Remote-Sensing Assessment of Wind Damage

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INTRODUCTION

Engineering studies of wind-damaged buildings over the past four decades have helped strengthen the built environment against the effects of severe windstorms by influencing building codes, improving mitigation measures, and identifying life-saving construction practices. Post-windstorm investigations are time- and labor-intensive, however, and critical damage evidence is often lost in cleanup and repair efforts before large damage areas can be surveyed. Digital satellite and aerial imagery offers a means of rapidly preserving critical damage evidence (e.g., roof damage and debris spread) and also enables engineers to see damage conditions in inaccessible areas. A wide range of wind damage states are visible from the exterior of buildings: ranging from minor roof-covering damage to removal of the entire structure from the foundation. Many wind damage states can also be detected from the condition of the roof alone with a high degree of accuracy, and wind damage is therefore subject to detection and assessment using remote-sensing imagery.

Significant advances in satellite and aerial remote-sensing image acquisition over the past decade have greatly advanced the possibilities for rapid detection and assessment of damage from windstorms [Womble, 2005]. Such recent and major hurricanes as Charley (2004), Ivan (2004), Katrina (2005), Rita (2005), and Wilma (2005), have been accompanied by an abundance of remote-sensing data. For Hurricane Katrina alone, digital images with various spatial, spectral, and temporal resolutions were acquired from 21 different platforms [Womble *et al.*, 2006].

CASE STUDY

A detailed study conducted by researchers at the Texas Tech University (TTU) Wind Science and Engineering Research Center (WISE) and ImageCat, Inc., described by Womble [2005] and Womble *et al.* [2007], demonstrates the use of remote-sensing imagery for: (1) the collection of field damage observations; (2) the qualitative description of wind damage to buildings from a remote-sensing perspective; (3) the eventual development of quantitative damage descriptions based on temporal changes in remote-sensing images; and (4) correlation of these damage metrics with field damage observations. This study is described briefly through the case study highlighted in this paper.

Data Collection

Hurricanes Charley and Ivan (2004) provided the first opportunity for the TTU/ ImageCat team to collect before-and-after satellite images as well as corresponding field-based damage observations of damage from a major U.S windstorm, and to thereby investigate the use of modern remote-sensing technology for post-windstorm damage assessment. Hurricane Charley struck southwest Florida on Aug. 13, 2004, as a Category 4 hurricane. Hurricane Ivan's landfall near Gulf Shores, AL and Pensacola, FL (Sept. 16, 2004) presented an opportunity to supplement the remote-sensing data and field observations.

The QuickBird satellite acquired 61-to-75-cm imagery of the severely damaged communities of Punta Gorda, FL (August 14 and 19) and Port Charlotte, FL (August 19) and preserved the disaster scene before most critical damage indicators (e.g., debris, roof damage, and fallen trees) could be removed. Pre-hurricane QuickBird images of the 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 efforts, and along with the August 19 images provided data for the qualitative and quantitative analyses of wind damage characteristics. QuickBird imagery of Pensacola, FL acquired on March 12, 2004 and September 21, 2004 provided additional remote-sensing imagery of buildings damaged by Hurricane Ivan.

Following Hurricanes Charley and Ivan, field deployments were launched to collect time-sensitive ground-truthing data (field observations) describing the damage characteristics of buildings and infrastructure. The ground surveys targeted areas with synoptic coverage by both pre- and post-hurricane satellite imagery and a broad range of windstorm damage levels to “residential” wood-frame-roof buildings as well as commercial-industrial buildings and manufactured homes. This data set formed the basis for the investigation of manual and automated windstorm damage to buildings using remote-sensing imagery. The field team used the ImageCat/MCEER VIEWS™ field-reconnaissance system, described by Adams *et al*. [2004a,b], to rapidly acquire damage-state observations. The VIEWS™ system integrates continuous digital video footage, digital still images, satellite-image base layers, and real-time GPS observations. With VIEWS™, the field team rapidly collected ground-based damage information for an average 2,500 buildings per day. Figure 1 shows a sample of building damage in Hurricane Charley, viewed from before-and-after QuickBird satellite images and from the VIEWS™ ground survey.

Figure 1. Examples of windstorm damage to residential buildings: pre- and post-storm QuickBird satellite images and ground-truthing photos. DigitalGlobe, Inc. <www.digitalglobe.com>.

Qualitative Description of Damage

The qualitative characterization of building damage from a remote-sensing perspective is an important step in the development of computer algorithms to perform automated damage assessments. In the creation of such algorithms, developers must understand how various levels of windstorm damage appear – first to the human cognitive system and then to digital image analysis techniques that aim to model human cognition. Temporal changes that help determine damage states for buildings can be described in terms of morphology (mathematical description of shapes), textures, colors (spectral signatures), brightness, edge intensity, edge linearity, and edge irregularity. Visually-based remote-sensing damage scales can therefore be devised for various building categories; such scales are a critical step towards the development of algorithms for the automated assessment of windstorm damage.

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 building occupancy because (1) post-storm conditions of roofing components are most distinguishable via overhead remote sensing and (2) because 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 consists primarily of low-rise buildings, enabling the qualitative analysis of four building (roofing) types: (1) Wood-Frame Roofs (nominally termed “Residential,” including single-family homes, some apartment buildings, and a few small offices buildings, and specifically those buildings constructed with wood-frame roofs covered with wood decking

Table 1. Remote-Sensing Damage Scale for Residential Construction [from Womble, 2005]

Damage Rating	Most Severe Physical Damage	Remote-Sensing Appearance
RS-A	No Apparent Damage	• No significant change in texture, color, or edges. • Edges are well-defined and linear. • Roof texture is uniform. • Larger area of roof and more external edges may be visible than in pre-storm imagery if overhanging vegetation is removed. • No change in roof-surface elevation.
RS-B	Shingles/tiles removed, leaving decking exposed	• Nonlinear, internal edges appear (new material boundary with difference in spectral or textural measures). • Newly visible material (decking) gives strong spectral return. • Original outside roof edges are still intact. • No change in roof-surface elevation.
RS-C	Decking removed, leaving roof structure exposed	• Nonlinear, internal edges appear (new material boundaries with difference in spectral or textural measures). • Holes in roof (roof cavity) may not give strong spectral return. • Original outside edges usually intact. • Change in roof-surface elevation. • Debris typically present nearby.
RS-D	Roof structure collapsed or removed. Walls may have collapsed.	• Original roof edges are not intact. • Texture & uniformity may/may not experience significant changes. • Change in roof-surface elevation. • Debris typically present nearby.

and either tile or asphalt shingles); (2) Metal Warehouses; (3) Built-Up Roofs; and (4) Manufactured Housing. Of these, the Residential category comprised the majority of the buildings; this category is selected for the case study described herein. Womble [2005] provides detailed descriptions of the visual damage characteristics of all four roofing categories.

Using the ground-based VIEWS™ survey data, a set of 77 residential buildings was selected for correlation of remote-sensing signatures and ground-truthing observations. Roof segments of these buildings were ranked according to increasing damage states. Visual examination of satellite images of buildings in each damage state revealed typical visual signatures of wind damage, which can be used in the development of damage-assessment algorithms. The results of the qualitative examination are expressed in the Remote-Sensing Damage Scale for Residential Construction (Table 1). This scale focuses specifically on elements that are critical for detection and assessment of damage at discrete levels using remote-sensing measures.

Quantitative Description of Damage

In addition to visual/qualitative assessment of damage, digital images also form the basis for the *automated* detection of windstorm damage. An ever-growing library of archived satellite images provides pre-storm information for most urban areas. Building damage and debris spread can be identified and classified by applying change-detection algorithms to temporal image sequences. In the comparison of before-and-after images, building damage appears as changes in shape, lines, colors, texture, etc. Theoretically, such temporal changes can be quantified and correlated with damage conditions observed in the field to develop algorithms for the automated assessment of building damage. The correlation of change-detection measures with actual damage conditions noted in the field is a critical part of the development of automated windstorm damage detection and is necessary to distinguish actual damage conditions from false indicators of building damage (e.g., lighting conditions and vegetation changes). The development of computer algorithms to detect and quantify building damages using digital images is therefore a critical component of automated damage assessment methodologies.

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 2. For each multispectral band, the pre- and post-storm histograms are superimposed on the same plot. These histograms demonstrate the appearance of damage to the roof facet from a quantitative remote-sensing perspective. Shifts in mean values are attributed to both illumination differences and to physical changes. Changes in dispersion are attributed to physical changes in the roof facet and are interpreted as damage.

As discussed by Womble [2005], the analysis of objects corresponding to individual roof facets, rather than full roof assemblies covering an entire building, is prompted by (1) inherent difficulties in normalizing the illumination of corresponding slopes of multi-faceted roofs between temporal image pairs acquired at different sun angles and light intensities and (2) aerodynamic discontinuities in damage between adjacent roof facets. Due to breaks in aerodynamic form at sharp edges, a particular building may have some roof facets which are not damaged as well as roof facets that are severely damaged.

From the study set of 77 residential buildings described above, classification of the individual roof facets according to the Remote-Sensing Damage Scale of Table 1 resulted in the following distribution: RS-A (94), RS-B (76), RS-C (48), and RS-D (49). DN values of pixels comprising each roof-facet object were extracted from the before-and-after digital image pairs for each of the four QuickBird multispectral bands. Object-level statistics were computed for each set of DN values, including standard deviation, variance, average deviation, skewness, uniformity, and entropy. Comparison of before-and-after object-level statistics (such as by differencing or ratioing) results in *damage metrics*, which numerically describe temporal changes in the roof facets. For this case study, nine separate damage metrics were examined: standard deviation (ratio and difference), variance (ratio), skewness (difference), average deviation (ratio), uniformity (ratio and difference), and entropy (ratio and difference). Complete results of this study are provided by Womble [2005].

Windstorm damage profiles form the basis for the automated assessment of windstorm damage based on characteristic changes in remote-sensing imagery. The windstorm damage profiles are plots of damage metrics versus actual damage states and define the correlation between remote-sensing measures of damage and the actual damage states observed in the field. The use of damage profiles to describe the severity of earthquake damage to various zones within a city was introduced by Eguchi *et al.* [2003]; the concept has been adapted for windstorm damage to individual roof segments by Womble [2005].

An idealized windstorm damage profile would uniquely define particular damage states for given values (or ranges) of damage metrics. Figure 3 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 general 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); however, the data contain too much scatter to accurately assign a unique damage state based on a given value of damage metric. Distinction between mid-level damage states (RS-B or RS-C) is difficult for damage profiles with large data spread.

Note that the uniformity ratio exhibits a trend reversal from a uniform (undamaged) roof (RS-A), to less-uniform roofs (partial damage at RS-B and RS-C) and then returning to a more uniform state (RS-D) when the roof assembly is removed and perhaps only a slab remains, creating a more uniform appearance than a partially damaged roof surface. Also of interest is the observation that roof facets producing apparent statistical outliers in damage metrics do not produce statistical outliers for all spectral bands, indicating that such damage metrics are sensitive to the specific spectral signatures (colors) of various roof covering materials. These results also highlight the importance of accurate edge delineation, since minor levels of wind damage are likely to be found at the edges of roofs – where failures initiate.

In addition, spectral signatures and band ratios (e.g., NDVI) can be employed to locate debris spread across lawns or water surfaces. Some false damage indicators, such as ponding of rainwater on building roofs and removal of overhanging vegetation, are also subject to detection via use of spectral signatures.

RECENT APPLICATIONS

Damage from Hurricane Katrina (2005) has prompted an unprecedented series of legal challenges pitting homeowners against property insurance companies. Settlement of these claims has required the separation of damage resulting from wind and water (storm surge). Remote-sensing imagery collected rapidly after the hurricane and months after the hurricane have proven useful for the determination of neighborhood damage patterns and probable losses to specific buildings.

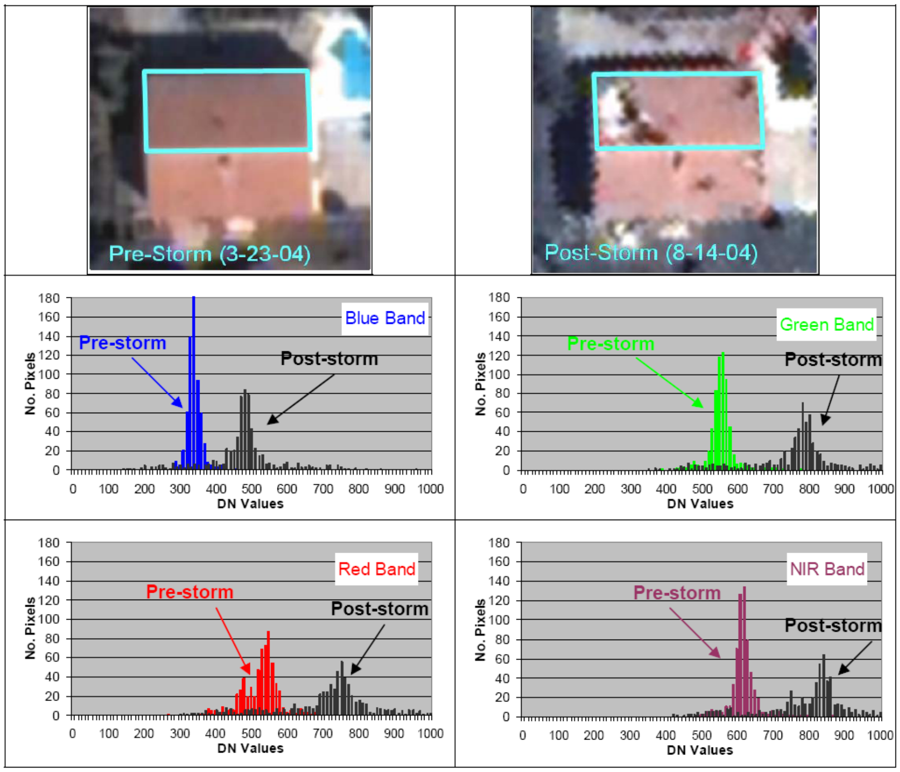

Figure 2. Comparison of pre- and post-storm object histograms for a single roof slope, from Womble [2005]. QuickBird imagery from DigitalGlobe, Inc. [www.digitalglobe.com].

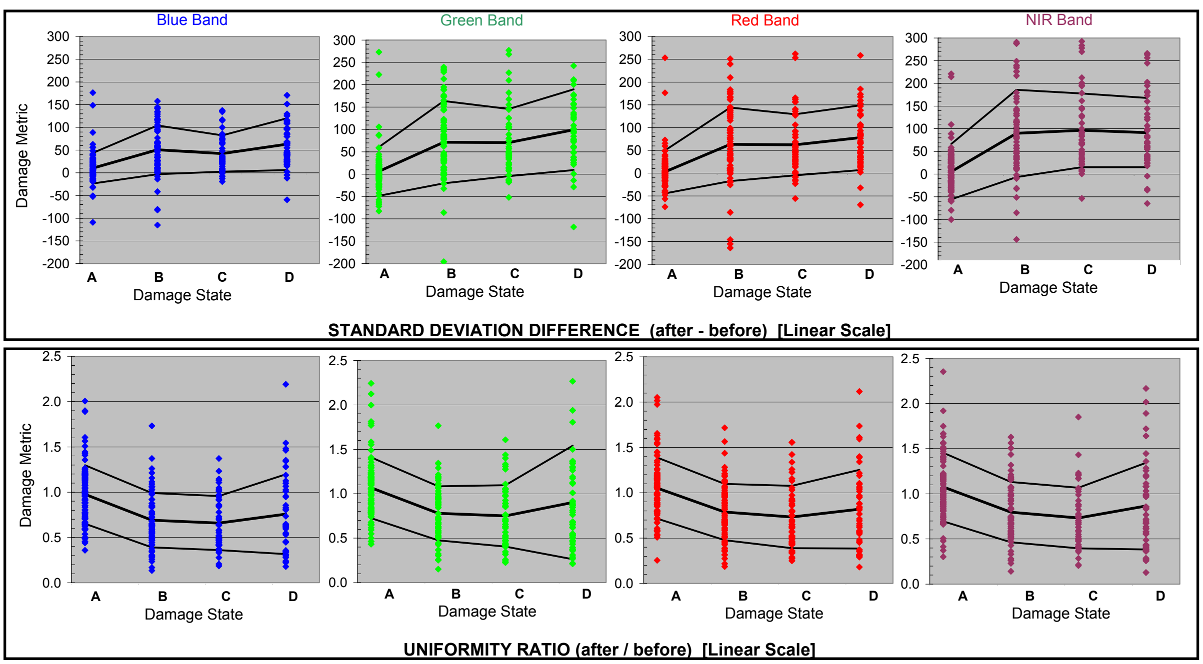

Figure 3. Sample windstorm damage profiles for the study sample of buildings subjected to Hurricane Charley and Ivan. Damage metrics are based on before-and after comparison of satellite images of 267 roof facets from 77 buildings. Damage states are defined by the Remote-Sensing Damage Scale (Table 1) and are based on ground-truthing surveys performed with the VIEWS™ system. Trend lines correspond to group means and (mean ± 1 standard deviation). From Womble [2005].

CONCLUSIONS

A pioneering examination of the use of remote-sensing imagery for wind damage assessment defines a methodology by which the automated assessment of windstorm damage may ultimately be achieved. The development of accurate and fully automated change-detection algorithms for wind damage to structures is a lengthy and continuing process involving extensive research in change detection, object delineation/extraction, development of damage metrics, and correlation with damages noted in the field.

Damage scales based on visual characteristics detectable by remote-sensing form important an important step towards the development of change-detection algorithms. From the case study described above, it is recommended that object-based change statistics, based on roof facets, can be used to quantify damage. General damage trends are apparent in the windstorm damage profiles resulting from an initial case study of residential buildings, indicating that object-based damage metrics are helpful for the correlation of field observations with remote-sensing signatures and thus for the training of computer algorithms to perform automated damage assessments. The damage profiles examined in this study contain significant data spread, indicating that these damage metrics are not sufficiently correlated with damage states to allow assignment of a unique damage state given a particular value of damage metric. (The development of additional damage metrics is the focus of future research efforts.)

We foresee that improvements in temporal and spatial resolutions will facilitate more accurate remote-sensing assessments of windstorm damage. Enhanced spatial resolutions will assist in more accurately delineating edges and therefore in detecting minor-to-moderate levels of damage. We also foresee that remote-sensing damage assessments will complement more-detailed surveys by providing a rapid and synoptic view of damage throughout an affected area, by serving as a screening tool for the strategic planning of detailed ground-based investigations, and by rapidly preserving untouched damage scenes. Extension of the technology to areas affected by tornadoes can ultimately enable engineers and scientists to rapidly determine EF-Scale ratings based solely on comparison of remote-sensing images without costly and time-consuming ground surveys.

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