed, “connection-level” building damage surveys has enhanced the understanding of near-ground wind fields and the effects of severe winds on buildings, has led to the identification of building failure mechanisms, and has helped develop strategies to mitigate building damages and protect human life.

For such investigations, surveyors have noted for individual buildings the important parameters influencing both the wind loading and structural resistance, including: exposure, geometry, aerodynamic form, material strengths, connection details, and windborne-debris transport. Collection of such data has typically involved walking surveys, whereby key information is recorded through photographs, maps, and written or oral (transcribed) notations. Typically, 20 to 100 buildings per day can be surveyed by one team, depending on the level of detail. At this rate, it is generally not possible to preserve the damage scene and classify levels of damage to all buildings throughout a large affected region. Prior experiences with windstorm damage surveys therefore reveal the need for new, rapid, and unbiased methods of capturing and preserving windstorm damage information throughout an affected region.

The new generation of high-resolution earth-imaging satellites offer sub-meter image resolutions, sufficient to discern damage to individual buildings. To date, these imaging satellites have proven effective for the discernment of earthquake damage, and thus hold promise for windstorm damage detection. Hurricane Charley made landfall in southwest Florida on August 13, 2004 as a Category 4 hurricane, and was the most powerful hurricane to strike the United States since Hurricane Andrew (1992). Importantly, it provided the *first* opportunity to obtain before-and-after high-resolution satellite imagery of areas damaged by a major U.S. windstorm, and to thereby begin exploring the usefulness of remote sensing technology for post-hurricane damage assessment. Prior development of the advanced-technology-based VIEWS™ (Visualizing Impacts of Earthquakes with Satellites) system to meet field reconnaissance needs

(Adams et al., 2004b) also presented the first opportunity to collect a large volume of detailed ground-truthing data throughout affected area.

The following sections describe the collection of remote sensing imagery and corresponding VIEWS™-based ground-truthing damage data.

## **2.1 Satellite and Aerial Imagery**

On August 14, the day following Hurricane Charley's landfall in southwest Florida, the Quickbird imaging satellite acquired near-vertical 61-cm imagery of the southwest Florida coast, including a small, cloud-free portion of the heavily damaged community of Punta Gorda (figure 2-1). Collection of imagery the following day effectively preserved the post-disaster scene before most critical damage indicators (e.g., debris, roof damage, and fallen trees) could be removed, covered, or repaired. With such rapid and comprehensive satellite coverage, Hurricane Charley offered a prime occasion to investigate the use of remote sensing for post-windstorm disaster assessment. During a subsequent orbit on August 19, Quickbird acquired extensive imagery of the hurricane area, including a mostly cloud-free scene of Punta Gorda and neighboring Port Charlotte (figure 2-2), imaged at approximately 28° off-nadir (oblique) with a nominal spatial resolution of 75 cm.

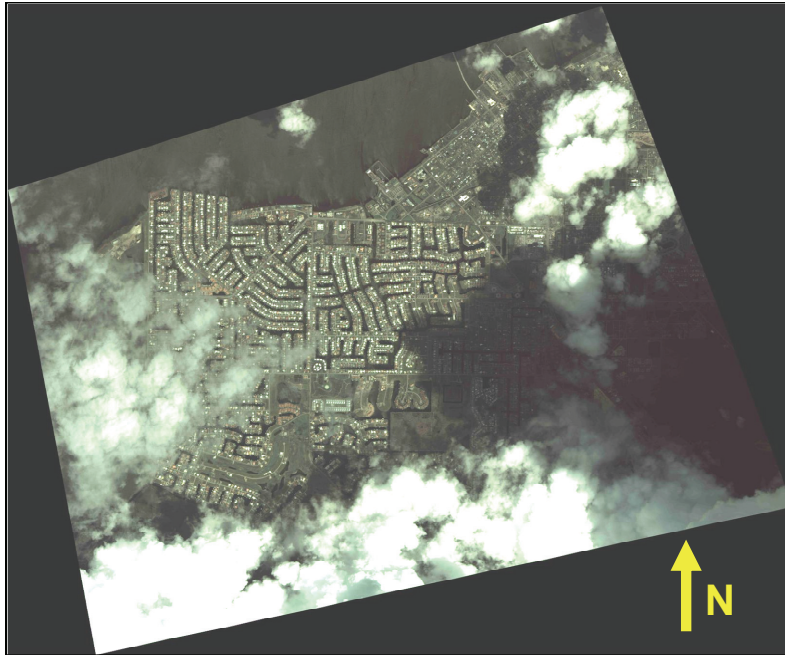
Pre-hurricane (archival) Quickbird images of the Punta Gorda–Port Charlotte area were also available from March 23, 2004. The March 23 and August 14 images served as a base map to guide the field reconnaissance conducted by investigators from the TTU WISE Research Center and ImageCat, Inc. The August 19 images provided additional imagery for use in the qualitative (Section 3) and quantitative (Section 4) analyses of damage characteristics.

The landfall of Hurricane Ivan near Gulf Shores, AL and Pensacola, FL on September 16, 2004 presented an opportunity to supplement the Hurricane Charley data. Quickbird imagery acquired on September 21, five days after landfall of Hurricane Ivan, provided an additional opportunity to collect remote sensing and field-based damage data.

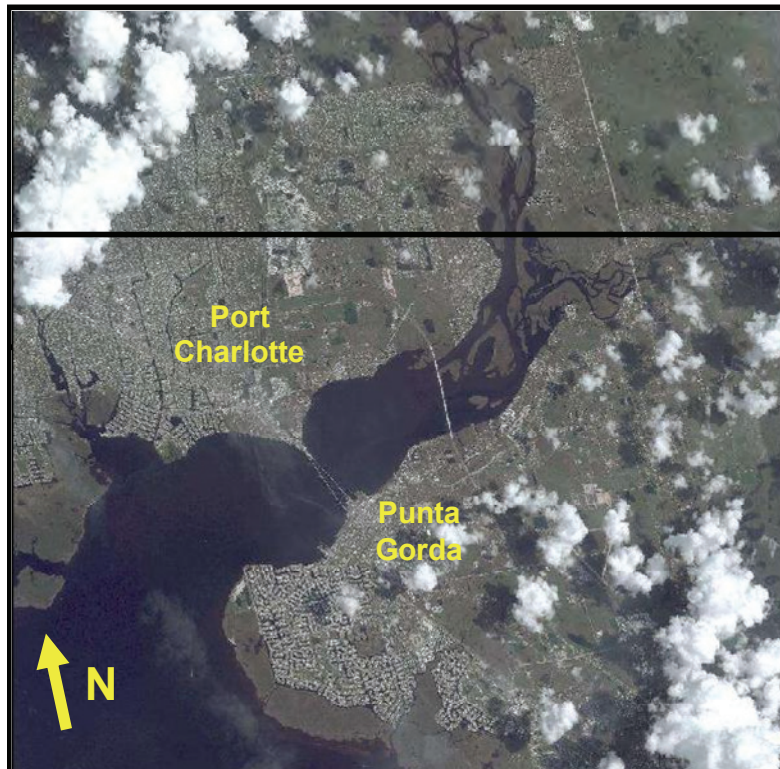
For use in this study, the research team purchased portions of the Quickbird scenes from March 23, August 14, and August 19, 2004 for the Punta Gorda–Port Charlotte area (table 2-2) as well as Quickbird scenes of the Pensacola area from March 12 and September 21 (table 2-3). This imagery underpinned the qualitative and quantitative evaluation of windstorm-damaged buildings (described in Sections 3 and 4).

DMK Associates acquired very-high-resolution digital imagery of a manufactured home park in Port Charlotte. Acquired on August 29, these images have a spatial resolution of approximately 5 cm, significantly finer than currently available satellite images. Through comparison with Quickbird satellite images of corresponding areas, these natural-color images (only blue-green-red bands) are helpful for evaluating the effectiveness of various image resolutions for detecting building damage states.





**Figure 2-1 Quickbird Multispectral Image of Punta Gorda, FL, Acquired One Day After Hurricane Charley. Image Date: August 14, 2004. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**



**Figure 2-2 Quickbird Satellite Images Covering Port Charlotte and Punta Gorda, FL, Acquired Six Days After Hurricane Charley. Image Date: August 19, 2004. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**

**Table 2-1 Quickbird Satellite Imagery Acquired for Hurricane Charley**

<b>Image Date</b>	<b>Coverage Areas</b>	<b>Off-Nadir Angle</b>	<b>Nominal Spatial Resolution of Imagery</b>
Mar. 23, 2004	Port Charlotte, FL	5°	61 cm
Mar. 23, 2004	Punta Gorda, FL	4°	61 cm
<i>Aug. 13, 2004</i>	<i>Hurricane Charley Landfall in Florida</i>		
Aug. 14, 2004	Punta Gorda, FL	6°	61 cm
Aug. 19, 2004	Port Charlotte, FL	28°	75 cm
Aug. 19, 2004	Punta Gorda, FL	28°	75 cm

**Table 2-2 Quickbird Satellite Imagery Acquired for Hurricane Ivan**

<b>Image Date</b>	<b>Coverage Areas</b>	<b>Off-Nadir Angle</b>	<b>Nominal Spatial Resolution of Imagery</b>
Mar. 12, 2004	Pensacola, FL	9°	62 cm
<i>Sept. 16, 2004</i>	<i>Hurricane Ivan Landfall in Alabama–Florida</i>		
Sept. 21, 2004	Pensacola, FL	30°	80 cm

NOAA’s Remote Sensing Division acquired some 2000 digital aerial images of coastal areas affected by Hurricane Ivan. This photo survey began September 17 (one day following landfall) and concluded on September 20. More than 1300 images were posted online on September 21 (NOAA, 2004). The NOAA images have a nominal spatial resolution of 37 cm, finer than currently available satellite images. Because of greater flexibility of the aerial data collection to proceed when weather (cloud) conditions were clear (as opposed to fixed-orbit satellite imaging), the NOAA aerial images were available prior to the Quickbird satellite images (acquisition of which was delayed by cloud cover during scheduled orbits in the damage area). For the present study, the post-storm NOAA aerial images provide a basis for qualitative comparison with a pre-storm Quickbird satellite image collected on March 12<sup>th</sup> 2004.

Womble (2005) provides a discussion of the relative merits of aerial and satellite imaging for rapid windstorm damage assessment. Aerial imaging systems can more easily acquire remote sensing imagery on-demand in rapidly changing weather conditions and, at present, offer finer spatial resolutions than satellite systems. Some present disadvantages of airborne systems such as employed by NOAA compared to present satellite systems include:

- Lack of pre-storm imagery for comparison with post-storm imagery;
- Lack of a near-infrared band for many aerial systems; and
- Lack of georeferencing information enabling the imagery to be directly imported to a GIS environment; and
- Additional time (several days) needed to provide the same coverage as a single satellite acquisition.

Accordingly, use of the Ivan remote sensing imagery was limited to the qualitative phase of this study. The quantitative analysis focused on hurricane Charley for which both pre- and post-event Quickbird imagery was acquired.

## **2.2 Collection of Field Data with the VIEWS™ System**

In the two weeks following Hurricane Charley, ground-level building damage data was collected in Punta Gorda and Port Charlotte by collaborative teams from ImageCat and the Wind Science and Engineering (WISE) Research Center of Texas Tech University (TTU). The objective of the field deployments (conducted August 18-21 and August 24-27) was to collect time-sensitive data describing the damage characteristics of buildings and infrastructure, which could later be used to identify visual (qualitative) signatures of damage distinguishable in the satellite imagery and to correlate quantitative damage measures with actual field observations.

The ground surveys targeted areas with:

- (1) synoptic coverage by both pre- and post-hurricane satellite imagery
- (2) a broad range of construction inventories,
- (3) a broad range of windstorm damage levels.

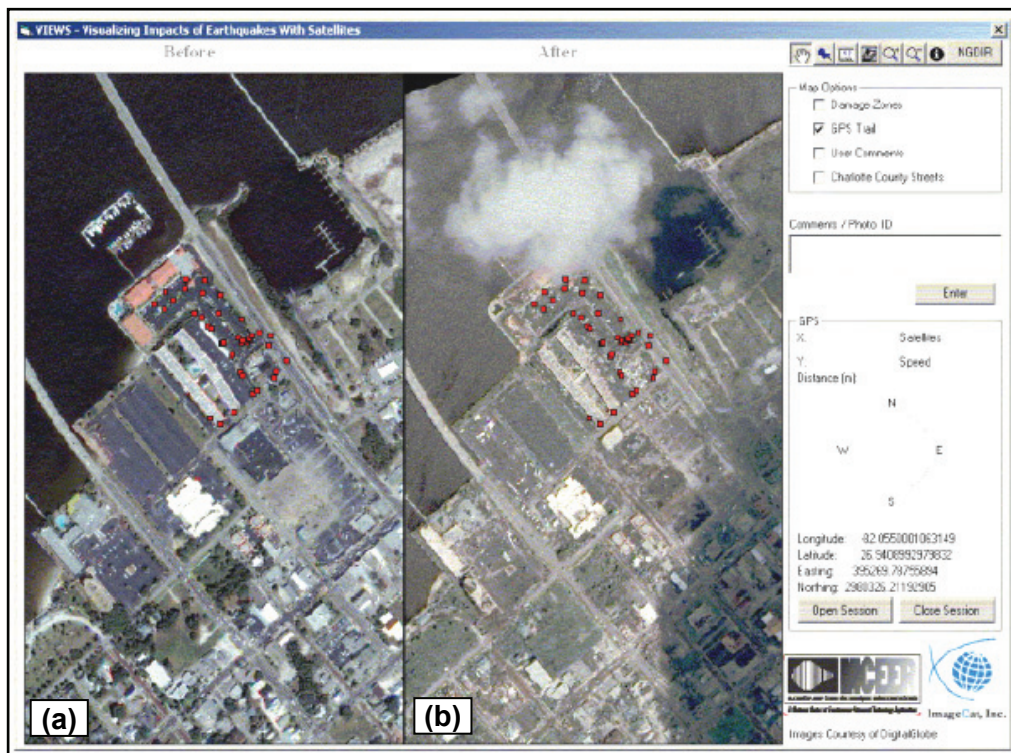
Subject buildings for the field study included residential-type wood-frame-roof buildings (including single-family homes and low-rise apartment buildings), commercial-industrial buildings, and manufactured homes in Punta Gorda and Port Charlotte. These data were supplemented with additional residential buildings and commercial-industrial buildings from the Pensacola area.

The field teams deployed an advanced technology-based field reconnaissance system to accelerate and streamline the collection of damage data across this broad area, and capture a permanent visual record of damage sustained by individual structures. VIEWS™ is a portable-computer-based system, developed by ImageCat, Inc., initially for earthquake field reconnaissance with funding from the National Science Foundation via the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The VIEWS™ system integrates before-and-after remote sensing imagery with real-time GPS readings and GIS (geographic information system) map layers, and operates in conjunction with digital still and video cameras (figure 2-3). The system can be deployed from a moving vehicle, on foot, or from an airplane, helicopter, or boat. In addition to the Collection mode, the VIEWS™ system also offers a Visualization mode for subsequent retrieval and study of the field data (figure 2-4). Given the large volume of building-performance data collected with the VIEWS™ survey, there is a tradeoff in terms of detail. The purpose of the VIEWS™ survey is to rapidly preserve a photographic record of the *overarching* damage scene, rather than forensic information about individual failures.

VIEWS™ was initially used for field reconnaissance following the December 2003 Bam (Iran) earthquake (Adams et al., 2004a). Hurricane Charley marked the first non-earthquake deployment of the system, which has subsequently been used for investigation of tsunami damage in southeastern Asia (Ghosh et al., 2005) and combined storm-surge, flooding, and wind

damage from Hurricane Katrina in Mississippi and Louisiana (Womble et al., 2006). Additional details of the VIEWS™ system are given by Adams et al. (2004b,c,d).

The VIEWS™ field survey for Hurricane Charley was conducted primarily from a high-profile moving vehicle driven at an optimal speed of about 10 mph (figure 2-5a). Detailed damage assessments were conducted on foot at approximately 15 sites, where the ground-survey teams devoted additional time to documenting damage and obtaining detailed photographic records (figure 2-5b). The reconnaissance teams focused on temporal changes (“damage”) in the before-and-after satellite images, together with FEMA damage maps to select a wide range of damage levels for the ground-truthing survey.



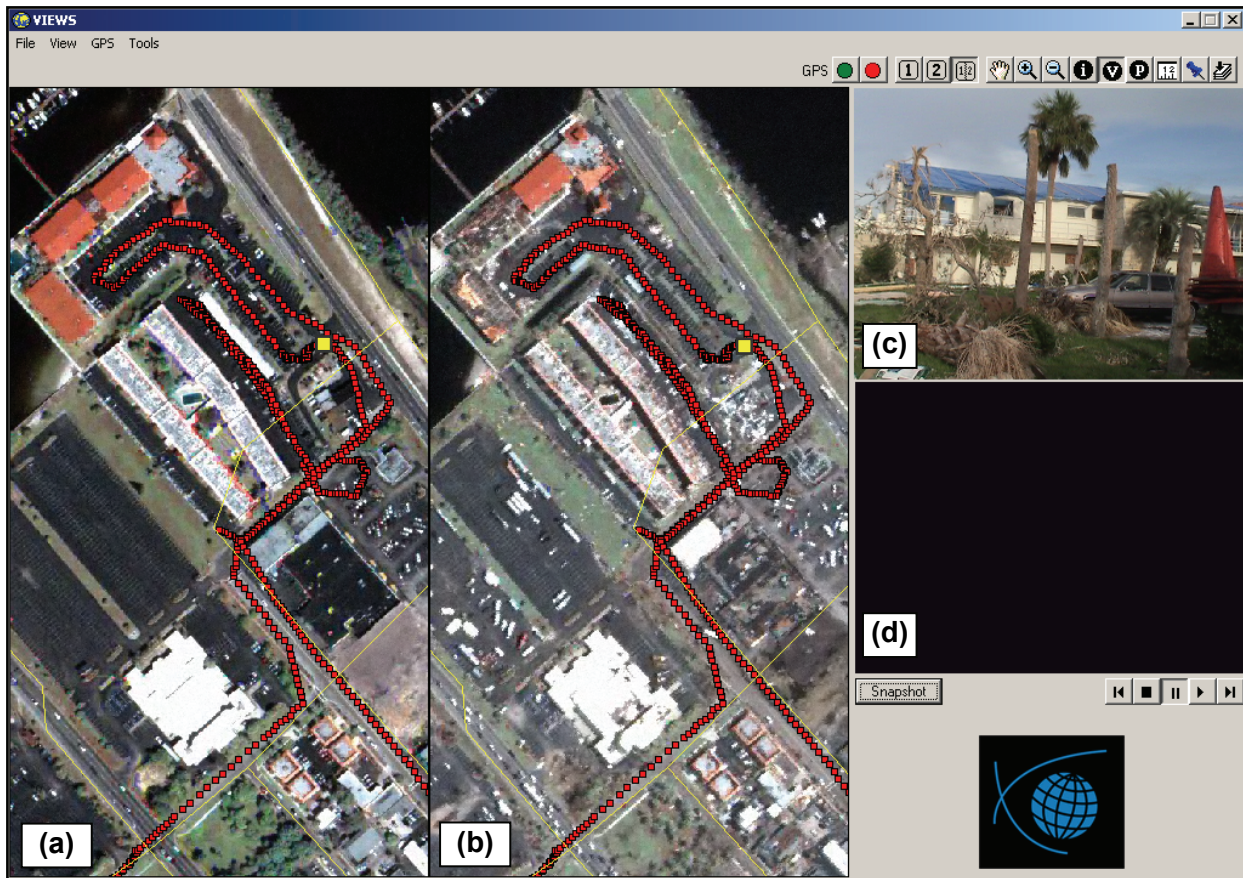
**Figure 2-3 VIEWS™ Software in Collection Mode During the Hurricane Charley Ground Survey. The Route Already Traversed is Shown by GPS Points (Red) Overlaid on (a) Pre-Storm and (b) Post-Storm Satellite Imagery. Credit: ImageCat, Inc. and DigitalGlobe, Inc. <www.digitalglobe.com>.**

Weather conditions and satellite orbits did not permit high-resolution imaging of the area devastated by Hurricane Ivan until five days after landfall. In this instance, the field team instead deployed with a baselayer of Landsat imagery (courtesy of NASA and USGS) and confirmed the intended satellite acquisition areas before the September 21-23 VIEWS™ collection, to help establish a focus area for the ground survey.

Whereas forensic ground surveys typically cover approximately 20–100 buildings per day, the four-day VIEWS™ deployment following hurricane Charley collected a vast archive of field data including 21 hours of digital video and 930 still photographs. This was achieved in a limited



timeframe, averaging approximately 2,500 buildings per day (figure 2-6). Following hurricane Ivan, 12 hours of georeferenced video and 1200 photographs were collected.

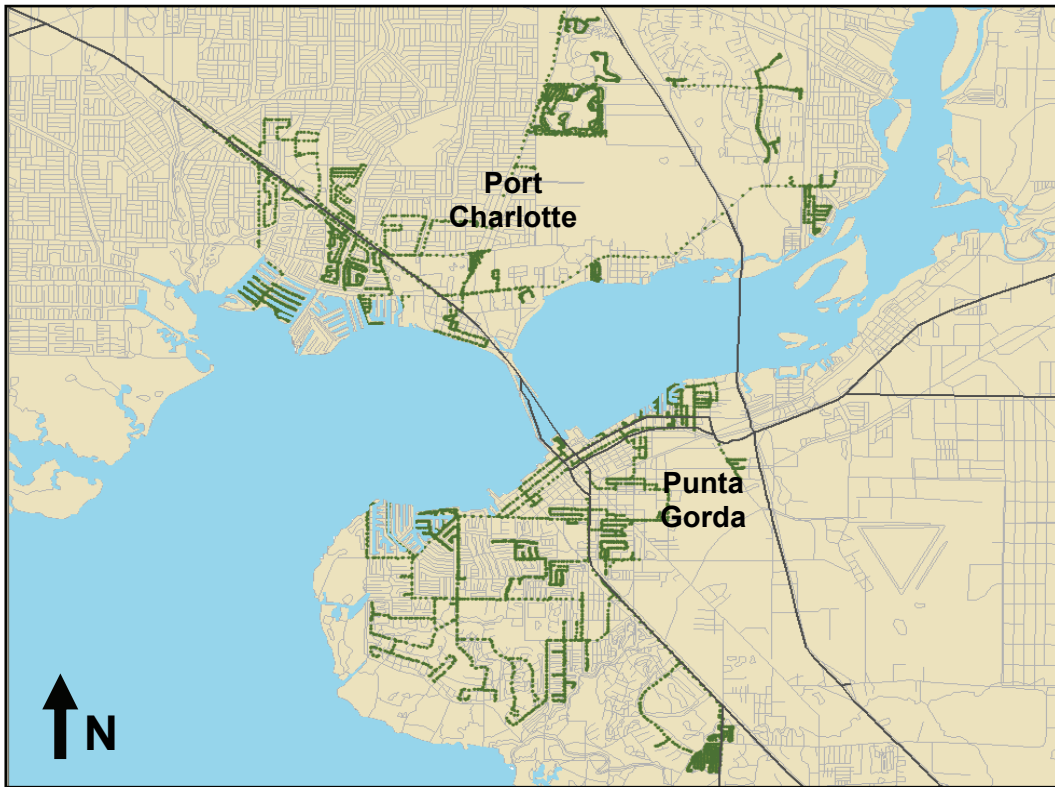


**Figure 2-4 VIEWS™ Software in Visualization Mode. The Route of the Ground Survey is Shown by GPS Points (Red) Overlaid on (a) Pre-Storm and (b) Post-Storm Satellite Imagery. Additional Windows Display (c) Selected Digital Photos and (d) Digital Video Clips Corresponding to the Selected GPS Point (Yellow). Credit: ImageCat and DigitalGlobe, Inc. [www.digitalglobe.com](http://www.digitalglobe.com)**

Figure 2-7 shows samples of the before-and-after Quickbird satellite imagery for hurricane Charley, along with corresponding ground-based images collected during the field survey. Visible changes between the pre- and post-storm images indicate several levels of damage including: roof-decking failure due to internal pressurization (figure 2-7c), loss of roof covering (figure 2-7d), scouring of roof gravel (figure 2-7e), loss of roof structure (figure 2-7f-g), and debris spread (figure 2-7h). Further details of this field investigation are described by Adams et al. (2004c).

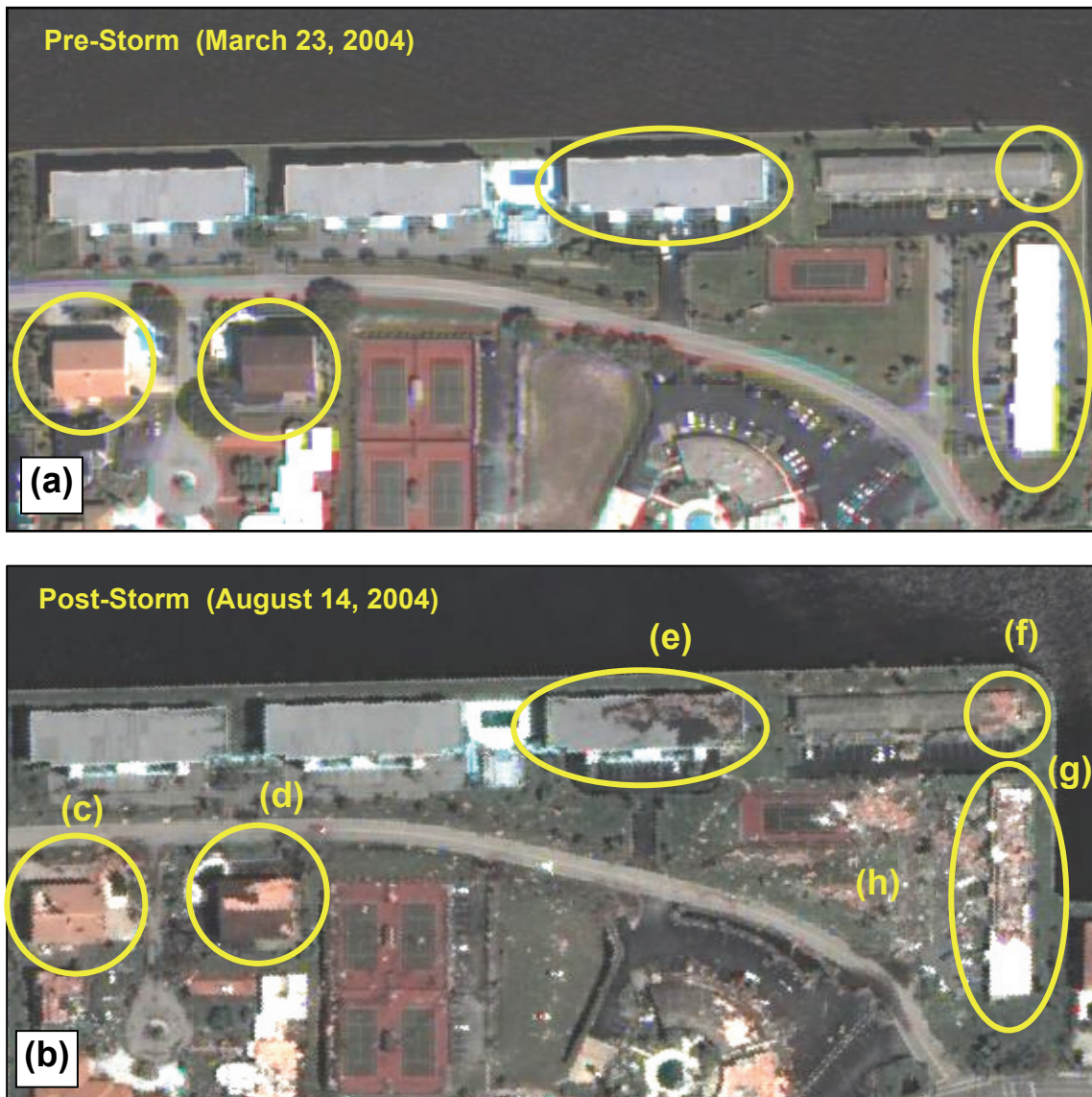


**Figure 2-5 Deployment of the VIEWS™ Field Reconnaissance System in Hurricane Charley for Field Data Collection (a) from Moving Vehicle and (b) on Foot**



**Figure 2-6 Locations of Ground Survey for Hurricane Charley in Punta Gorda and Port Charlotte**





**Figure 2-7 Comparison of Pre- and Post Storm Building Conditions in Satellite Images, Along with Ground-Survey Photos. These Quickbird 61-cm Natural-Color Satellite Images of Punta Gorda, FL were Acquired (a) Five Months Prior to Hurricane Charley (March 23, 2004) and (b) One Day After Hurricane Charley (August 14, 2004). From Womble (2005). Base Imagery from DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>**



**Figure 2-7 (continued). Comparison of Pre- and Post Storm Building Conditions in Satellite Images, Along with Ground-Survey Photos. Ground-Survey Photos Demonstrate: (c) Partial Roof Deck Failure (Combined Internal And External Pressures); (d) Shingles Partially Removed but Deck Intact; (e) Scoured Roof Gravel (Not Visible from Ground Survey); (f) Partial Roof Structure Failure; (g) Severe Roof Structure Failure; (h) Windborne Debris from Nearby Building Deposited on a Parking Lot, Roadway, and Tennis Court. From Womble (2005).**



## SECTION 3

### A REMOTE SENSING-BASED WIND DAMAGE SCALE

The goal of this initial qualitative evaluation is to develop *remote sensing-based wind damage scales* through characterizing building damage information within high-resolution imagery. Qualitative characterization of building damage is important both for the development of visual inspection techniques (for assistance with an overall ground-survey methodology), and also as an initial step towards the development (“training”) of computer algorithms to perform statistically based assessments of windstorm damage. In the development of such algorithms, it is important to understand how various levels of windstorm damage appear qualitatively – first to the human cognitive system and then to digital image analysis techniques which strive to model human cognition.

This activity focuses on the systematic manual examination of remote sensing images and field data to assess which levels of damage can be determined using remote sensing images for various construction categories. The development of a Remote Sensing Damage Scale (RSDS) for wind is fundamental to the characterization of hurricane damage when a rapid geographically extensive overview is required, or ground access is limited. The present study demonstrates a damage scale for residential structures. The development of equivalent scales for commercial and industrial buildings is a focus for future research.

#### 3.1 Methodology

For the qualitative characterization of building damage, structures within the Hurricane Charley and Ivan study areas were classified according to their roofing system (type of roof construction) rather than the HAZUS-based approach utilizing occupancy class. The alternate classification was chosen because it was hypothesized that post-storm conditions of roofing components are most distinguishable via overhead remote sensing, with occupancy playing a less crucial role for remote sensing-based damage assessment. The type of roofing construction is also closely linked to the damage mechanisms of buildings, and thus roofs of a similar construction type tend to exhibit similar visible damage characteristics. The library of damage data collected for Hurricanes Charley and Ivan primarily consists of low-rise buildings (typically 5 stories or less in height) and enables a qualitative analysis of four building types:

For the purposes of this study, the available building damage data were separated into the following four categories:

1. Metal Warehouses (with a single-ply metal surface covering the structural frame)
2. Flat Built-Up Roofs (typically flat or low-sloped roofs with multiple layers of insulating and weatherproofing materials; chiefly used for commercial and industrial purposes, but also for multi-family residential)
3. Manufactured Housing (specifically mobile homes, typically with wood-frame roofs with metal or asphalt coverings)

4. Wood-Frame Roofs (including single-family homes, many apartment buildings, and a few small offices buildings – specifically those buildings constructed with wood-frame roofs covered with wood decking and either tile or asphalt shingles).

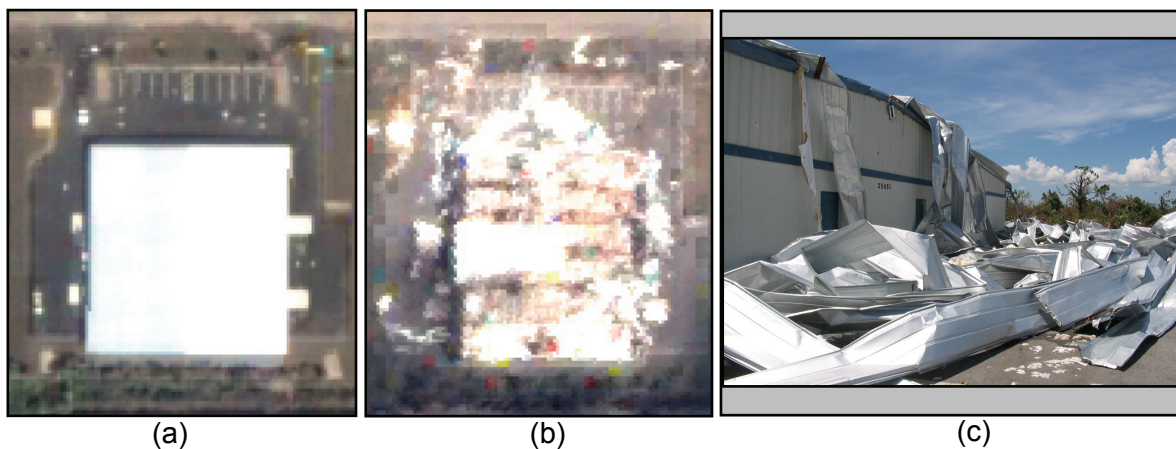
Within each roofing category, corresponding remote sensing and ground-based images are examined for buildings exhibiting various levels of damage, ranging from minor damage to complete destruction. From these visual analyses, the damage was characterized by its appearance in the remote sensing imagery. Recognizing that image spatial resolutions are subject to improvement as the technologies are refined, investigation of the effectiveness of various image resolutions for the discernment of windstorm damage was also conducted for available data.

### 3.2 Damage Characteristics

#### 3.2.1 Metal Warehouses

Of all construction inventories, the metal warehouse building is among the simplest to assess a windstorm damage state via remote sensing, due to characteristically large roof areas, simple roof geometry, uniform roof texture, and distinct spectral characteristics of the metallic roof surfaces, all of which promote accurate delineation of the roof and detection of damage at even relatively coarse spatial resolutions. The HAZUS-Hurricane model identifies four key elements for assigning damage states to a metal building: *Entry/Overhead Door Failures*, *Metal Roof Deck Failures*, *Metal Wall Siding Failures*, and *Missile Impacts on Walls*.

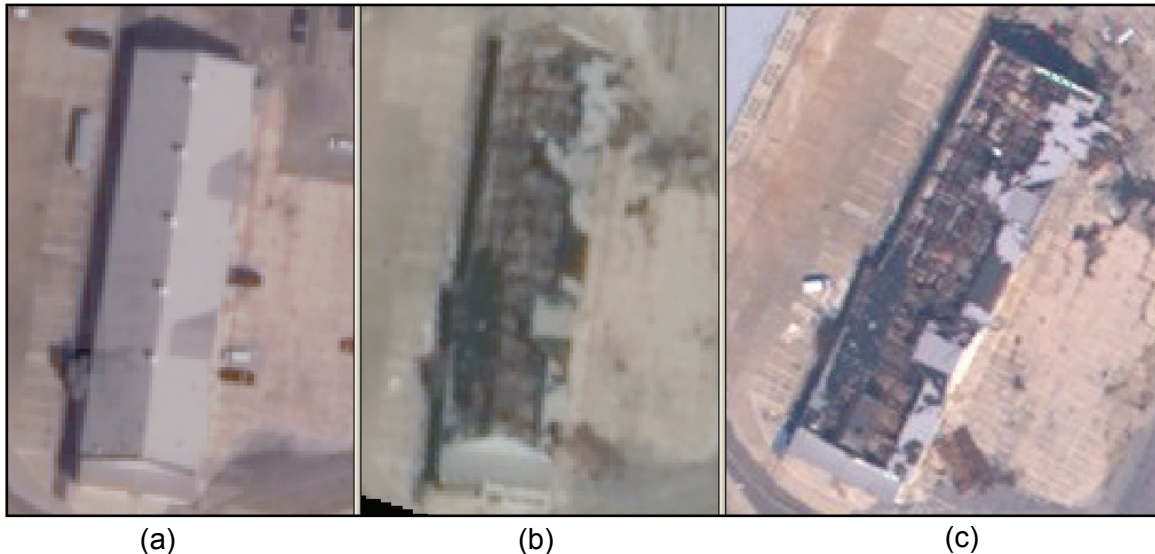
As shown in figures 3-1 and 3-2, the presence of roof damage is clearly visible in the post-storm images as a change in overall shape or as the appearance patches with different colors and/or textures. The Quickbird images of 61- to 80-cm resolution shown in figures 3-1 and 3-2 are adequate to detect damage (i.e., the absence of metal panels from the post-hurricane imagery). Higher-resolution images (e.g., 37-cm NOAA aerial images) can better resolve the underlying structural supports in areas where cladding pieces have been removed (figure 3-2c).



**Figure 3-1 Example of Wind Damage to Metal Warehouse Building: (a) Pre-Storm Quickbird 61-cm Imagery (Mar. 23, 2004); (b) Post-Storm Quickbird 61-cm Imagery (Aug. 14, 2004); (c) Ground-Truthing Photo. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**

### 3.2.2 Flat Built-Up Roofs

A large class of commercial and industrial buildings employs nominally flat roof geometry (slopes of  $10^\circ$  or less), covered by either a built-up-roofing (BUR) cover consisting of multiple plies of roofing felt, adhesive, and (often) a gravel topping (FEMA, 2003). Because these roofs are low-sloped, often the roof condition cannot be assessed from the ground-survey alone, and remote sensing imagery becomes critical for the detection of such damage. Figures 3-3 and 3-4 present satellite images of windstorm damage to flat-roof buildings; shown for each building are before-and-after Quickbird images, along with higher-resolution NOAA aerial images.



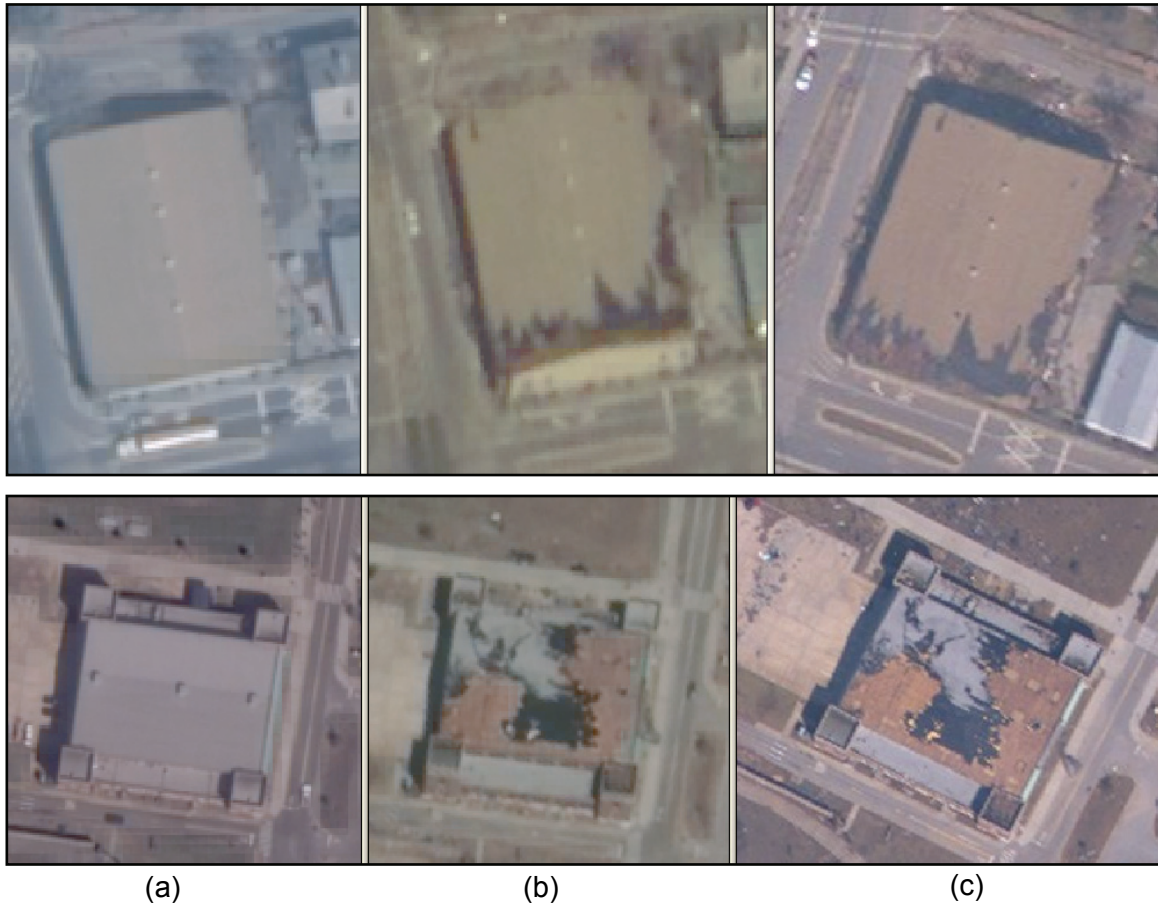
**Figure 3-2 Example of Windstorm Damage to Metal Warehouse Building: (a) Pre-Storm Quickbird 61-cm Imagery (Mar. 12, 2004); (b) Post-Storm Quickbird 80-cm Imagery (Sept. 21, 2004); (c) NOAA 37-cm Aerial Imagery (Sept. 2004). Credits: DigitalGlobe, Inc. and NOAA.**

For industrial buildings, the HAZUS-Hurricane model identifies six damage indicators used in assessing the overall building damage level: *Roof Cover Failure*, *Door Failures*, *Roof Deck Failures*, *Missile Impacts on Walls*, *Joist Failures*, and *Wall Failures*. Changes in BUR roofs can be detected via remote sensing imagery and image-analysis routines. As shown in figure 3-3, the *presence* of damage is clearly visible in the post-storm images as a change in overall shape and texture and by the appearance of multi-colored streaks. The assignment of a damage state for BUR roof covers is more complicated than for single-ply metal-panel warehouse roofs, due to the multiple layers which can be difficult to discern from holes in the roof decking.

The satellite images of 61-75 cm resolution shown in figures 3-3 and 3-4 are adequate to detect the presence of damage for the BUR and SPM roofs. Higher-resolution images (e.g., 37-cm NOAA aerial images) can further help to distinguish the level of damage (whether or not the roof decking is still in place). The removal of roof decking is generally clear in areas where the supporting structure is visible figure 3-4c.

From a remote sensing perspective, commercial–industrial flat roofs are typically quite uniform in texture, color, and illumination in the pre-storm condition. Middle levels of damage are generally characterized by the appearance of multi-colored spots or streaks where various layers

of the roof covering have been removed (or where gravel has been scattered), exposing additional layers of BUR, roof decking, or a building cavity beneath. These damage areas typically have a ragged and streaked form due to scattered tearing of the roof coverings from their mechanical or adhesive fastenings and in this way can typically be distinguished from the blocked appearance of damage to metal-panel roofs.



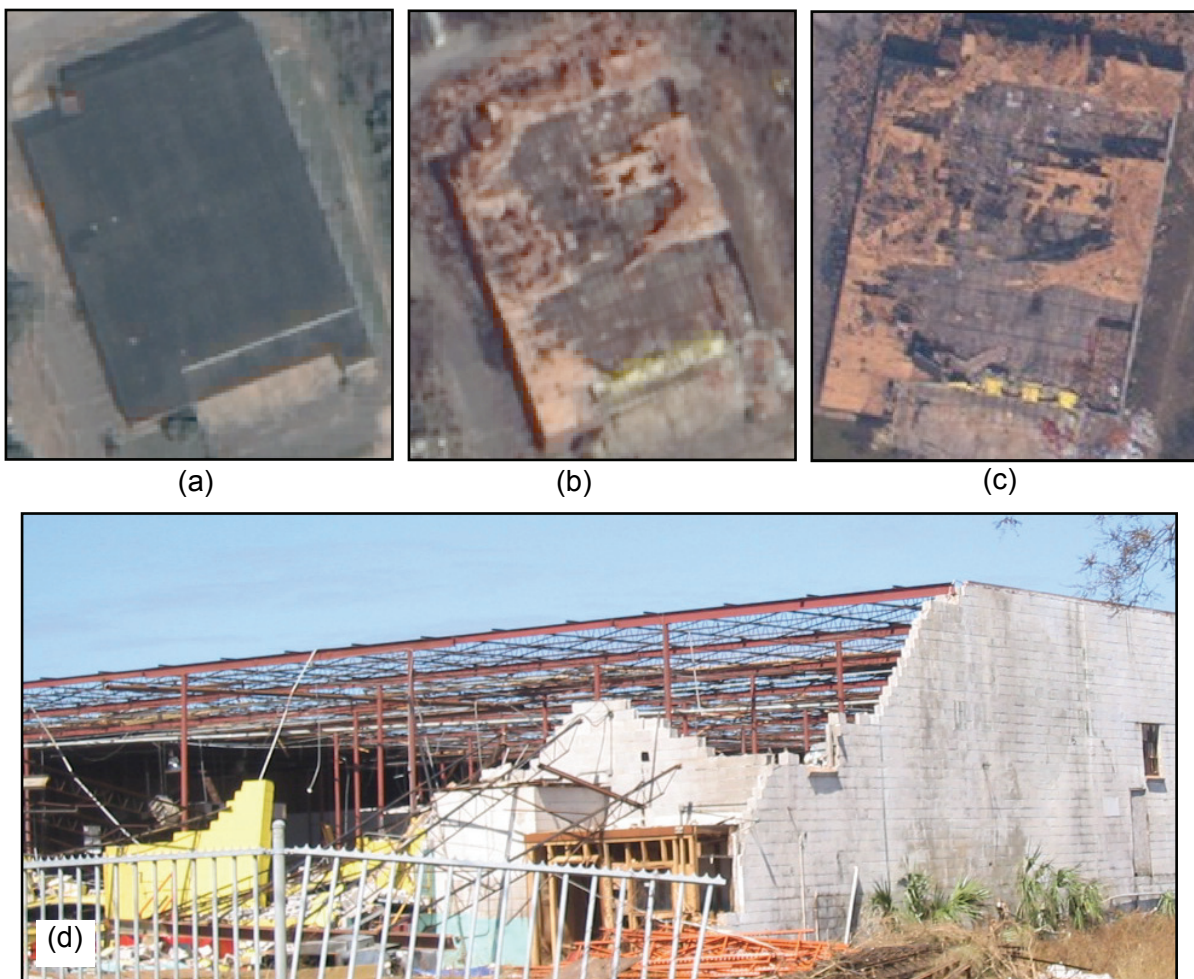
**Figure 3-3 Examples of Wind Damage to Flat-Roof Commercial and Industrial Buildings, Pensacola, FL: (a) Pre-Storm Quickbird 62-cm Imagery (Mar. 12, 2004); (b) Post-Storm Quickbird 80-cm Imagery (Sept. 21, 2004); (c) Post-Storm NOAA Aerial 37-cm Imagery (Sept. 2004). Credits: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)> and NOAA.**

### 3.2.3 Manufactured Housing

From a remote sensing perspective, the relatively simple (rectangular) form, flat or low-slope roofs, and bright metallic roof coverings of manufactured homes (figure 3-5) make them particularly suitable for delineation by digital-image-analysis algorithms. Most damage states for manufactured homes, described by (FEMA, 2003) are visible from overhead, including *Roof Cover Damage*, *Roof Sheathing Failures*, and *Foundation to Ground Anchor Failures* (resulting in sliding or overturning). *Roof to Wall* and/or *Wall to Foundation Connection Failures* may also be visible, depending on the spatial resolution of the imagery.



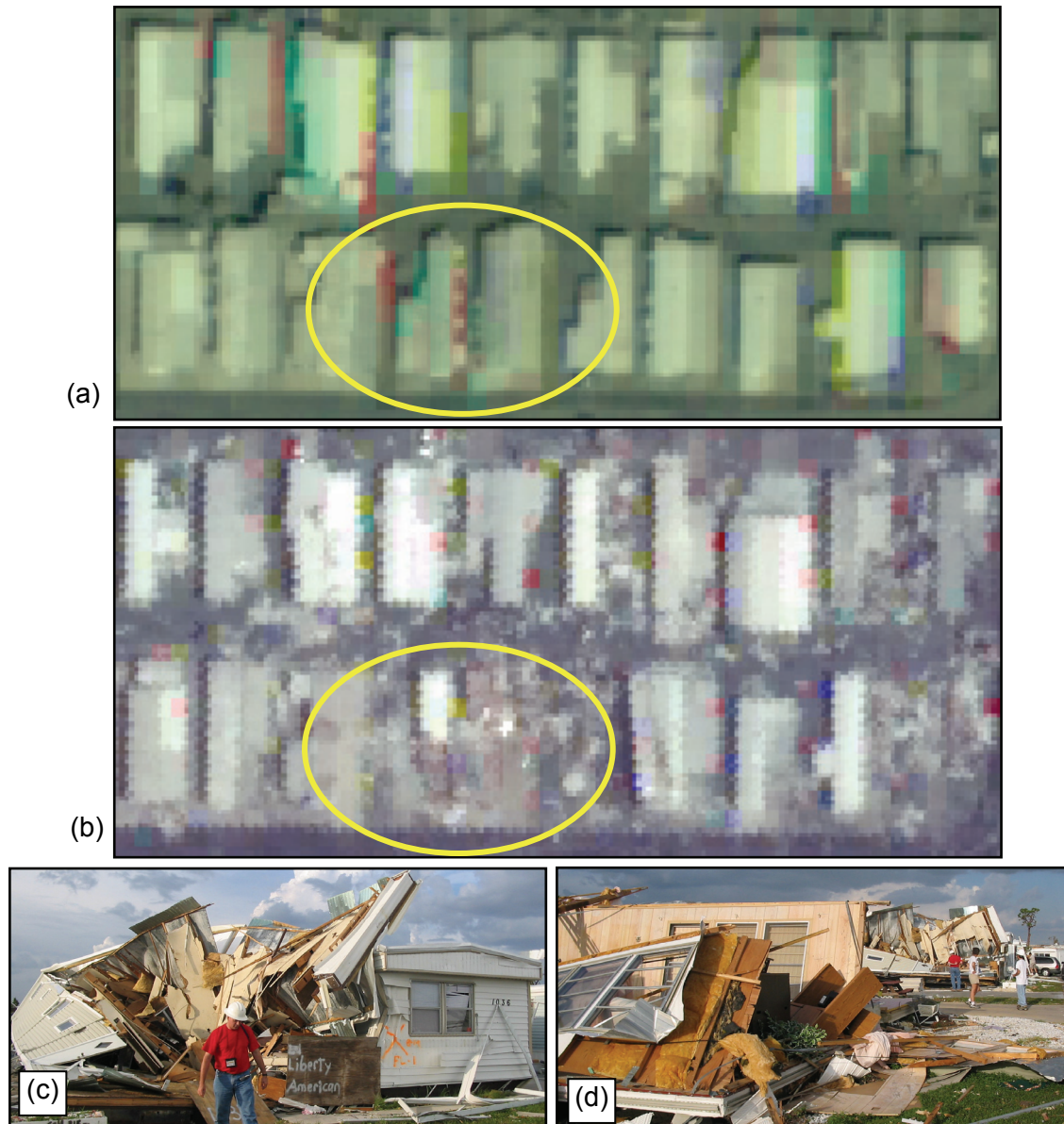
The extent to which damage levels for manufactured houses can be determined via remote sensing imagery is highly dependent on the spatial resolution, primarily because of the relatively small size of manufactured homes. Figure 3-6 compares Quickbird satellite images (61-cm pre-storm and 75-cm post-storm) with high-resolution (5-cm) digital aerial images obtained courtesy of DMK Associates. While the satellite images reveal that the roofs have undergone changes (sustained damage), it is difficult to resolve the extent of the damage with the satellite imagery alone. The 5-cm aerial images are adequate to resolve the individual damage states. The ability to accurately assess damage states via satellite imagery is thus expected to improve as satellite-image resolutions improve. The satellite images can clearly detect whether or not a manufactured home is still in place (figure 3-5), but may have difficulty determining if a unit has slipped off its supporting blocks.



**Figure 3-4 Example of Wind Damage to Flat-Roof Commercial/Industrial Building: (a) Pre-Storm Quickbird 62-cm Imagery (Mar. 12, 2004); (b) Post-Storm Quickbird 80-cm Imagery (Sept. 21, 2004); (c) Post-Storm NOAA Aerial 37-cm Imagery (Sept. 2004); (d) Ground-Survey Photo. Credits: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)> and NOAA.**

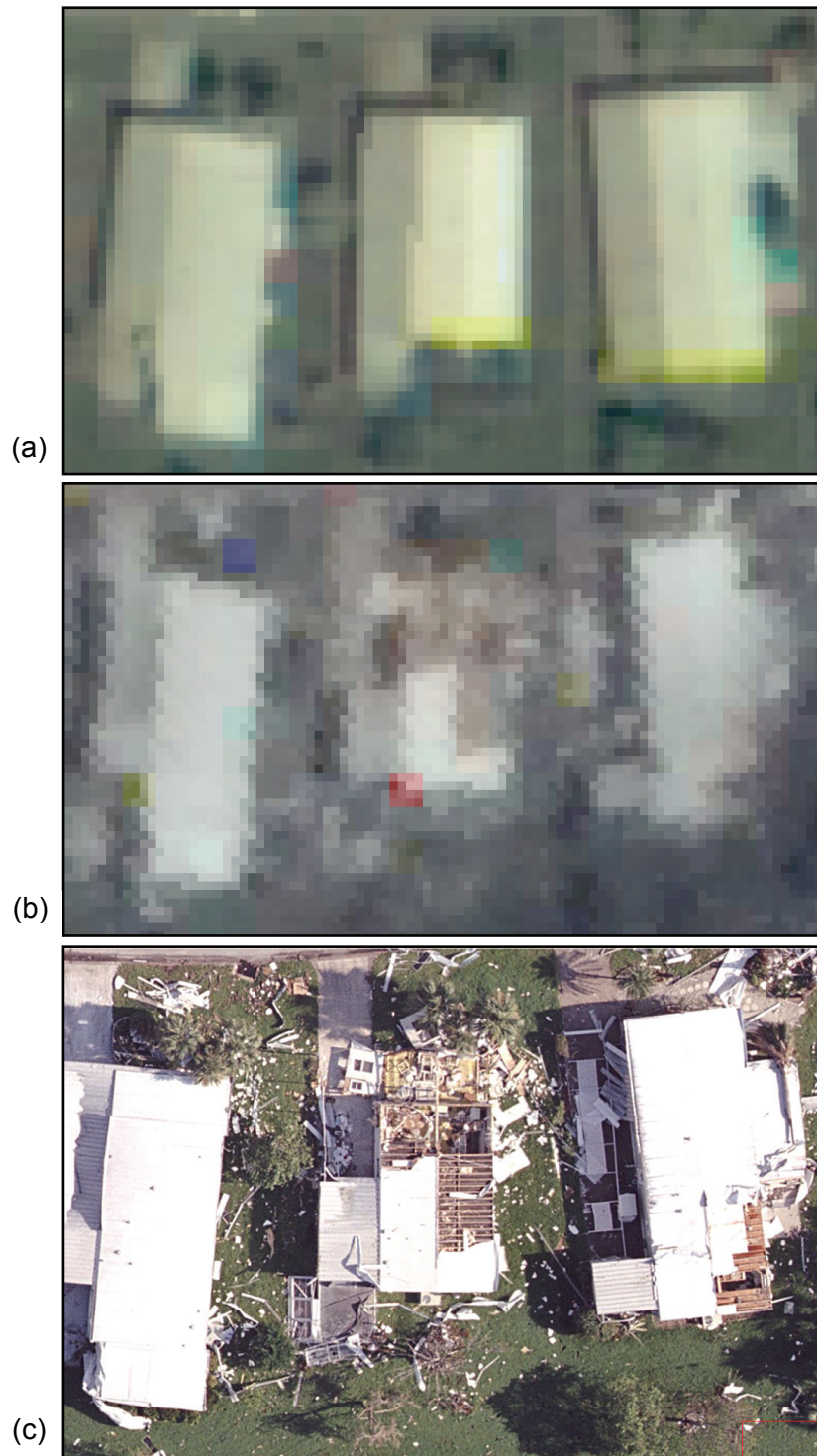
The metal awnings, carports, and enclosed patios that are commonly attached to manufactured homes typically sustain far greater damage than the manufactured homes themselves (figure 3-

7). Metal components of these attachments also tend to be a source of debris. Because these attachments appear similar to the main manufactured-home units themselves in remote sensing images (e.g., metallic and rectangular), they can be difficult to distinguish and can therefore lead to false indications of damage to the main structure.

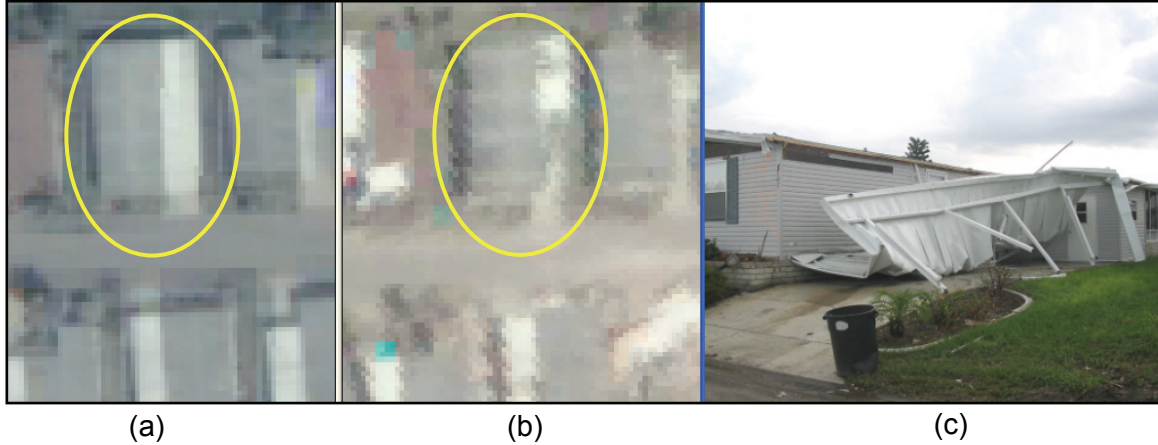


**Figure 3-5 Examples of Windstorm Damage to Manufactured Homes: (a) Pre-storm Quickbird 61-cm Imagery (Mar. 23, 2004); (b) Post-storm Quickbird 75-cm Imagery (Aug. 19, 2004); (c,d) Ground-Truthing Photos. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**





**Figure 3-6 Comparison of Satellite and Digital Aerial Images Showing Windstorm Damage to Manufactured Homes: (a) Pre-Storm Quickbird 61-cm Imagery (Mar. 23, 2004); (b) Post-Storm Quickbird 75-cm Imagery (Aug. 19, 2004); (c) Digital Aerial 5-cm Imagery (Aug. 29, 2004). Credits: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)> and DMK Associates.**



**Figure 3-7 Examples of Windstorm Damage To Manufactured Homes. Damage to Attached Structures (Carpports and Covered Patios) is Often More Severe than the Main Structure. (a) Pre-Storm Quickbird 61-cm Imagery (Mar. 23, 2004); (b) Post-Storm Quickbird 75-cm Imagery (Aug. 19, 2004); (c) Ground-Truthing Photo. Credit: DigitalGlobe, Inc. <www.digitalglobe.com>.**

### 3.2.4 Wood-Frame (“Residential”) Roofs

This building category is characterized by a wood-framing system (rafters or trusses) clad with wood-plank or plywood decking and typically covered with either asphalt shingles (underlain by a sheet of roofing felt), wood shingles (also underlain with felt), or clay tiles (attached by mechanical fasteners or by setting in mortar). The exterior walls may be either wood or masonry construction, as this does not directly influence the remote sensing appearance of the roof. This building category may nominally be referred to as “residential,” though it encompasses most single-family houses, many apartment buildings, some motels, and a few commercial and office buildings. This roof style is generally the most geometrically complex – combining a variety of styles (hip and gable), slopes, and setbacks and resulting in roofs with numerous facets. Such roofs are generally much smaller than metal-warehouse roofs and commercial–industrial flat roofs, but are typically larger than manufactured-home roofs.

Because of the large number of structural and cladding components constituting their roofs, residential buildings provide a particularly broad range of damage states, most of which are detectable with remote sensing technologies. Figure 3-8 demonstrates a variety of residential-building damage states as viewed in Quickbird satellite images, along with corresponding ground-survey photos. The HAZUS-Hurricane Damage States for Residential Construction, reproduced here as table 3-1, include six different physical indicators of damage; three of the six are directly visible via remote sensing technology: *Roof Cover Failure*, *Roof Deck Failure*, and *Roof Structure Failure*. *Wall Structure Failure* is implied by rubble immediately adjacent to the building. The presence of debris (detectable by remote sensing) signals the possibility of *Missile Impacts on Walls*, while, conversely, the absence of debris immediately following a windstorm decreases the likelihood that missile impacts have occurred. *Window and Door Failures* are accompanied by an increased pressurization of the building interior.



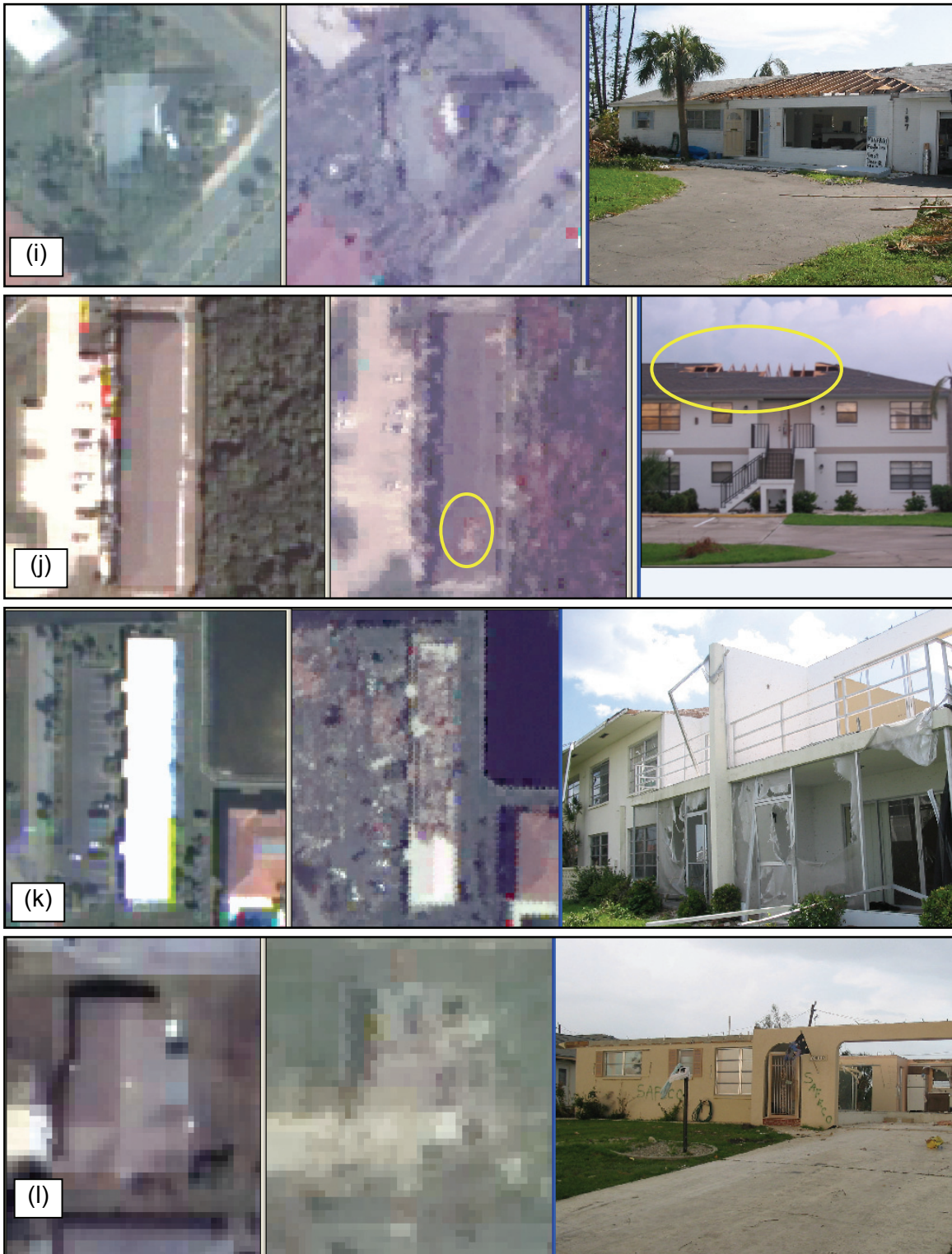


**Figure 3-8 Examples of Windstorm Damage to Residential Buildings: Pre- and Post-Storm Quickbird Satellite Images and Ground-Truthing Photos. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**



**Figure 3-8 (continued) Examples of Windstorm Damage to Residential Buildings: Pre- and Post-Storm Quickbird Satellite Images and Ground-Truthing Photos. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**





**Figure 3-8 (continued) Examples of Windstorm Damage to Residential Buildings: Pre- and Post-Storm Quickbird Satellite Images and Ground-Truthing Photos. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**

**Table 3-1 HAZUS-Hurricane Damage States for Residential Construction**

Damage State	Qualitative Damage Description	Roof Cover Failure	Window & Door Failures	Roof Deck	Missile Impacts on Walls	Roof Structure Failure	Wall Structure Failure
0	<b>No Damage or Very Minor Damage</b> 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	<b>Minor Damage</b> 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	<b>Moderate Damage</b> 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	<b>Severe Damage</b> 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	<b>Destruction</b> 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

**NOTES:**

If any one of the conditions in the shaded cells of a given row is true, the building is placed in that damage state. Source: FEMA (2003).

Examination of the before-and-after satellite images shows that minor levels of damage (e.g., HAZUS Damage State 0) (figure 3-8b) are not readily distinguishable and can even be lost in the “noise” (pixelation) of a roof edge. Intermediate levels of damage, such as HAZUS-Hurricane Damage States 1 and 2, are generally visible via satellite images because of the characteristic removal of the roof covering surface. Even very small areas of damage are readily detected if the damage produces a high contrast with the surrounding area (figure 3-8c). Larger areas of damage are likewise visible because of changes in contrast or texture (figure 3-8e). The particular appearance of additional scenarios of damage conditions is discussed at length by Womble (2005).

Large areas of removed shingles or tile can be difficult to detect *visually* at present satellite-image resolutions if such damage does not result in a high contrast (figure 3-8f). Multispectral

material-detection methods (discussed in Section 4) can be helpful in distinguishing such damage.

Loss of roof decking, common to HAZUS-Hurricane Residential Damage Levels 2 and 3 is also generally apparent in the post-storm images. Small areas of removed decking at the roof edge may be hard to distinguish with present satellite resolutions, as such damage can be confused with the roof-edge delineation (figure 3-8g). Larger areas of removed decking are typically clearly visible in post-storm imagery due to changes in brightness, texture, color, and/or shape (figure 3-8h,i,j), as well as the appearance of new edges (boundaries between materials). The appearance of the roof structure (e.g., rafters and trusses) in the post-storm imagery also confirms the loss of roof cladding, though finer spatial resolutions are typically necessary to distinguish these structural elements.

Damage to the roof structure (HAZUS Damage Level 4), is visible in optical remote sensing imagery because of the inherent change in roof appearance as well as the presence of nearby windborne debris (figure 3-8k,l), which often has come from the building roof itself. From a remote sensing perspective, partial damage or complete removal of the roof structure is typically accompanied by a loss of distinct edges for the roof (the disappearance of edges), and sometimes by an increase in texture.

The smaller size and increased geometric complexity of residential buildings, compared to metal warehouses and flat-roof commercial–industrial buildings, makes the assessment of individual damage states more challenging. On a percent-area basis, damage to the much larger buildings is easier to detect at resolutions offered by present satellite-imaging systems (61+ cm) because of the sheer size (number of pixels) involved. With the 61-cm+ resolution of the Quickbird images (e.g., figure 3-9a,b) it is often difficult to discern small areas of damage; higher-resolution images (such as the 5-cm digital aerial image of figure 3-8c) greatly assist in resolving small areas of damage, as well as in delineating the edges of roof slopes.

### **3.3 Remote Sensing Damage Scale**

The above sections have identified important characteristics of before-and-after optical images for the identification of wind damage from a remote sensing perspective. Temporal changes that help determine damage states for buildings can be described in terms of edges, textures, colors, and brightness (see Section.4). Visually-based remote sensing damage scales can therefore be devised for various building categories; such scales are a first step towards the development of algorithms for the automated assessment of windstorm damage.

Using the suite of remote sensing damage observations discussed above, the Remote Sensing Damage Scale in table 3-2 has been developed for residential (wood-frame-roof) buildings, focusing specifically on elements that are critical for detection and assessment of damage at discrete levels using remote sensing measures. The RSDS generally corresponds with the damage levels for residential buildings employed by the HAZUS-Hurricane model. Table 3-3 shows the correspondence between the HAZUS and remote sensing damage scales.



**Figure 3-9 Comparison of Spatial Resolutions for Images of Residential Buildings (Hurricane Charley): (a) Pre-Storm 61-cm Quickbird Images; (b) Post-Storm 75-cm Quickbird Images; (c) Post-Storm 5-cm Digital Aerial Images. Credits: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)> and DMK Associates.**

The Remote Sensing Damage Scale represents the major output from the qualitative analysis of the damage characteristics recorded by thousands of buildings within the satellite imagery and field observations for Hurricane Charley. Womble (2005) provides in-depth discussion of the image-processing technologies considered in the development of the RSDS, and describes the respective damage scales in further detail. The RSDS is used to classify damage at the individual roof-facet level (rather than the full-roof level) for the quantitative analysis of damaged buildings. These damage states are further utilized in Section 4 for the quantitative demonstration of changes in building roofs.



**Table 3-2 Remote Sensing Damage Scale for Residential Construction. From Womble (2005).**




<b>Damage Rating</b>	<b>Most Severe Physical Damage</b>	<b>Remote sensing Appearance</b>
<b>RS-A</b>	No Apparent Damage	<ul style="list-style-type: none"> <li>• No significant change in texture, color, or edges.</li> <li>• Edges are well-defined and linear.</li> <li>• Roof texture is uniform.</li> <li>• Larger area of roof (and more external edges) may be visible than in pre-storm imagery if overhanging vegetation has been removed.</li> <li>• No change in roof-surface elevation.</li> </ul>
<b>RS-B</b>	Shingles/tiles removed, leaving decking exposed	<ul style="list-style-type: none"> <li>• Nonlinear, internal edges appear (new material boundary with difference in spectral or textural measures).</li> <li>• Newly visible material (decking) gives strong spectral return.</li> <li>• Original outside roof edges are still intact.</li> <li>• No change in roof-surface elevation.</li> </ul>
<b>RS-C</b>	Decking removed, leaving roof structure exposed	<ul style="list-style-type: none"> <li>• Nonlinear, internal edges appear (new material boundaries with difference in spectral or textural measures).</li> <li>• Holes in roof (roof cavity) may not give strong spectral return.</li> <li>• Original outside edges usually intact.</li> <li>• Change in roof-surface elevation.</li> <li>• Debris typically present nearby.</li> </ul>
<b>RS-D</b>	Roof structure collapsed or removed. Walls may have collapsed.	<ul style="list-style-type: none"> <li>• Original roof edges are not intact.</li> <li>• Texture and uniformity may or may not experience significant changes.</li> <li>• Change in roof-surface elevation.</li> <li>• Debris typically present nearby.</li> </ul>

**NOTES:**

Damage states apply to individual roof facets, rather than the full roof.

For all damage states, the presence of debris can indicate damage to walls, doors, and windows, which is not directly visible via vertical, optical imagery. Independent verification is necessary for such damage.

**Table 3-3 Comparison of HAZUS-Hurricane and Remote-Sensing Residential Building Damage Scales for a Full Range of Wind Damage States**

HAZUS-Hurricane Model Damage States	Remote-Sensing Damage States	Examples of Damage Observed in Field Studies
0	RS-A	
1	RS-B	
2-3 (combined)	RS-C	
4	RS-D	



## SECTION 4 WINDSTORM DAMAGE PROFILES

The goal of this activity is to investigate the quantitative characteristics of hurricane building damage. Building on results obtained from the qualitative evaluation (Section 3), quantitative characterization of building damage correlates change-detection measures obtained through image processing temporal (pre-and-post-storm) image pairs, with the actual damage states. This demonstration constructs *windstorm damage profiles* for the residential or “wood-frame-roof” construction class by computing quantitative measures of changes sustained by image objects and comparing these change measures to actual damage states noted in the field survey. This semi-automated quantitative methodology developed here serves as an overall demonstration of procedures that through subsequent research could be refined and automated to accomplish the rapid and systematic detection of building damage using multitemporal remote sensing data.

### 4.1 Methodology

Spectral characteristics of damage were investigated. Characteristic spectral reflectance curves can be used to identify different materials within an optical image. Figure 4-1 shows spectral reflectance curves for materials commonly found in urban scenes, superimposed with Quickbird multispectral bands (blue, green, red, and near-infrared: B-G-R-NIR). While the human eye perceives light in the visible range (nominally B-G-R bands), optical satellite systems such as Quickbird measure reflected light in bands of the visible range as well as the NIR range. Vegetation and common construction materials also have important distinguishing spectral characteristics in the NIR wavelengths, and thus satellite systems can perceive spectral information beyond what the human eye can.

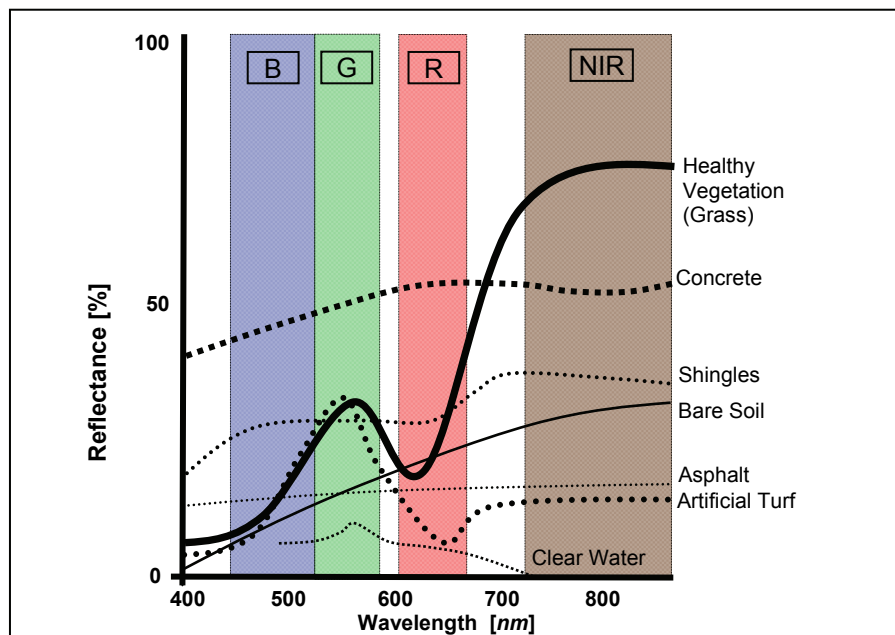
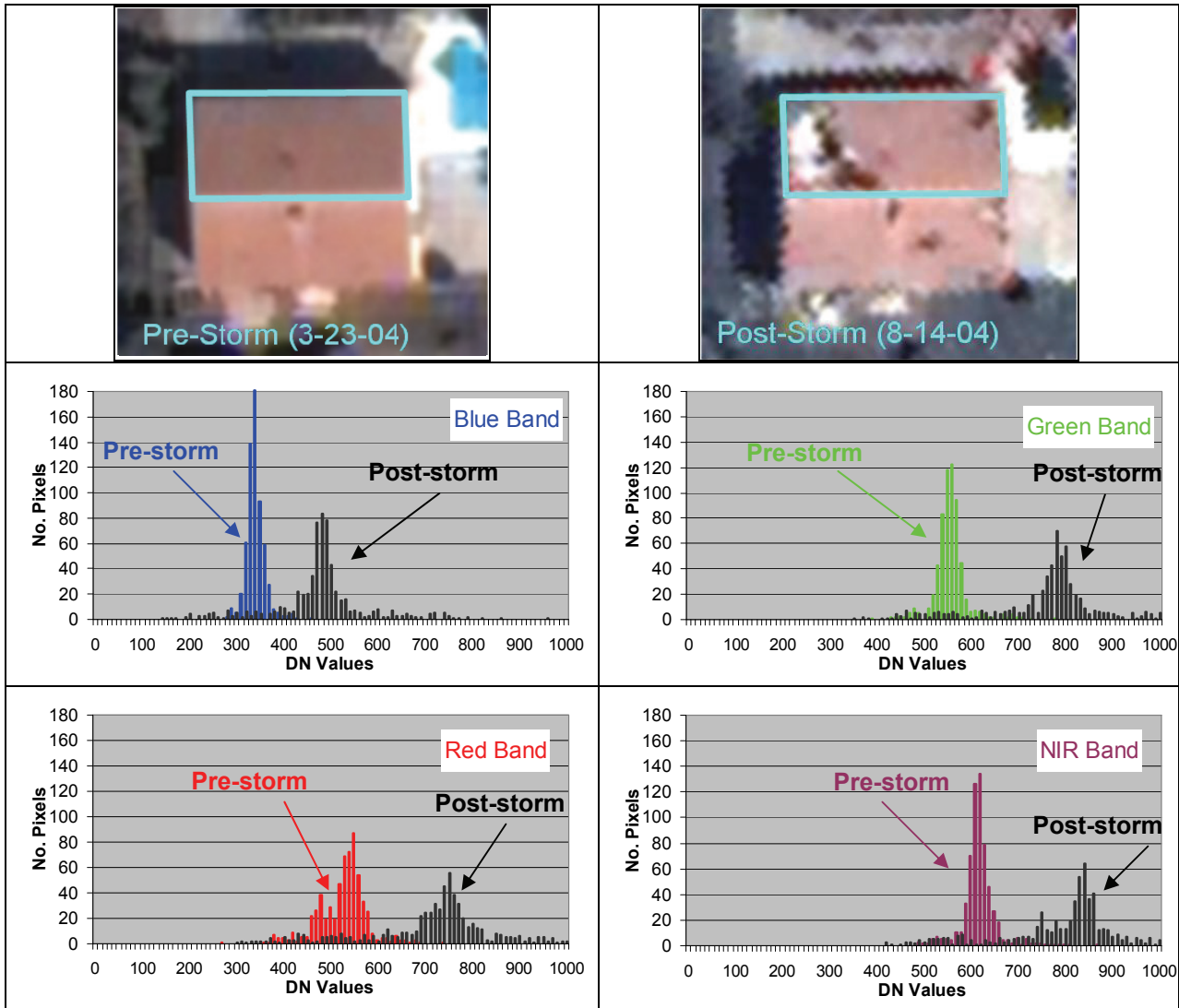


Figure 4-1 Spectral Reflectance Curves for Selected Materials in the Visible Wave-Lengths (400-700 nm) and Near-Infrared Wavelengths (700-900 nm), Superimposed with Quickbird Multispectral Bands (B-G-R-NIR). Adapted from Jensen (2000).

Physical changes in buildings can be illustrated quantitatively with the use of object histograms formed from the pixels constituting an object, such as an individual roof slope (facet). For example, pre- and post-storm histograms for a single roof facet are shown in figure 4-2. For each multispectral band, the pre- and post-storm histograms are superimposed on the same plot. These histograms help to demonstrate the appearance of damage to the roof facet from a remote sensing perspective. Shifts in mean values are attributed to both illumination differences (shadows) and to physical changes. Changes in dispersion (e.g., standard deviation or variance) are attributed to physical changes in the roof facet and are interpreted as damage.



**Figure 4-2 Sample Comparison of Pre- and Post-Storm Object Histograms for a Single Roof Slope (Facet). In Each Spectral Band, the Histograms Experience a Shift in Mean Values Due to Physical Change as Well as Illumination Differences, and a Change in Standard Deviation Due to Physical Changes. Credit: DigitalGlobe, Inc. <www.digitalglobe.com> and Womble (2005).**

For this exploratory study, a 9-step processing methodology was developed to quantify building damage. Steps in this procedure are discussed in detail by Womble (2005) and briefly outlined below.

*(1) Pre-processing operations* to prepare the temporal image pairs for comparison (including pan-sharpening, geometric registration, mosaicking, and subsetting of images). Womble (2005) further discusses issues complicating the illumination normalization of individual building-roof surfaces and presents a justification for the omission of illumination-normalization procedures and for the comparison of individual roof facets, rather than full roof assemblies. Womble (2005) explores complications encountered with the automated delineation of before-and-after roof-facet pairs from remote sensing images acquired at different look angles and spatial resolutions, and presents a methodology for the manual delineation of roof facets.

*(2) Creation of a GIS database* for use in storing and retrieving building information, and for use in the delineation of individual roof-facet objects (see Step 5 below). The before-and-after satellite images serve as the base layers for the GIS database.

*(3) Selection of building samples* for comparison of remote sensing signatures and ground-truthing observations. Using the ground-based VIEWS™ survey data, a set of “residential” (wood-frame-roof) buildings was selected, representing a full range of damage levels. The number of sample buildings falling into various damage states defined by the HAZUS-Hurricane scale for residential buildings (table 3-1) is as follows:

- HAZUS Damage State 0      5 buildings (no damage);
- HAZUS Damage State 1    16 buildings;
- HAZUS Damage State 2    16 buildings;
- HAZUS Damage State 3    21 buildings; and
- HAZUS Damage State 4    19 buildings.

*(4) Classification of damage using the Remote sensing Damage Scale.* As discussed by Womble (2005), this classification is made at the individual roof-facet level, rather than for full roof assemblies, and is based on VIEWS™ field observations. The use of facet-level analysis is prompted by inherent difficulties in normalizing the illumination of the various slopes of multi-faceted roofs among temporal image pairs. Due largely to building aerodynamics, a particular building may have some roof facets which are not damaged, as well as roof facets that are severely damaged; thus the facet-level damage determination also aids in more accurately describing damage to buildings. Each roof facet constitutes an object (group of pixels) and forms the basic element for temporal change-detection comparisons. Classification of the roof facets according to the Remote sensing Damage Scale of table 3-2 resulted in the following distribution:

- Damage State RS-A 94 facets;
- Damage State RS-B 76 facets;
- Damage State RS-C 48 facets;
- Damage State RS-D 49 facets.

(5) Delineation of individual objects (roof facets) for the selected buildings in the before-and-after images. This delineation was accomplished through the use of GIS shapefiles traced atop the satellite imagery in the GIS database created in Step 2 above. To achieve the best possible set of roof-facet objects, manual delineation of roof-facet objects was employed for this study. Automated delineation of roof facets is an important element of the eventual development of fully automated damage classification procedures, but still requires significant development.

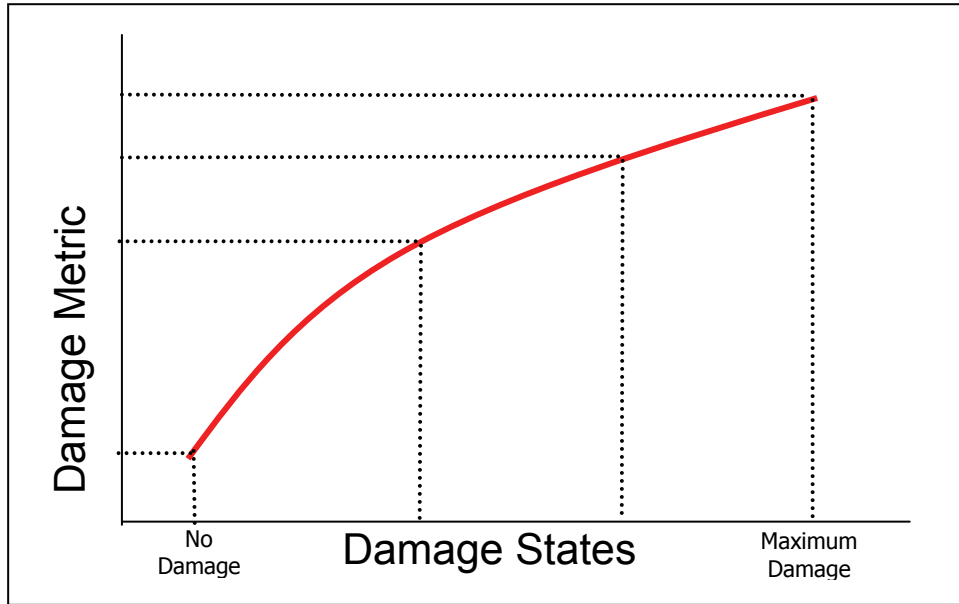
(6) Extraction of the DN values for each roof-facet object. Using ENVI™ image-analysis software and the shapefiles defined in Step 5 above, sets of numeric DN values were extracted from the Quickbird images for each roof-facet object and for each of the four multispectral bands. Resulting from this step are eight sets of DN values, each representing the reflectance values of the pixels constituting each roof-facet object in four spectral bands and in two images (before-and-after).

(7) Computation of object-level statistical measures from the sets of multispectral DN values in the before-and-after satellite images, using customized MatLab computer codes. These object-level statistics include *standard deviation*, *variance*, *average deviation*, *skewness*, *uniformity*, and *entropy* of the pixel DN values constituting each object.

(8) Formulation of “damage metrics” for each roof-facet object. Damage metrics result from comparison (e.g., difference or ratio) of the pre- and post-storm statistical measures for each roof-facet object, which quantitatively represent temporal changes (damage) in each object. The various damage metrics examined for this research include:

- standard deviation ratio
- standard deviation difference
- variance ratio
- skewness difference
- average deviation ratio
- uniformity ratio
- uniformity difference
- entropy ratio
- entropy difference

(9) Formulation of “windstorm damage profiles”, which are plots of damage metrics (Step 8) versus actual damage states (from Step 4). Figure 4-3 shows an idealized windstorm damage profile. The windstorm damage profiles define the correlation between remote sensing measures of damage to roof facets and the actual damage states of those roof facets. The windstorm damage profiles form the basis for the automated assessment of windstorm damage based on characteristic changes in remote sensing imagery. The concept of damage profiles for earthquake damage on a regional basis is presented in Eguchi et al. (2003). The present research has modified the use of the damage profiles for windstorm damage, applied to individual building roof facets rather than geographic areas.



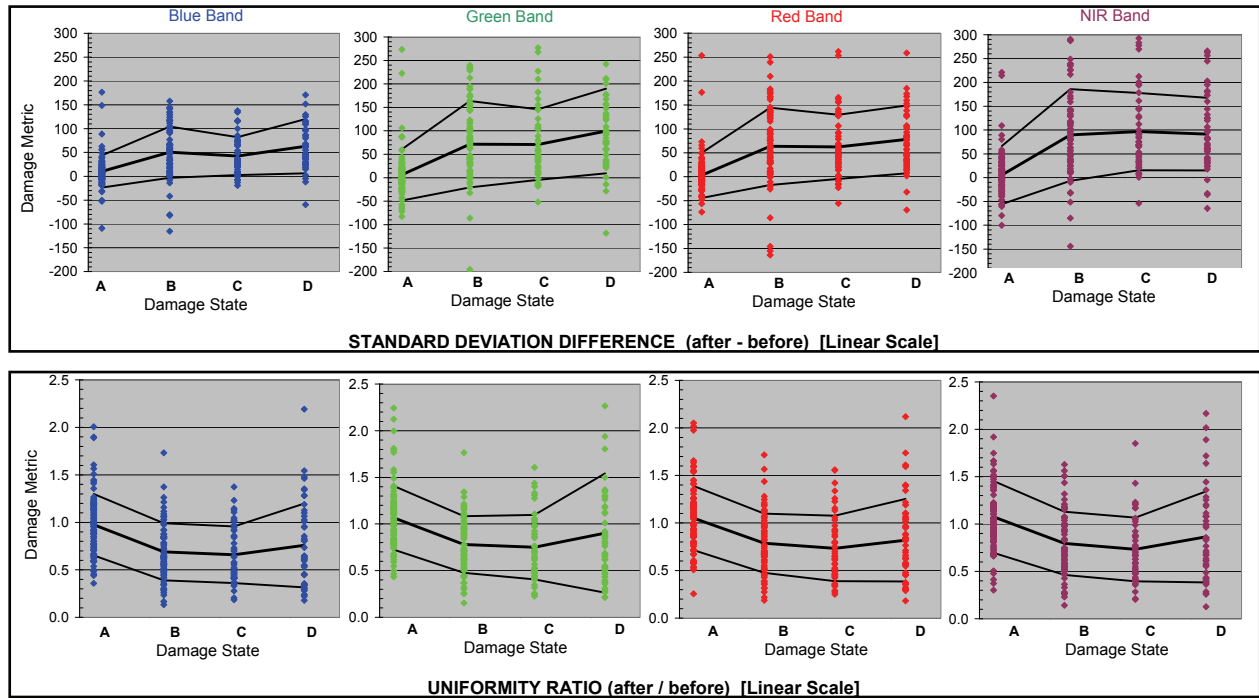
**Figure 4-3 Idealized *Windstorm Damage Profile*, Relating Damage Metrics to Actual Damage States**

## 4.2 Results

The results of the qualitative characterization of building damage are the *windstorm damage profiles* discussed in Step 9 above. The resulting damage profiles show the relationship between various remote sensing measures of change (the “damage metrics” from Step 8 above) and actual damage states. The windstorm damage profiles form the basis for the automated assessment of windstorm damage based on characteristic changes in remote sensing imagery.

A challenge in the development of algorithms for remote sensing-based damage assessment is the definition of damage metrics which uniquely correspond to a distinct damage state. Figure 4-4 shows sample damage profiles resulting from the above methodology. These damage profiles are typical of the suite of damage profiles developed in this study and are useful for discussion of the major resulting trends.

The sample damage profiles exhibit overall trends for the variation of damage metrics with damage states. The damage profiles exhibit strong trends for the distinction of “no-damage” (RS-A) from “damage” conditions (RS-B, RS-C, and RS-D), but the data contain too much scatter to accurately assign a damage state based on a given value of damage metric. Distinctions between mid-level damage states (RS-B or RS-C) are difficult to make for damage profiles with large data spread, as shown here.



**Figure 4-4 Sample Windstorm Damage Profiles for the Study Sample Of Buildings Subjected to Hurricane Charley and Ivan. The Damage Profiles are Separated by Spectral Bands. Damage Metrics are Based on Before-and After Comparison of Satellite Images of 267 Roof Facets from 77 Buildings. Damage States are Defined by the Remote Sensing Damage Scale in Table 3-2 and are Based on Ground-Truthing Surveys Performed with the VIEWS™ System. Trend Lines Indicate Group Means and (Mean ± 1 Standard Deviation). From Womble (2005).**

## SECTION 5 MAPPING HURRICANE DEBRIS

The goal of Research Activity 4 is to demonstrate the mapping and quantification of debris using semi-automated imagery analysis procedures.. The use of remote sensing to study debris patterns, composition and density is of particular significance in the analysis of windstorm effects on the built environment. Windborne debris is often removed quickly following a windstorm (before investigators can arrive on the scene), destroying evidence that is needed to fully understand the spatial patterns of wind damage. Remote sensing imagery provides a means of capturing and preserving the spread of debris. Digital multispectral imagery also lends itself to the automated mapping and quantification of debris spread.

### 5.1 Methodology

From visual inspection of pre- and post-disaster imagery, debris is readily identifiable due to its distinctive bright and chaotic appearance relative to the underlying land surface. Accordingly, it may be hypothesized that debris can be identified as a function of temporal changes in the textural and spectral signatures of vegetated areas, pavement, and water surfaces, stemming from the addition of debris materials.

The Normalized Difference Vegetation Index (NDVI) has been widely used in remote sensing studies to detect changes in the land surface cover, and in a disaster context to identify changes caused by storm surge and tsunami scour (Adams et al., 2005a,b; Chang et al., 2006; Womble et al., 2006). This research activity explored its use to detect and map the spread of debris in terms of change in NDVI. The NDVI is calculated from a mathematical combination of the red (R) and near-infrared (NIR) bands as follows:

$$NDVI = \frac{(NIR - R)}{(NIR + R)}$$

The near-infrared band is particularly effective at highlighting changes in vegetation. Through comparison of the pre- and post-hurricane NDVI statistics for discretized areas of the remote sensing scenes, the spectral signature of debris lends itself to the detection and mapping of debris spread.

### 5.2 Results

Figure 5-1 shows an example of a lawn area (delineated in yellow) scattered with windborne debris from a nearby roof. The pre-and post-storm satellite images are displayed in natural color and infrared-false color (where the NIR band appears as red and the R band appears as green) to accentuate the spectral differences in vegetation and windborne debris (primarily made of construction materials). Figure 5-2 shows histograms formed from the DN values of the pixels constituting the lawn area in the pre- and post-storm for each of the four Quickbird multispectral bands. As is evident in these bands, the lawn area exhibits different spectral signatures for the different bands. Mean differences in the DN values can be caused by physical change (addition of debris) as well as illumination differences and possible seasonal changes in the reflectance of



vegetation. The change in variance (and standard deviation) is attributed to presence of the windborne debris.

A histogram of pre- and post-storm NDVI values (figure 5-3) is also demonstrated for the pre- and post-storm area. The leftward shift of the NDVI distribution for the post-storm case is indicative of the vegetated surface being covered by other materials (debris). The NDVI analysis may thus be used to detect the presence of debris within a given area.



**Figure 5-1 Example of Windborne Debris Spread. Quickbird Images from Before and After Hurricane Charley Show Windborne Debris from a Nearby Building Spread Across a Vegetated (Lawn) Area (Delineated in Yellow). Images are Shown in (a) Natural Color (B-G-R Bands) and (b) False-Color (G-R-NIR bands) to Highlight the Spectral Signature of Debris Atop the Vegetation Area. Credit: DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)> and Womble (2005).**



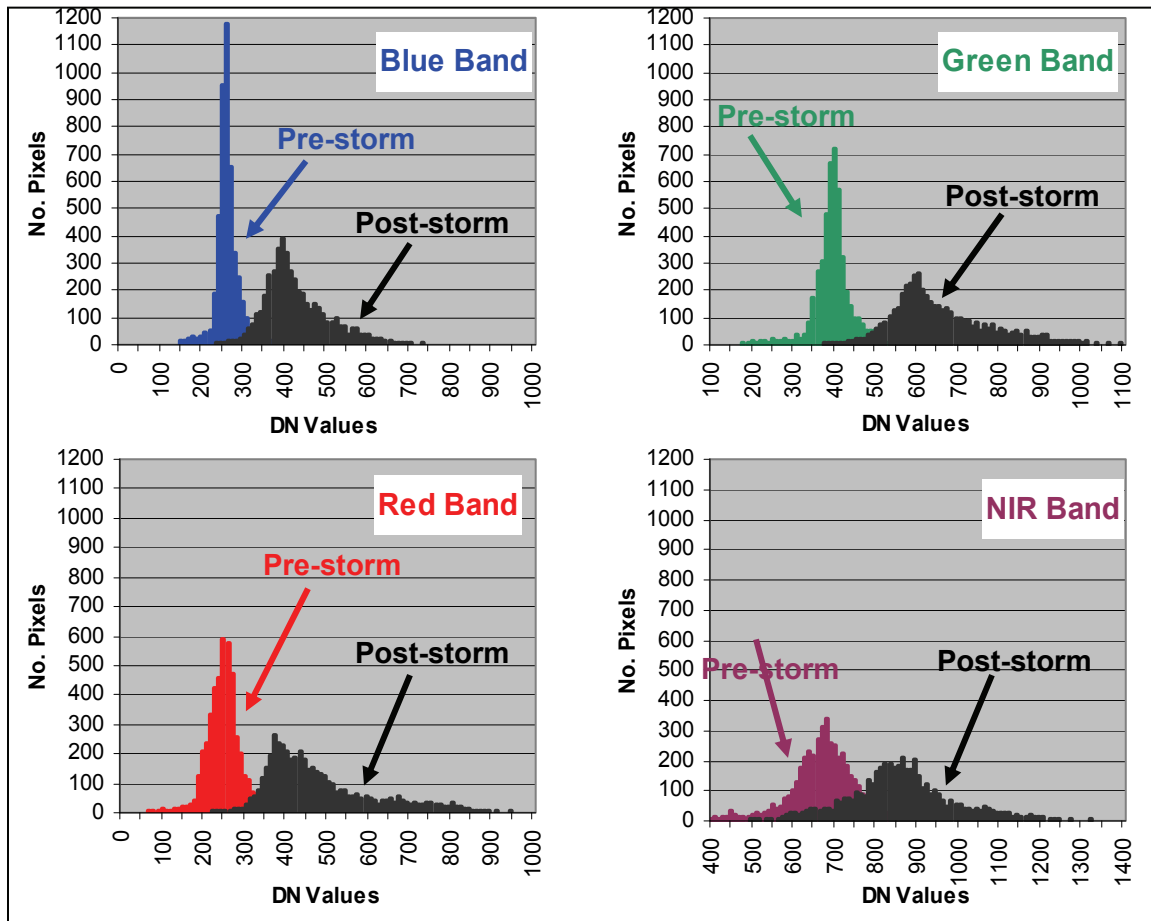


Figure 5-2 Spectral-Band Histograms for the Lawn Area Delineated in Figure 5-1. For Each Spectral Band, the Pre-Storm Values are Plotted in the Band Color, and Post-Storm Values are Plotted in Black. From Womble (2005).

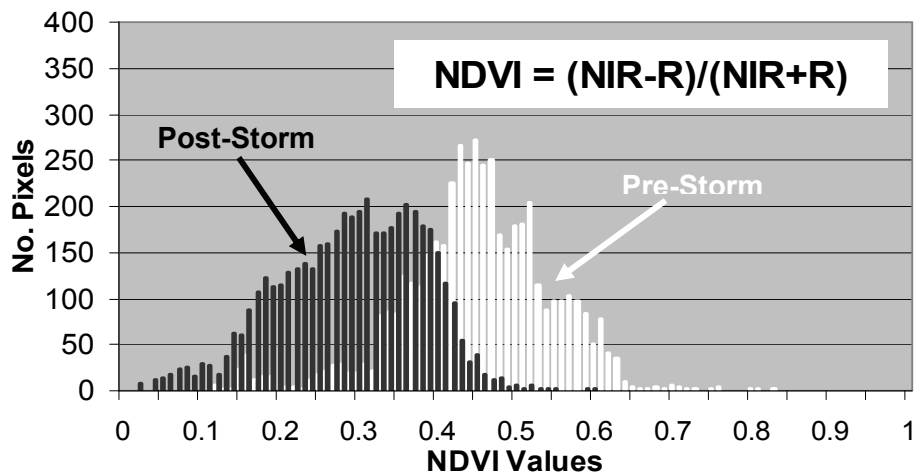


Figure 5-3 Pre-and Post-Storm Histograms of NDVI Values for the Lawn Area Delineated in Figure 5-1. For Each Spectral Band, the Pre-Storm Values are Plotted in the Band Color, and Post-Storm Values are Plotted in Black. From Womble (2005).

As discussed by Womble (2005), histograms do not preserve the spatial relationship of the constituent pixels, and therefore the location of debris within a given area is not obvious from the histogram alone. The use of multiple, small areas (i.e., a gridwork or mesh of finite areas) is thus suggested for locating and mapping debris. For instance, areas could be specified forming concentric rings around a building; debris spread could thus be quantified by its density and its proximity to the building. The use of semivariograms (Carr, 1996; Carr and Miranda, 1998; Chica-Olmo and Abarca-Hernandez, 2000; Saito and Spence, 2004), as used for earthquake rubble detection, may likewise prove useful in quantifying windborne debris spread and is suggested for further investigation.

## SECTION 6

### REMOTE SENSING IMAGERY AS A SURROGATE DAMAGE INDICATOR

This research activity discusses whether *surrogate damage indicators* can be used to infer the windstorm damage state. While satellite imagery captures roof surfaces in general, it is difficult to directly observe damage to walls, windows, and doors, together very small areas of roof damage that can still enable rainwater to enter the buildings. However, a number of related damage features observable in satellite imagery may indicate the occurrence of unseen structural and non-structural damage. There is significant need for research to develop and refine surrogate damage indicators, to extend the ability of remote sensing technologies to make holistic assessments of damage. The usefulness of remote sensing imagery is considered as a potential indicator for identifying the occurrence of: missile impacts, internal pressurization, blue tarpaulins (temporary roof covers) and roof cover replacement.

The identification of surrogate damage indicators was accomplished through the review of VIEWS™ ground-based survey data and associated post-hurricane satellite imagery for instances of damage that are directly visible only from the ground survey, but for which “indirect” evidence is available in the remote sensing imagery. A review of the actual failure mechanisms associated with debris spread and roof damage (both of which are visible to overhead imagery) was then conducted to formulate logic structures associated with the indirect detection of damage. The following sections detail the logic, preliminary findings, and suggestions for future work associated with each surrogate damage indicator observed.

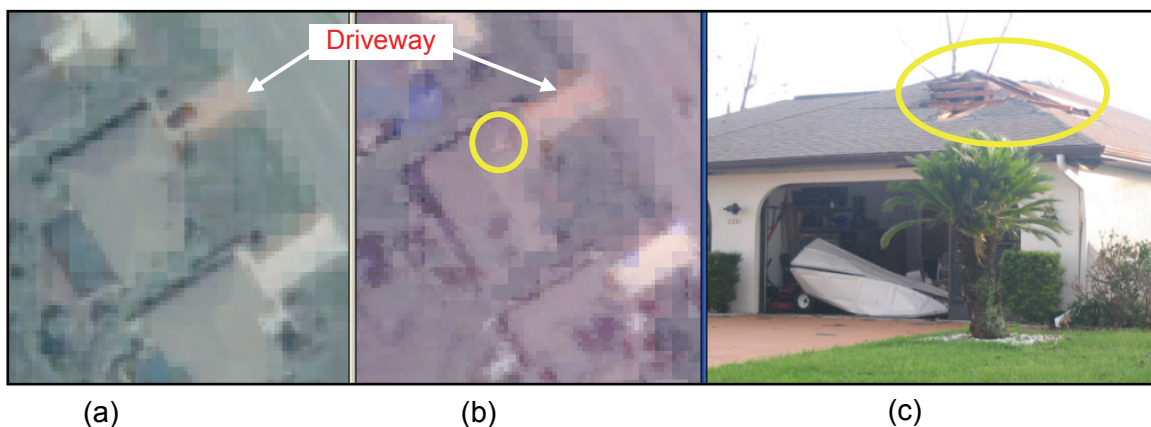
#### **6.1 Missile Impacts**

As shown in table 3-1, *Missile Impact* is an important category for the designation of damage states to residential as well as other buildings. Although missile impacts to vertical surfaces (walls, doors, windows) are not directly visible in overhead imagery, evidence of missiles (e.g., lumber and metal panels – typically dislodged from nearby structures) is generally visible in overhead imagery as debris spread on the ground. Field investigations show that debris is typically found on the ground near its point of impact. The acquisition of remote sensing imagery as soon as possible following a windstorm (before cleanup efforts commence) is critical for preserving the evidence of debris. The presence of debris in a remote sensing scene does not automatically ensure that missile impacts have occurred; however, evidence of missiles (debris) can be a necessary condition for the occurrence of missile impacts on nearby buildings. As debris is a logical indicator of possible damage, further work in the remote sensing identification and quantification of debris is needed, as are methods for determining the probability of sustaining unseen wall, window, and door damage when debris (with certain characteristics) is present.

#### **6.2 Internal Pressurization**

Possible penetration of walls, doors, and windows can also be indicated by the failure of roof decking directly above the penetration area. Such failures are attributed to the combination of external uplift pressures acting in tandem with internal pressures (admitted to the interior of the building through the penetration areas) to create locally high pressures on the roof surface above. Womble et al. (1998) show that internal pressures are highly correlated with external suction

pressures on roof surfaces directly above windward openings. Field inspections of windstorm-damaged residences described by Gardner et al. (2000) show that wind-induced failures of garage doors (initiating from missile impact and/or wind pressurization) are common failure mechanisms tending to cause a loss of garage roofs. While the garage doors are not visible to overhead imagery, the location of garage doors can be indicated by adjacent driveways, which are visible to overhead imagery (figure 6-1). Failure of roofing elements adjacent to driveways can thus indicate (though not guarantee) possible failure of garage doors. Suggestions for future work include the development of logic structures to identify driveways and walks adjacent to damage areas.

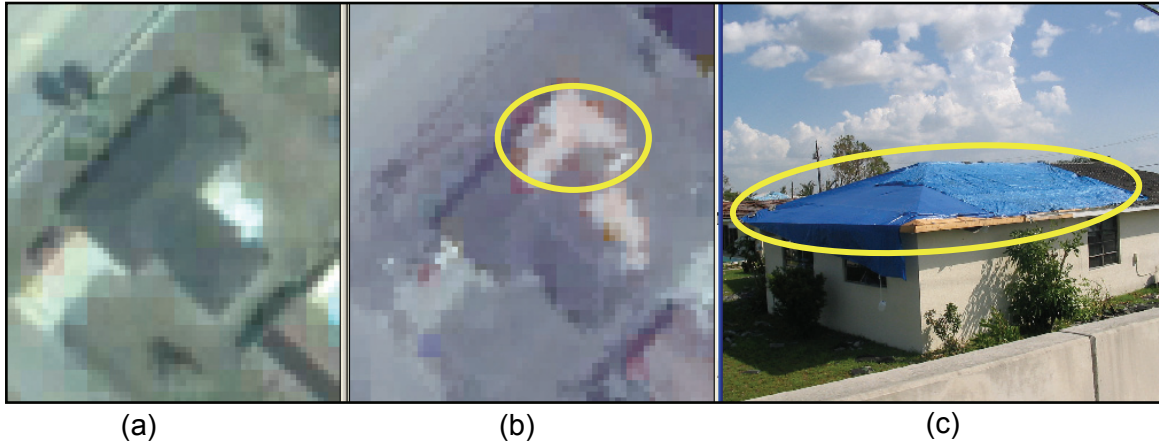


**Figure 6-1 Examples of Surrogate Indices for Garage Door Failures. The Presence of a Driveway Visible in the (a) Pre-Storm and (b) Post-Storm Quickbird Images Indicates the Presence of a Garage Door. The Roof Damage Above the Garage Indicates the *Possibility* of a Failed Garage Door, Permitting Wind Pressurization of the Building Interior. Credit: DigitalGlobe, Inc. <www.digitalglobe.com>.**

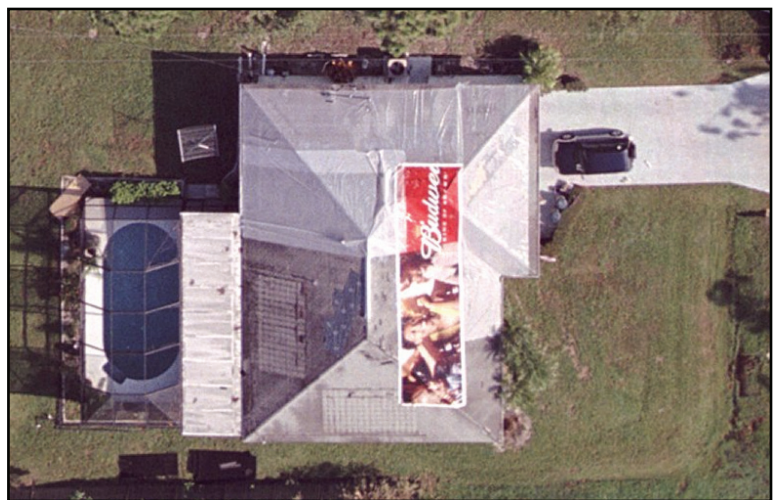
### 6.3 Blue Tarpaulins and Temporary Roof Covers

The above discussions of debris and roof failures depend on the collection of imagery as quickly as possible following a windstorm. Examination of the temporal sequence of Quickbird images collected following Hurricane Charley has also given rise to another surrogate damage indicator – temporary roof covers.

In the wake of Hurricane Charley, FEMA provided blue tarps to numerous homeowners with damaged roofs (figure 6-2). Other homeowners used a variety of waterproof materials to provide temporary cover (figure 6-3). The appearance of temporary roof covers implies that some degree of damage has occurred to the roof, although exact details of the damage sustained is difficult to determine once the roof is covered. It must be realized that the installation of temporary roof covers is quite subjective, depending on individual homeowners' perceptions of the need for temporary covering and ability to obtain and install the cover (or have it installed). Nonetheless, an analysis of temporary roof covers provides some general guidance to the levels of damage indicated by their presence.



**Figure 6-2 Quickbird Images Collected (a) Before and (b) One Day After Hurricane Charley, and (c) Ground-Survey Photo. The Damaged Portion of the Roof is Apparent in the Post-Storm Image, but was Covered with a Blue Tarp Prior to the Ground Survey. Credit: DigitalGlobe, Inc. <www.digitalglobe.com>**

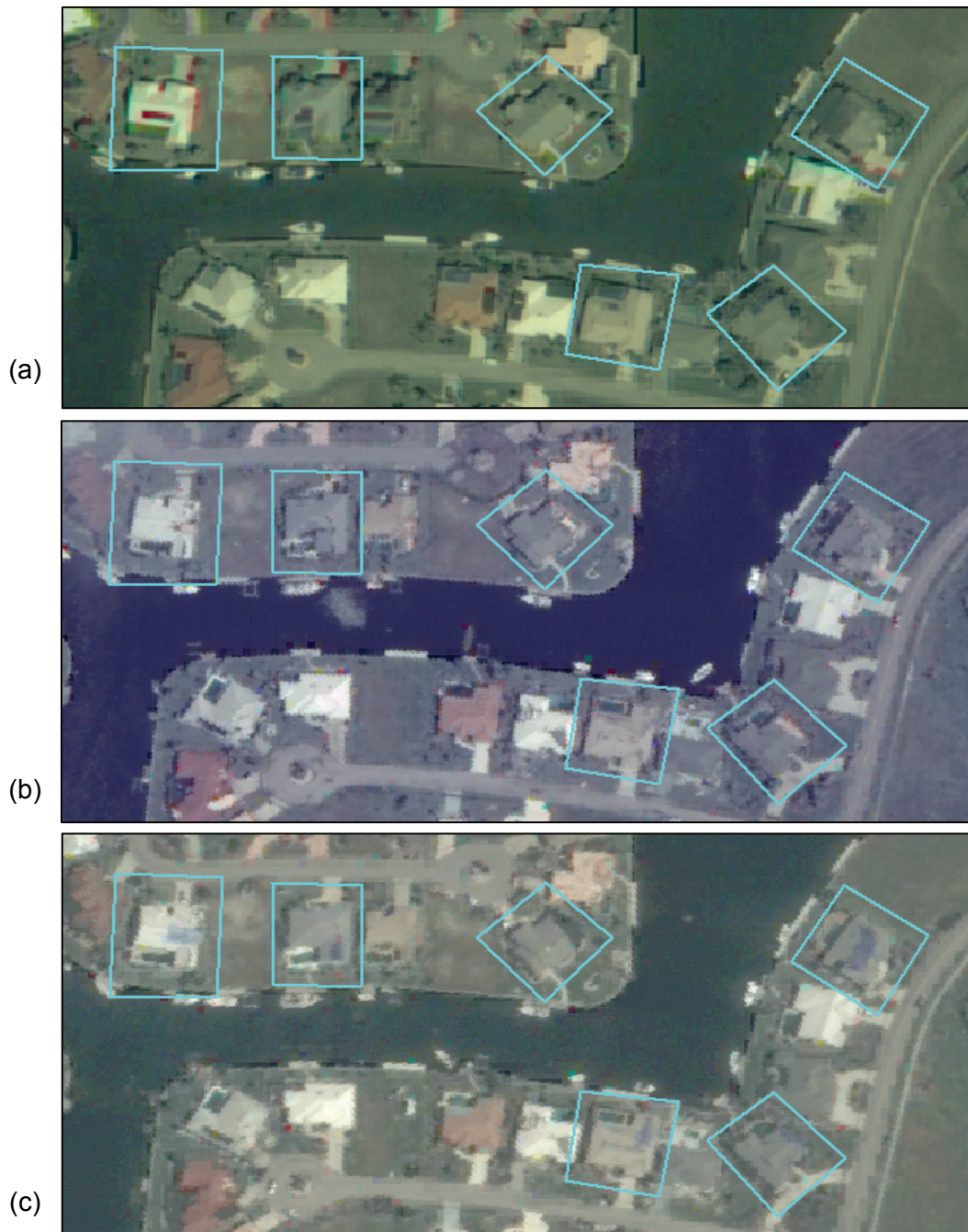


**Figure 6-3 The Appearance of Temporary Roof Coverings on Buildings Indicates the Presence of Damage, but can also Obscure the Damage. Post-Storm Imagery Acquired Before the Roof Covers Appear is also Needed to Assess the Level of Damage to the Roof. Credit: DMK Associates.**

The temporal sequence of Quickbird images of Punta Gorda facilitates a brief study of the temporary roof covers. The March 23 imagery (figure 6-4a) provides a baseline “no-damage” case, while Quickbird imagery collected on August 14, one day after Hurricane Charley’s landfall (figure 6-4b), shows the pristine damage condition of roofs in a residential neighborhood of Punta Gorda (in most cases prior to the installation of temporary roof covers). Many temporary roof covers appeared in the week following, as evident in the Quickbird imagery of the same neighborhood collected on August 19 (figure 6-4c). With such temporal image sequences, the later images (with roof covers in place) can be used to locate roofs that are damaged, while the immediate post-storm images can be used to determine the extent and nature



of roof damage. The appearance of roof covers in the later imagery can also indicate damage that may not be visible (at current image resolutions) in the immediate post-storm imagery.



**Figure 6-4 Temporal Image Sequence Showing (a) Pre-Hurricane Condition on March 23, 2004; (b) Condition on August 14, 2004 (One Day Following Hurricane Charley); and (c) Temporary Roof Covers (Blue Tarps) in Place on August 19, 2004. Quickbird Images from DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**



A review of the temporal image sequence of Punta Gorda showed that 58 residences with temporary roof coverings (blue tarps) in the August 19 imagery. Figure 6-5 graphically shows the various damage scenarios. Of these 58 residences, 2 residences already had temporary covers in place when the hurricane struck, while 56 residences did not already have the temporary covers in place on August 14. The post-storm conditions of these roofs were thus visible in the August 14 imagery. Of the 56 roofs uncovered on August 14, 47 roofs had visible damage discernable in the August 14 imagery (figure 6-6), while 9 roofs had no signs of damage discernable by visual inspection of the August 14 imagery (figure 6-7). Of the 47 roofs with discernable damage, 45 were visually classified as having worst-case-facet damage corresponding to damage state RS-B (tables 3-2 and 3-3); while the remaining 2 may have had either damage state RS-B or RS-C (not visually discernable from the imagery and not visible in the ground-based data).

<b>58 residential roofs</b> with temporary covers on August 19 (Residences were also visible in March 23 and August 14 imagery)			
<b>2 roofs</b> already with temporary covers on August 14, obscuring the actual damage state.	<b>56 roofs</b> without temporary covers on August 14, allowing visual inspection of the damage conditions.		
	<b>9 roofs</b> with no signs of damage visible by inspection of the August 14 imagery	<b>47 roofs</b> with signs of damage visible by inspection of the August 14 imagery	
		<b>2 roofs</b> with damage that could be classified as RS-B or RS-C	<b>45 roofs</b> with damage classified as RS-B by visual inspection of the August 14 imagery

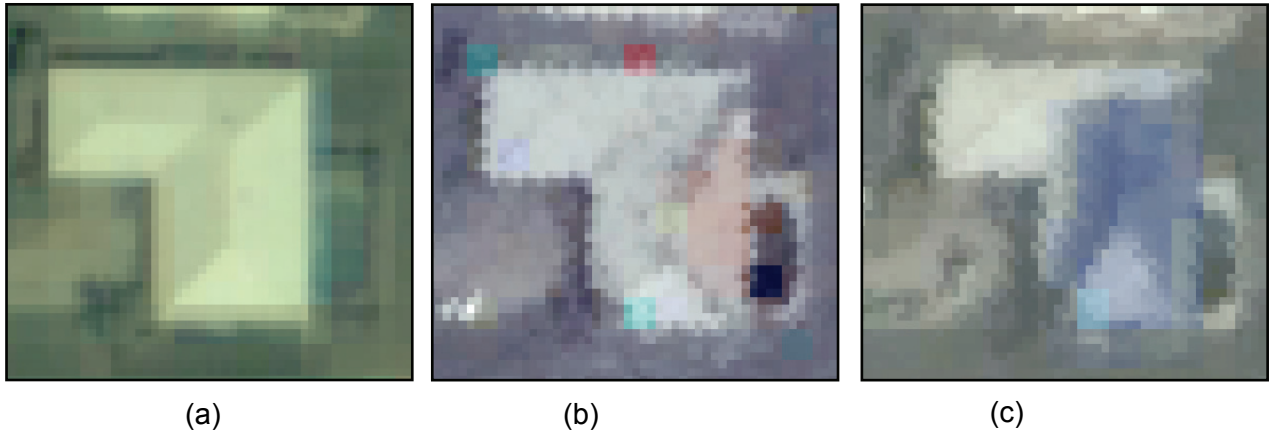
**Figure 6-5 Graphical Presentation of the Brief Study of Temporary Roof Covers Using the Temporal Sequence of Quickbird Satellite Images Acquired on August 14 and August 19**

From this brief study, several general conclusions can be drawn concerning the use of temporary roof covers:

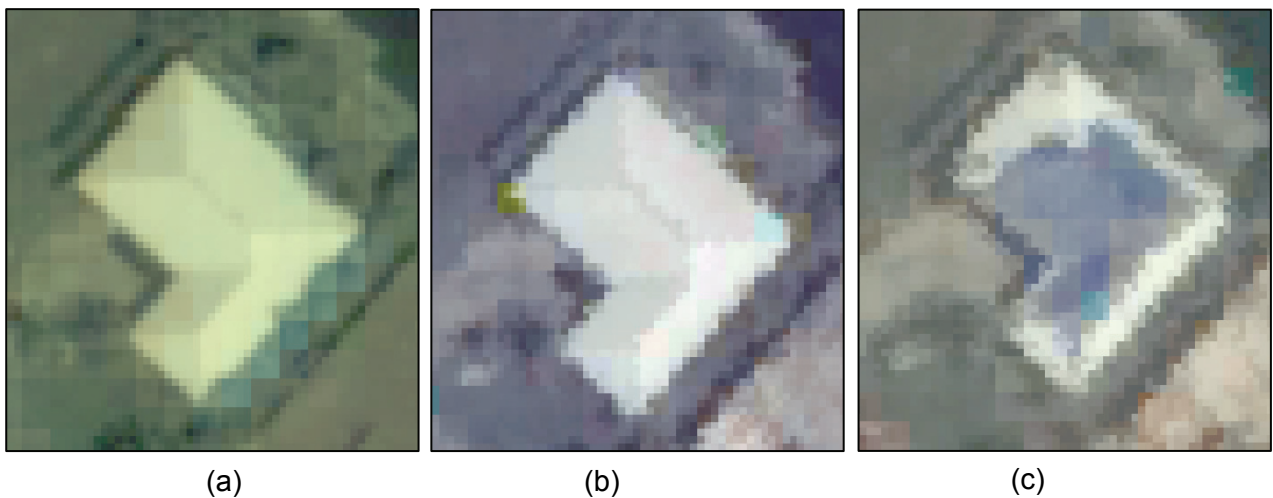
- Most temporary covers were not in place on the day following the hurricane.
- A short time window exists to obtain remote sensing imagery detailing the actual condition of the roofs before temporary covers begin to appear.
- In a few cases (~16% in this instance), the presence of temporary roof covers indicates the presence of damage that is not otherwise visible in immediate post-storm imagery.
- Most temporary covers were applied to residences with damage state RS-B. The most severely damaged roofs (RS-D) likely resulted in the complete destruction of building

contents, leaving little incentive to cover the roof, as well as little physical means for attaching a temporary cover. Based on this analysis, it may be concluded that the appearance of temporary blue covers in general indicates low-to-moderate levels of damage.

Future work can logically include the automated detection of temporary roof coverings. Coverings such as the blue tarps have a definite spectral signature which can be used to detect the presence of the cover.



**Figure 6-6 Temporal Image Sequence Showing (a) Undamaged Condition on March 23, 2004; (b) Damaged Roof on August 14, 2004 (One Day Following Hurricane Charley); and (c) Temporary Roof Cover (Blue Tarp) in Place on August 19, 2004 (Indicating the Presence of Damage but Obscuring the Exact Damage Condition). Quickbird Images from DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**



**Figure 6-7 Temporal Image Sequence Showing (a) Undamaged Condition on March 23, 2004; (b) Roof on August 14, 2004 (One Day Following Hurricane Charley) *Without Visible Damage*; and (c) Temporary Roof Cover (Blue Tarp) in Place on August 19, 2004 (Indicating The Presence of Damage). Quickbird Images from DigitalGlobe, Inc. <[www.digitalglobe.com](http://www.digitalglobe.com)>.**

## **6.4 Roof-Cover Replacement**

Evidence of re-roofing efforts also indicates that some amount of damage has occurred to the roof. Replacement of roof covering appears in remote sensing imagery as a uniformly cleared roof surface (cleared of covering), whereas an undisturbed damaged roof typically exhibits a non-uniform removal of roof covering. Comparison of imagery collected in the immediate aftermath of a windstorm with imagery collected several days later can also help to identify instances of roof-covering replacement. Further analysis is needed to develop this surrogate indicator, including the automated detection of (likely) re-roofing activities.



## SECTION 7 SUMMARY OF KEY FINDINGS AND FUTURE WORK

The research documented here has resulted in a number of significant findings regarding the use of remote sensing and advanced technologies for promoting resilience through rapid and resourceful hurricane disaster response. Overarching findings that stem from this research effort include:

- Satellite remote sensing provides a new means for rapidly capturing and analyzing the pristine damage scene in the wake of a windstorm. Satellite imagery can often be obtained rapidly enough to direct an associated ground-truthing survey.
- As demonstrated in the aftermath of Hurricane Ivan, aerial images can sometimes be acquired and distributed sooner than satellite images. Experience has shown that the platform for first-available imagery varies on a case-by-case basis. Aerial images can also, at present, offer higher-resolution imagery. The aerial images do not typically include near-infrared band information, or the georeferencing information needed to utilize the images in GIS-based applications. The availability of pre-storm aerial imagery is limited, compared to satellite imagery.
- Advanced technologies integrating satellite imagery, global positioning systems, geographic information systems, and digital imaging provide a rapid means of capturing, analyzing, and retrieving perishable, georeferenced, and ground-based damage information (e.g., the VIEWS™ system).
- Satellite remote-sensing imagery provides a means for systematically and uniformly assessing damage conditions across an entire windstorm-affected region. While remote sensing does not replace detailed forensic studies of building damage, it does provide complementary information about the overall damage conditions of buildings as well as the spatial distribution of damage throughout a region.
- With the 61-cm+ resolution of the Quickbird images (e.g., figure 3-9a,b) it is often difficult to discern small areas of damage; higher-resolution images (such as the 5-cm digital aerial image of figure 3-9c) greatly assist in resolving small areas of damage, as well as in delineating the edges of roof slopes.
- Remote-sensing imagery and digital-image-analysis techniques provide a basis for the rapid and ultimately automated assessment of windstorm damage. Development of this technology requires in-depth understanding of windstorm damage to buildings from a remote-sensing standpoint, as well as the correlation of quantitative remote-sensing-based damage measures with actual damage states.
- Remote-sensing technologies also provide a means for mapping and quantifying windborne debris.
- Surrogate indicators of damage can be used to identify possible damage that is not directly visible in remote-sensing imagery.

Key findings for the specific tasks documented in this volume include:

a) Remote sensing-based damage scale for wind: The qualitative characterization of building damage from a remote-sensing perspective identifies visual signatures of windstorm damage to buildings. These signatures are important for visual interpretation of remotely sensed damage scenes as well as the training of computer algorithms to perform automated damage assessments. Specific findings stemming from the research activity include the following:

- A Remote-Sensing Damage Scale (table 3-2) has been developed, which will enable the rapid visual interpretation of damage to residential buildings. It also constitutes an important initial step towards the development of change-detection algorithms for damage assessment. This damage scale provides a “new look” at windstorm damage from a remote-sensing perspective. It is compatible and can be used in conjunction with the HAZUS-Hurricane damage scale for residential buildings.
- The extent to which damage can be assessed via remote-sensing imagery depends on the spatial resolution of the imagery, as well as the size, composition (material layers), and geometric complexity of building roofs. Present spatial resolutions are helpful for determining the presence of damage. Higher-resolution imagery is needed to make more accurate assessments of damage, particularly to conventional wood-frame roofs (residential buildings) and manufactured homes. The accuracy of remote-sensing damage assessments should therefore increase as image resolutions become finer.
- Suggestions for future work include the development of remote-sensing-based damage scales for other structural types (e.g. commercial, industrial).

b) Quantitative characterization of windstorm damage: The quantitative characterization of building damage is fundamental to the automated detection and assessment of windstorm damage to buildings. This research activity developed a methodology that may lead to automation. Specific findings include the following:

- The facet-level comparison of roofs conditions for the quantitative description of damage is necessitated by difficulties in accurately normalizing the illumination of roof surfaces in temporal images.
- Object-based statistics (in which objects are individual roof facets) form the basis for quantitative characterization of building damage. Quantitative comparison of pre-storm and post-storm object statistics is accomplished with a suite of *damage metrics*, formed by differencing or ratioing object-based statistics.
- *Damage profiles* serve to correlate damage metrics with actual damage states and form the critical link for making automated assessments of building damage based on changes in remote-sensing imagery.
- The windstorm damage profiles shown in this study contain significant data spread, meaning that the damage metrics are not sufficiently correlated with damage states to allow assignment of damage state given a particular value of damage metric. Additional work is needed to refine the damage profiles for the accurate determination of damage states from changes in remote-sensing imagery. Investigation of the remote-sensing signatures of different roof-covering materials is a possible candidate for continued research.



- The study of debris remains a critical research emphasis for wind engineers. As debris is quickly removed from the scene following a windstorm, the detailed study of debris is extremely time-critical.
- Remote sensing provides a method for rapidly preserving the post-disaster scene.
- Multispectral images acquired before and after a windstorm can be used to map and quantify the spread of windborne debris. Identification of debris can be accomplished through use of the spectral properties of the debris and the surface on which it lands. Spectral analysis techniques, such as NDVI, provide a means of material recognition for the location of debris.
- Use of a mesh of cells (discrete areas) within a remote-sensing scene is recommended for the mapping of debris.

c) Surrogate indicators for detecting windstorm damage: Surrogate indicators of damage (which are visible in remote-sensing imagery) are useful for the designation of potential damages that are not visible in the imagery. Some specific surrogate damage indicators stemming from the Hurricane Charley investigation are described below.

- The presence of debris in a remotely sensed scene serves as a surrogate indicator of possible missile impacts to nearby buildings.
- The failure of roof panels adjacent to a driveway serves as an indicator of possible garage door failures.
- The appearance of temporary roof coverings (or evidence of re-roofing activity) serves as an indicator of roof damage and can indicate roof damage that has otherwise gone unnoticed in earlier post-storm imagery. In general, the appearance of temporary coverings indicates low-to-moderate damage levels.
- Suggestions for future work include the statistical characterization of surrogate indices; in simplest terms, when debris is present, what is the probability that missile impacts have also occurred? Additional research can target the automated detection of temporary roof covers as an indicator of damage that has otherwise been un-detected.

d) Future Research: As Volume 5 of this five volume series marks a seminal effort into the remote-sensing assessment of windstorm damage, it identifies a number of specific opportunities for future research.

- Hurricane Charley has provided a good initial basis for research; however, the techniques employed herein need to be tested and revised using similar data in future storms to help standardize the approach.
- While Hurricane Charley was a major wind-damage event, it was accompanied by relatively little storm surge and flooding. Additional work is needed to study the juxtaposition of wind damage with associated storm-surge and flooding damage, as these damage mechanisms will produce different visual signatures.
- Further research is needed to facilitate the use of available pre-storm imagery with first-available post-storm imagery. The first-available post-storm imagery may be either satellite

or aerial platform. Additional work is needed to facilitate the rapid use of aerial imagery (e.g., addition of georeferencing information to the aerial imagery).

- Using the example presented in this report, remote-sensing-based damage scales can be developed for other building inventories (e.g., commercial, high-rise, manufactured housing). Remote-sensing damage scales can also be expanded to include debris measures and surrogate indices.
- Further work is needed to advance the use of object-based building delineation procedures and to combine this delineation with quantitative damage measures for the development of automated damage-detection algorithms.
- Additional work is needed to identify damage metrics that are uniquely correlated with actual damage states to achieve accurate automated damage assessments.
- Statistical-sampling studies can be used to provide probabilities of unseen damage (e.g., missile impacts) based on visible surrogate indicators (e.g., debris).
- Studies relating the spatial extent, trajectories, and material recognition of debris could be integrated with remote-sensing technologies to advance the study of windborne debris.
- Further research is needed to characterize the damage indicated by the appearance of temporary roof coverings in the recovery period following a windstorm.

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