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Remote Sensing for Resilient Multi-Hazard Disaster Response

Volume I: Introduction to Damage Assessment Methodologies

by
Beverley J. Adams and Ronald T. Eguchi

Technical Report MCEER-08-0020

November 17, 2008

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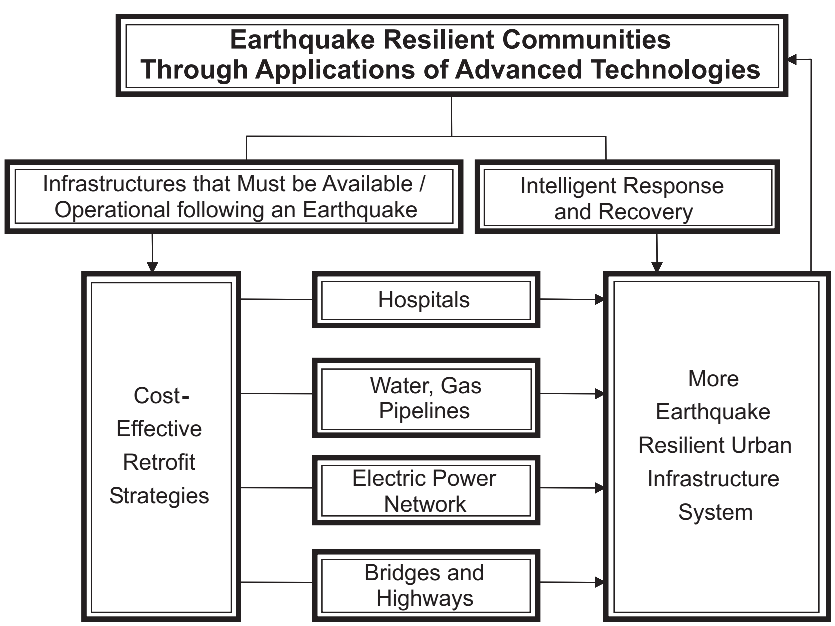
Preface

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 introduces the use of remote sensing and advanced technologies for resilient multi-hazard disaster response. The roles of technology push and user pull as factors leading to the increasing use of remote sensing within operational disaster situations are discussed, together with their contribution towards enhancing resilience through more rapid and resourceful response. A tiered reconnaissance framework is presented, which serves as a conceptual model for organizing post-disaster deployments. Tier 1 presents a 'regional' perspective on damage; Tier 2 offers a more detailed neighborhood presentation of damage within a community; and Tier 3 offers a highly detailed per-building record of loss. The role of MCEER and its Remote Sensing Institute is described, and an overview of 16 events after which MCEER teams have performed laboratory- and field-based damage assessments is presented. This is Volume I of a five part series of reports that investigate 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

The overarching purpose of this five volume series of technical reports is to serve as a benchmark for the current state-of-the-art in multi-hazard remote sensing and GIS-based damage assessment techniques. It provides a collected account of the remote sensing and GIS-based damage assessment methodologies and applications, focusing in detail on specific damage detection techniques that have recently been developed and implemented by MCEER researchers and collaborators at US and International research organizations in the aftermath of the Bam earthquake, hurricane Charley and flooding caused by hurricane Katrina.

Volume I introduces the use of remote sensing and advanced technologies for resilient multi-hazard disaster response. The roles of Technology Push and User Pull as factors leading to the increasing use of remote sensing within operational disaster situations are initially discussed, together with their contribution towards enhanced *resilience* through more rapid and resourceful response.

A Tiered reconnaissance Framework is presented, which serves as a conceptual model for organizing post-disaster deployments. Tier 1 presents a 'regional' perspective on damage. Tier 2 offers a more detailed neighborhood presentation of damage within a community. Tier 3 offers a highly detailed per-building record of loss. The role of MCEER and its new Remote Sensing Institute is described, and an overview presented of 16 events after which MCEER scientists have performed laboratory- and field-based damage assessments.

A detailed literature review is provided of prior research activities using advanced technologies including remote sensing, GIS and georeferenced in-field data collection, to assess post-disaster damage. This literature review is used to establish outstanding research thrusts, which provide a framework for the activities described within the subsequent four volumes of this report series. The overarching goal and individual aims of these volumes are presented: Volume II addresses techniques for counting the number of collapsed buildings after an earthquake; Volume III combines images from different satellites to offer more robust damage assessments with the 'first available image'; Volume IV utilizes cloud penetrating radar to robustly detect flooding during the immediate aftermath of storms when viewing conditions are typically poor; and Volume V addresses post-disaster access issues, presenting a HAZUS-compatible remote sensing-based damage scale that enables teams to assess losses when roads are impassable.

Finally, the three case study events: (1) the Bam earthquake; (2) hurricane Charley; and (3) hurricane Katrina, are described, serving as a segue way from this introductory Volume to the subsequent Volumes II, III, IV and V, which focus on technical details of the methodologies, results and key findings.

ACKNOWLEDGEMENT

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Additionally, we would like to acknowledge the following individuals for their contributions to the work documented in these five volumes:

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Shubharoop Ghosh, ImageCat, Inc.

Marjorie Greene, EERI

Kishor Mehta, WISE Center, Texas Tech University

Jeremy Morley, Department of Geomatic Engineering, UCL

Keiko Saito, Cambridge University Centre for the Risk in the Built Environment (CURBE)

J. Arn Womble, WindForce Associates, Inc

Thuy Vu, GTRC, Japan

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SECTION 1

REMOTE SENSING FOR RESILIENT DISASTER RESPONSE

1.1 Introduction

The new millennium is witnessing the increasingly widespread deployment of advanced technologies, including remote sensing imagery and GIS- (Geographic Information Systems) and IMS (Internet Map Server)-based applications, to support and enhance response activities in the aftermath of catastrophic disasters in the US and around the world. The purpose of this five volume series of technical reports is to serve as a benchmark for the current state-of-the-art in multi-hazard remote sensing and GIS-based damage assessment techniques. It provides a collected account of the remote sensing and GIS-based damage assessment methodologies and applications that have recently been developed and implemented by MCEER researchers and collaborators in the aftermath of major earthquakes, floods and hurricanes; case study events include the 2003 Bam earthquake, hurricane Charley and hurricane Katrina. Volume I of this series provides an overview of prior and ongoing uses of remote sensing for resilient multi-hazard disaster response by MCEER and other researchers, presenting theoretical background for the specific research activities documented in the subsequent volumes.

The rapid growth in advanced technology deployment after disasters such as earthquakes, hurricanes and floods is largely attributable to two complementary factors: (1) technology push; and (2) user pull (Adams, 2005). The user pull emanates from an urgent need for reliable information in the immediate aftermath of the event. Whether the decision maker is concerned with directing emergency responders to affected areas, allocating international aid, or estimating insured losses, their common requirement is for accurate and timely information about the severity of urban damage and extent of affected populations. Couple this with the increasing frequency of disasters as global urban development continues to expand, plus a five-fold increase in the direct cost from natural disasters in the past two decades, and the pressing need for routinely available, low-cost post-disaster information is apparent. Key sectors benefiting from this information include: Re/Insurance and Emergency Management.

In terms of technology push, the increasing availability of highly detailed, yet relatively low-cost images from satellites and aircraft, has been one important driving force behind operational implementation. Images captured by sensors such as Quickbird and IKONOS, which have a spatial resolution of 0.6m-1m, enable post-disaster damage sustained by individual structures to be identified. This so called 'direct' sensing of damage[1] has proved highly effective for distinguishing the extent and severity of damage after events such as hurricane Katrina and the Indian Ocean tsunami. Through integration into field survey systems such as VIEWS (Adams et al., 2005b) it has also streamlined and accelerated the collection of perishable post-disaster damage observations for damage assessment and validation activities. The photo mosaic in figure 1-1 provides examples of building damage observable in high-resolution imagery.

[1] In theoretical terms, a basic distinction can be drawn between 'direct' approaches, where damage is recorded through its signature within the imagery versus 'indirect' indicators, using a surrogate measure such as nighttime lighting levels from DMSP (Hashitera et al., 1999).

A second factor driving the technology push has been the continued investment made by research organizations, such as MCEER, in developing techniques and methodologies to extract critical and timely information about the unfolding disaster scene. For a number of years, MCEER researchers have, through funding support from the US National Science Foundation (NSF), been pioneering new remote sensing-based techniques for *resilient* disaster response that rapidly quantifies the severity and extent of damage (Adams et al., 2003, 2004a, 2004b; Eguchi et al., 2003b; Huyck et al., 2004a, 2005).

Figure 1-1 Photo Mosaic Illustrating Building Damage for Recent US Hurricanes, Captured Using High-Resolution Optical Satellite and Aerial Images and In-Field Observations

Embracing the resilience concept promises a number of important benefits to the end user (Bruneau et al., 2003), including reduced consequences from infrastructure failure, and reduced time to recovery. According to the MCEER definition (Tierney and Bruneau, 2007), resilience encompasses four key dimensions: (1) rapidity; (2) resourcefulness; (3) redundancy; and (4) robustness. Specifically, the outputs from MCEER's remote sensing research and development activities offer end users an additional level of resilient disaster support through:

Rapidity **– The capacity to provide swift, objective and accurate urban damage and loss assessments**

Resourcefulness **– The capacity to identify affected areas, establish priorities and allocate resources in a multi-hazard context. Remote sensing provides non-restricted views of the post-disaster situation, when access on the ground-based is limited or precluded.**

1.2 MCEER Research Activities

MCEER's remote sensing-based disaster response research and deployment activities have a *multi-hazard* focus. They encompass a wide range of natural disasters, spanning:

- Flood
- Earthquake
- Storm surge
- Tsunami wave
- Wildfire
- Hurricane
- Tornado
- Man-made events such as the World Trade Center attack.

The origins for MCEER's disaster response work lie in the realm of earthquake engineering, with exploratory research and initial testing taking place after the 1999 Marmara (Turkey) (see, for example, Eguchi et al., 2000a, 2000c, 2002; Huyck et al., 2002, 2004a), 2003 Boumerdes (Adams et al., 2004a) and 2003 Bam (Iran) earthquakes (Adams and Huyck, 2006; Adams et al., 2004b; Huyck et al., 2005). However, as the scope of MCEER's resilience concept has progressively broadened to include other types of peril, advanced technology applications have followed accordingly.

In 2004, Hurricane Charley saw the initial development and implementation of remote sensing-based damage assessment methodologies and applications for a major windstorm (Adams et al., 2004c). These techniques have since been enhanced, extended and deployed operationally in the aftermath of major events including hurricanes Ivan, Wilma, Rita, Dennis and Katrina. With the 2004 Indian Ocean tsunami, the scope of disaster response work was extended once more (Ghosh et al., 2005), while Hurricane Katrina enabled new flood and surge dimensions to be added. The 2007 California wildfires, together with the recent 2008 tornados in Tennessee further extended the scope of MCEER's resilient response activities to encompass two new disaster types. The so-called ‘Coming of Age’ for many of these damage assessment methodologies and applications (Adams 2005) has now arrived, with the launch of MCEER’s Remote Sensing Institute (RSI), through which operational damage assessment services are being offered.

Table 1-1 outlines the major remote sensing research thrusts and collaborations that have taken place between MCEER and both US-based and international research organizations from Italy, the United Kingdom, Japan and Canada. The principal collaborators contributing to the research documented in this report series are:

- Volume II: DISTART at the University of Bologna
- Volume IV: Department of Geomatic Engineering at University College London (UCL)
- Volume V: Wind Science and Engineering (WISE) research center at Texas Tech University

Table 1-1 MCEER Collaborators, Involved in Remote Sensing Research for Disaster Response

Collaborator	Research Thrust
MCEER and Texas Tech Wind Science and Engineering Research Center	▪ Advanced technologies for rapid and efficient post-hurricane and post-tornado reconnaissance activities ▪ Developing a remote sensing-based damage scale for hurricane to enable assessments when ground access is restricted
MCEER and Louisiana State University Hurricane Center	▪ Advanced technologies for rapid and efficient storm surge and flood reconnaissance activities ▪ Developing a remote sensing-based damage scale for storm surge to enable assessments when ground access is restricted ▪ Developing an integrated flood-wind damage scale for assessing the damage after multi-hazard events
MCEER and UCL	▪ Urban flood detection using radar for rapid 24/7 all-weather damage assessment
MCEER and University of Bologna	▪ Object-based techniques for counting post-earthquake building collapse and rapidly determining the appropriate magnitude of response
MCEER and Chiba University	▪ Advanced technologies for rapid and efficient post-tsunami damage assessment
MCEER and the Coastal Development Center, Thailand, University of North Carolina at Chapel Hill and University of British Columbia	▪ Assessing coastal degradation caused by the tsunami ▪ Benchmarking recovery in tsunami-affected areas

This report series will draw on the multi-hazard events that MCEER researchers and their collaborators have responded to around the world (see figure 1-2). For earthquake, events studied include the 1999 Marmara Turkey, the 2003 Boumerdes Algeria, and the 2003 Bam Iran events. MCEER researchers also deployed advanced technologies to support field reconnaissance data collection after the 2004 Niigata and 2004 Parkfield earthquakes. In the case of windstorm, damage assessments were conducted after hurricanes Charley and Katrina, with accompanying advanced technology-based data collection after Charley, Ivan and Katrina, and operational in-field reconnaissance for the Re/Insurance industry after Hurricanes Dennis, Katrina, Rita, and Wilma. Table 1-2 outlines these events and the techniques employed. Its also highlights the subset of events featured within this report series, which are listed in table 1-3.

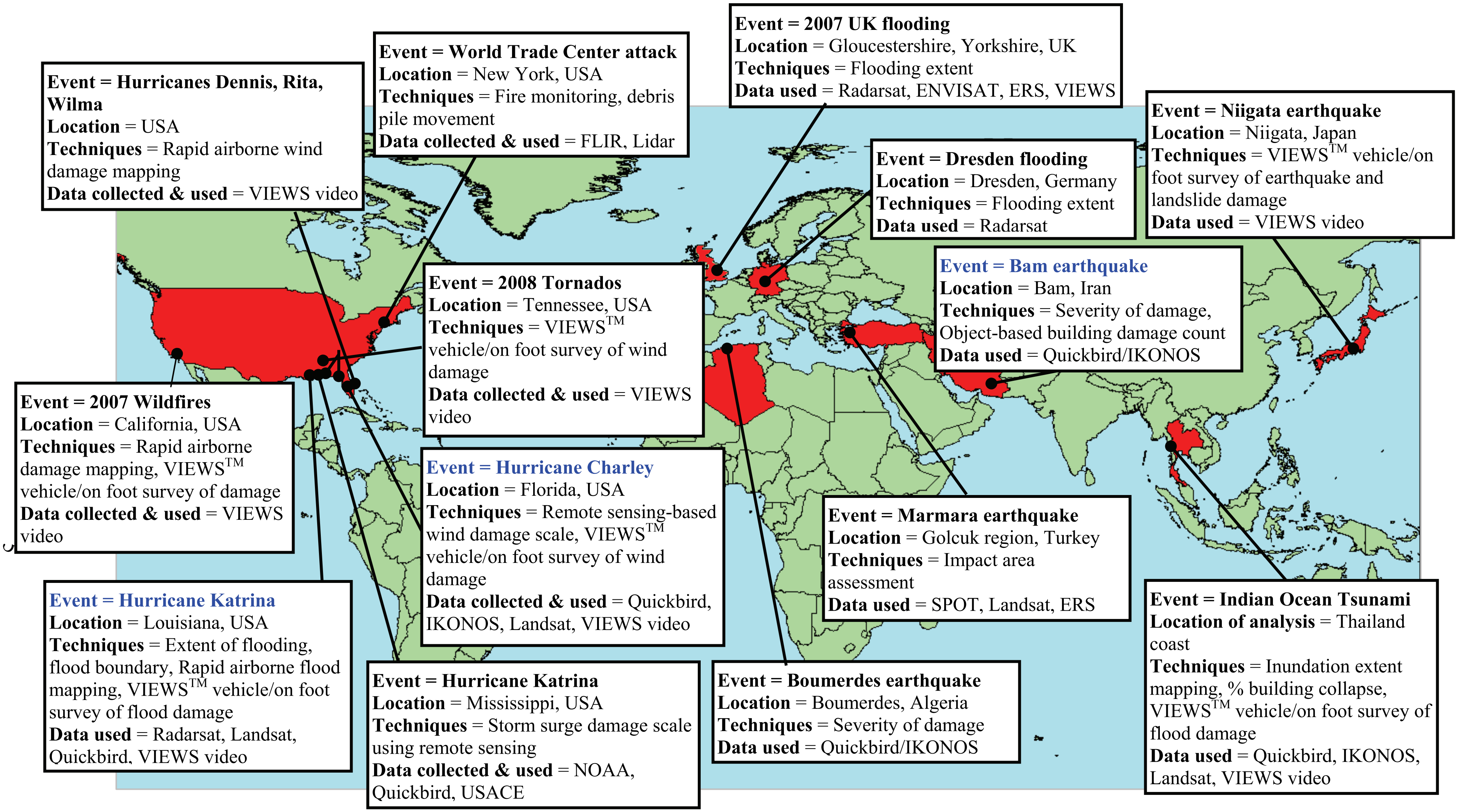


Figure 1-2 Global Multi-Hazard Research and Development Activities Conducted by MCEER Researchers and Collaborators. Events Highlighted in Blue are Featured in the Present Report Series. See Text for References Featuring Other Events.

Table 1-2 Multi-Hazard Events Studied by MCEER Researchers and Selected Case Studies (Highlighted in Yellow). Events are Organized According to their Assessment Position within the Tiered Reconnaissance Framework (see Section 1.2 and Figure 1-3).

	TIER 1 (Regional)	TIER 2 (Neighborhood)	TIER 3 (Per-Building)
Earthquake	Event = Marmara earthquake Location = Golck region, Turkey Technique = Impact area assessment Data used = SPOT, Landsat Sensor type = optical, satellite Reference = Huyck et al. (2004a)	Event = Bam earthquake Location = Bam, Iran Technique = Severity of damage using multi-sensors Data used = Quickbird/IKONOS Sensor type = optical, satellite Reference = Present report series	Event = Bam earthquake Location = Bam, Iran Technique = Object-based building damage count Data used = Quickbird, IKONOS Sensor type = optical, satellite Reference = Present report series, Gusella (2006)
	Event = Marmara earthquake Location = Golcuk region, Turkey Technique = Impact area assessment Data used = ERS Sensor type = radar, satellite Reference = Huyck et al. (2004a), Eguchi et al. (2003a)	Event = Boumerdes earthquake Location = Boumerdes, Algeria Technique = Severity of damage Data used = Quickbird/IKONOS Sensor type = optical, satellite Reference = Adams (2004)	Event = Niigata earthquake Location = Niigata, Japan Technique = VIEWS™ vehicle/on foot survey earthquake & landslide damage Data used = VIEWS video, Quickbird Sensor type = optical, ground-based, satellite Reference = Huyck et al. (2006)
Flood	Event = Hurricane Katrina Location = Louisiana, USA Technique = Rapid airborne flood mapping using PDV Data used = VIEWS video Sensor type = optical, aerial Reference = Womble et al. (2006a)	Event = Hurricane Katrina Location = New Orleans, USA Technique = Flood boundary & extent mapping Data used = Radarsat I, Quickbird Sensor type = radar, optical, satellite Reference = Present report series, Womble et al. (2006a)	Event = Hurricane Katrina Location = New Orleans, USA Technique = VIEWS™ vehicle/on foot survey flood damage Data used = VIEWS video, Quickbird Sensor type = optical, ground-based, satellite Reference = Womble et al. (2006a)
	Event = Hurricane Katrina Location = Louisiana, USA Technique = Mapping of flood extent Data used = Landsat 5 TM Sensor type = optical, satellite Reference = Womble et al. (2006a)		Event = Hurricane Katrina Location = New Orleans, USA Technique = Remote sensing building flood/wind damage scale Data used = VIEWS, Quickbird images Sensor type = optical, aerial, satellite Reference = Womble et al. (2006a)
	Event = 2007 UK floods Location = Gloucestershire, Yorkshire, UK Technique = Radar mapping of flood extent Data used = Radarsat, ERS, ENVISAT Sensor type = radar (SAR), satellite Reference = McMillan et al. (2007)	Event = 2007 UK floods Location = Gloucestershire, Yorkshire, UK Technique = Radar mapping of flood extent Data used = Radarsat, ERS, ENVISAT Sensor type = radar (SAR), satellite Reference = McMillan et al. (2007)	

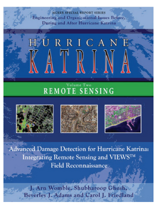
	TIER 1 (Regional)	TIER 2 (Neighborhood)	TIER 3 (Per-Building)
	Event = 2007 UK floods Location = Gloucestershire, Yorkshire, UK Technique = Rapid wind damage mapping using PDV/VIEWS Data used = VIEWS aerial video Sensor type = optical, aerial Reference = see www.imagecatinc.com		
Tornado			Event = 2008 Tennessee tornados Location = Settlements around Nashville, USA Technique = VIEWS™ vehicle/on foot survey flood damage Data used = Online images and Quickbird imagery Sensor type = optical, aerial, satellite Reference = see www.mceer.buffalo.edu
Hurricane	Event = Hurricanes Wilma, Dennis, Rita Location = Florida, USA Technique = Rapid wind damage mapping using PDV/VIEWS Data used = VIEWS aerial video Sensor type = optical, aerial Reference = Womble et al. (2006a)	Event = Hurricane Katrina Location = Mississippi, USA Technique = Severity ranking of wind damage Data used = NOAA images Sensor type = optical, aerial Reference = Womble et al. (2006a)	Event = Hurricane Charley Location = Port Charlotte & Punta Gorda, Florida, USA Technique = Remote sensing wind damage scale Data used = Quickbird & IKONOS images Sensor type = optical, aerial Reference = Present report series, Womble (2005)
			Event = Hurricane Charley Location = Port Charlotte & Punta Gorda, Florida, USA Technique = VIEWS™ vehicle/on foot survey of wind damage Data used = VIEWS video Sensor type = optical, ground-based Reference = Present report series, Adams et al., (2004c)
Storm Surge	Event = Hurricane Katrina Location = Mississippi, USA Technique = Surge extent mapping Data used = Landsat 5 TM Sensor type = optical, satellite Reference = Womble et al. (2006a)	Event = Hurricane Katrina Location = Mississippi coast, USA Technique = Storm surge boundary mapping Data used = NOAA images Sensor type = optical, aerial	Event = Hurricane Katrina Location = Settlements along Mississippi coast, USA Technique = Remote sensing surge damage scale Data used = NOAA, USACE, Quickbird images Sensor type = optical, aerial, satellite Reference = Friedland and Adams (2006) Friedland et al. (2007)

	TIER 1 (Regional)	TIER 2 (Neighborhood)	TIER 3 (Per-Building)
			Event = Hurricane Katrina Location = Settlements along Mississippi coast, USA Technique = Temporal sequence of VIEWS™ vehicle/on foot surveys of surge damage Data used = VIEWS video Sensor type = optical, ground-based Reference = Womble et al. (2006a), Hill et al. (2006)
Tsunami	Event = Indian ocean tsunami Location = Andaman coast, Thailand Technique = Inundation extent mapping Data used = Landsat 5 TM Sensor type = optical, satellite Reference = Chang et al. (2006)	Event = Indian ocean tsunami Location = Ban Nam Khem, Thailand Technique = % building collapse Data used = Quickbird/IKONOS Sensor type = optical, satellite Reference = Chang et al. (2006)	Event = Indian ocean tsunami Location = Ban Nam Khem, Thailand Technique = Temporal sequence of VIEWS™ vehicle/on foot surveys of damage Data used = VIEWS video Sensor type = optical, ground-based Reference = Ghosh et al. (2005); Chang et al. (2006)
Wildfire	Event = 2007 California wildfires Location = San Diego, Santa Clarita, Lake Arrowhead, Lake Gregory, Malibu USA Technique = Rapid fire damage mapping using PDV/VIEWS™ Data used = VIEWS aerial video Sensor type = optical, aerial Reference = see www.rms.com		Event =2007 California wildfires Location = Grass Valley, Ramona, Poway, Rancho Bernado, Technique = VIEWS vehicle/on foot survey flood damage Data used = Online images VIEWS video Sensor type = optical, aerial Reference = see www.mceer.buffalo.edu
Terrorism	Event = World Trade Center attack Location = New York, USA Technique = Thermal hotspot assessment Data used = SPOT thermal imagery Sensor type = Thermal, satellite Reference = Huyck and Adams (2002)	Event = World Trade Center attack Location = Manhattan, New York Technique = Temporal evaluation of burn area & temperature Data used = FLIR thermal imagery Sensor type = Thermal, aerial Reference = Huyck and Adams (2002)	Event = World Trade Center attack Location = Ground Zero, New York, USA Technique = Temporal evaluation of changes in debris pile shape and elevation Data used = LIDAR imagery Sensor type = LIDAR, aerial Reference = Huyck and Adams (2002)

Table 1-3 Summary Listing of Events and Techniques Described in this Damage Detection Report Series

Location in report series	Hazard	Event	Techniques described and information obtained
Volume II	**Earthquake**	Bam	✓ Count the number of collapsed buildings
Volume III **Volume IV** **Volume V**	**Earthquake** **Flood** **Hurricane**	Bam Katrina Charley	✓ Detect and map damage severity with multi-sensor integration ✓ Flood boundary & extent mapping using radar ✓ Remote sensing-based damage scale for wind ✓ Detect and map the regional impact area ✓ Aerial survey of damage extent and severity using VIEWS ✓ Ground survey of building damage using VIEWS

The events featured in this volume series encompass major outcomes and achievements from MCEER's research between 1999-present. In a number of instances, important response-focused research activities have already been comprehensively documented in published reports, and thus are not described in detail here[2]. Important examples include:



Womble, J.A., Ghosh, S., Adams, B.J. and Friedland, C,J. (2006a) Advanced Damage Detection for Hurricane Katrina: Integrating Remote Sensing and VIEWS™ Field Reconnaissance, MCEER Special Report Series Hurricane Katrina, Volume II, MCEER: Buffalo.

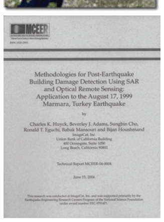
http://mceer.buffalo.edu/publications/Katrina/06-SP02.asp

Adams, B.J., Womble, J.A., Turner, J., Mio, M., Mehta, K. and Ghosh, S. (2004c) Collection of Satellite-Referenced Building Damage in the Aftermath of Hurricane Charley, MCEER/NHRAIC Response Report, MCEER: Buffalo.

http://mceer.buffalo.edu/research/Reconnaissance/Charley8-13-04/04-SP04.pdf

Huyck, C.K. and Adams, B.J. (2002) Emergency Response in the Wake of World Trade Center Attacks: The Remote Sensing Perspective, MCEER Special Report Series on the World Trade Center Attack Volume III MCEER-02-SP05, MCEER: Buffalo.

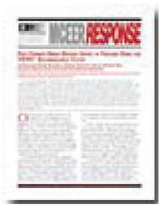
http://mceer.buffalo.edu/publications/wtc/WTCReports/



Huyck, C.K., Adams, B.J., Cho, S., Eguchi, R.T., Mansouri, B. and Houshmand, B. (2004a) Methodologies for Post-Earthquake Building Damage Detection Using SAR and Optical Remote Sensing: Application to the August 17, 1999 Marmara, Turkey Earthquake, MCEER Research Reports, MCEER: Buffalo.

http://mceer.buffalo.edu/research/Remote_Sensing/Reports.asp

[2] MCEER research activities are by no means limited to the response phase of the disaster management cycle. For example, mitigation, preparedness and recovery initiatives fall outside the scope of the present response-focused study. For further details of these complementary research thrusts see Adams and Huyck (2006), Hill et al. (2006), and Chung et al., (2004), Sarabandi et al. (2004, 2005, 2006).



Ghosh, S., Adams, B.J., Huyck, C.K., Mio, M., Eguchi, R.T., Yamazaki, F., and Matsuoka, M. (2005) MCEER Response: Post-Tsunami Urban Damage Survey in Thailand Using the VIEWS Reconnaissance System, MCEER Response Report, MCEER: Buffalo

http://mceer.buffalo.edu/research/Reconnaissance/tsunami12-26-04/

McMillan, A., Morley, J.G., Adams, B.J. and Chesworth, S. (in review) A study of multi-temporal and multi-resolution SAR imagery for post-Katrina flood monitoring in New Orleans, *International Journal of Remote Sensing*.

For details of this research, see Volume IV of this report series

MCEER researchers have been working with practitioners from a range of different industries to test, validate and begin implementing the techniques and methodologies described in this report series. Selected examples include the Re/Insurance sector, where operational post-hurricane damage assessment activities following Katrina, Rita, Wilma and Dennis, and post-wildfire loss estimation were conducted in collaboration with Risk Management Solutions (RMS) (see, for example, DigitalGlobe, 2005; RMS, 2008; Womble et al., 2006a). From the engineering sector, EERI (Earthquake Engineering Research Institute) has deployed MCEER field data collection and visualization equipment with field teams following the Bam and Niigata earthquakes. MCEER researchers also supported the WISE center at Texas Tech with their advanced technology field data collection system during post-hurricane deployments following Charley and Ivan, leading to a long-term research collaboration that has recently been extended to tornado. NIST field teams also implemented the data collection system to assess damage following hurricane Rita and Katrina (NIST, 2006).

1.3 Tiered Reconnaissance Framework

Within this report series, multi-hazard damage assessment techniques are presented within a three (3)-stage Tiered Reconnaissance Framework (see Adams et al., 2004a, 2005; Friedland et al., 2007; Womble et al., 2006a). The basic premise is that information garnered from one tier informs analysis conducted and decisions made at the next tier. From figure 1-3, information about the regional extent of damage obtained from Tier 1 (Regional) guides the identification of severely impacted areas, which are focused on further at Tier 2. Tier 2 (Neighborhood) assessment of damage severity within impacted neighborhoods offer guidance for forensic evaluations undertaken at Tier 3 on a per-building basis.

Returning to the event summary in table 1-2, multi-hazard disasters studied by MCEER researchers are organized according to the Tiered Reconnaissance Framework. In terms of advanced-technology implementation, at Tier 1 the spatially extensive coverage offered by moderate-resolution sensors such as Landsat-5 Thematic Mapper (TM) and the PDV VIEWS system offer a “quick-look” region-wide perspective for establishing the broadscale extent of the event (Adams, 2004, Adams et al., 2005a, 2005c). At Tier 2, high-resolution optical and radar imagery distinguishes damage severity in terms of hardest-hit and lesser-affected neighborhoods (e.g., Adams et al., 2004a; Saito et al., 2004; Chiroiu et al., 2006). At Tier 3, high-resolution optical imagery determines damage to individual buildings. In the specific case of damage assessment, Tier 3 technology may further facilitate in-field structural damage assessment through its integration into field-reconnaissance tools such as VIEWS™ (Womble, 2005; and Womble et al., 2006a).

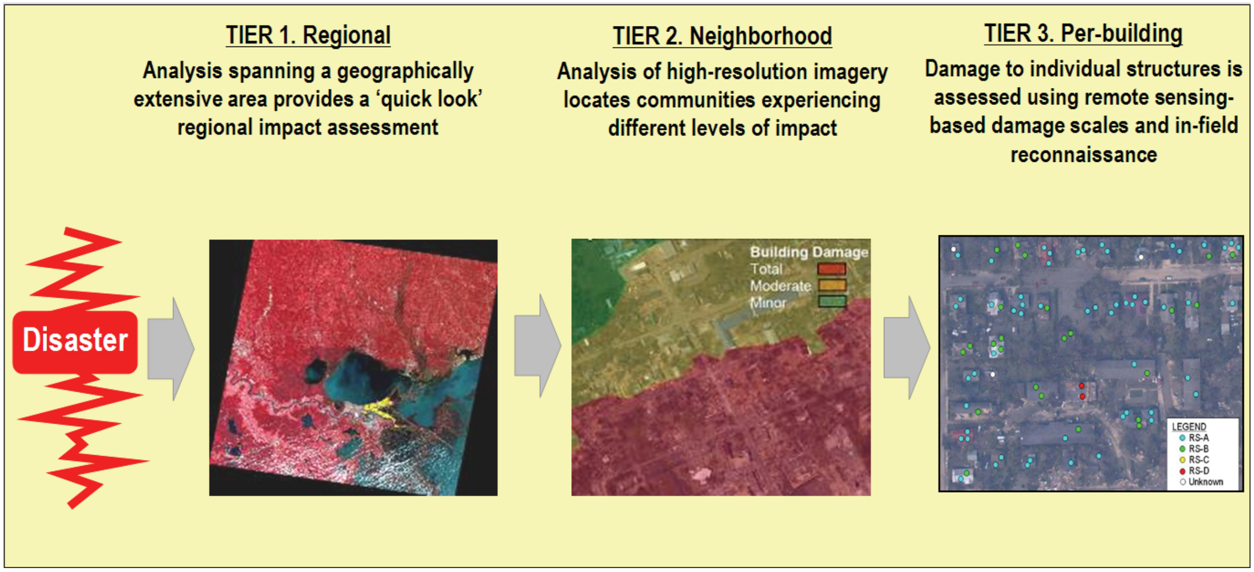


Figure 1-3 Tiered Reconnaissance Framework within which Damage Assessment Methodologies and Applications are Presented

A range of different techniques and methodologies may be employed, depending on the level of analysis within the Tiered Reconnaissance Framework. In the case of earthquake, techniques described in this report series range from the *neighborhood* assessment of damage severity using a methodology that integrates 'before' and 'after' images captured by different satellites, to counting the number of collapsed *buildings* though object-oriented damage assessment. For flood, a *neighborhood* assessment of flood extent is conducted using a temporal sequence of radar imagery. In the case of windstorm and storm surge, a remote sensing-based *per building* damage scale is presented. These examples demonstrate how damage severity can be remotely, yet swiftly determined after an event, in a manner that is independent of ground accessibility and if necessary can avoid placing personnel at risk through deployments to dangerous in-field locations. The remote sensing damage scale is also consistent with popular damage scales such as HAZUS-MH.

Specifically, Volume II of this report series presents a Tier 3 methodology counting the frequency of collapsed buildings, using optical imagery of the Bam earthquake as a case study. Bam is also the focus of Volume III, which compares the performance of three different Tier 2 methodologies for mapping the extent and severity of building damage. Volume IV presents a Tier 2 radar-based study of urban flood boundary and area mapping in New Orleans following hurricane Katrina. Finally, Volume V documents a range of different Tier 3 satellite and ground-based methods for mapping wind damage following hurricane Charley.

1.4 Aims and Objectives

The overarching goal of the multi-hazard research activities presented in this five volume report series is:

> ***Overarching Goal* – To develop robust methodologies for characterizing the extent and severity of post-disaster urban damage using high-resolution satellite imagery**

In this report, for each hazard type, prior research activities and progress made to date are reviewed, with the goal of highlighting important thrusts that require further attention. The MCEER research activities documented here seek to address these major thrusts, and as such, within this broad agenda, the following aims are identified for earthquake, flood, windstorm and surge hazard:

		<u>**Aim of Research Volume**</u>
Volume I	Multi-hazard	**An introduction to the use of remote sensing for resilient multi-hazard disaster response**
Volume II	Earthquake	**To develop an object-oriented methodology for rapidly counting the number of collapsed buildings in the immediate aftermath of a major earthquake**
Volume III	Earthquake	**To develop a multi-sensor pixel-based image fusion methodology, combining before and after images from different satellites to assess neighborhood damage extent and severity**
Volume IV	Flood	**To investigate the performance of multi-resolution SAR data to detect urban flooding**
Volume V	Hurricane	**To investigate the use of remote sensing technology for improving response to extreme windstorm events, using perishable field data and supporting satellite imagery**

The logistical framework diagram in figure 1-4 summarizes the methodological approaches used to address these objectives, details of which are presented in the respective volumes.

GENERAL AIM	**To develop robust methodologies for characterizing the extent and severity of post-disaster urban damage using high-resolution satellite imagery**			
AIM of SPECIFIC VOLUME	Volume II: Develop an object-oriented methodology for rapidly counting the number of collapsed buildings in the immediate aftermath of a major earthquake	Volume III: Develop a multi-sensor pixel-based image fusion methodology, combining before and after images from different satellites to assess neighborhood damage extent and severity	Volume IV: Investigate the performance of multi-resolution SAR data to detect urban flooding	Volume V Investigate the use of remote sensing technology for improving response to extreme windstorm events, using perishable field data and imagery
LEVEL OF TRS	Tier 3 (per building)	Tier 2 (Neighborhood)	Tier 2 (Neighborhood)	Tier 3 (per building)
STUDY LOCALE	Bam, Iran	Bam, Iran	New Orleans	Port Charlotte and Punta Gorda, FL
GENERAL APPROACH	Use an object-oriented approach to delineate buildings. Quantitatively characterize and count collapsed buildings using before and after images.	Apply cross-sensor pre-processing techniques. Quantitatively compare spectral and textural characteristics of images captured before and after the earthquake using pixel-based approaches.	Apply change detection techniques using pre- and post-imagery acquired in fine and standard beam modes. Use New Orleans to develop and validate signature for urban flooding.	Conduct qualitative and quantitative investigations of damage characteristics using remote sensing and in-field VIEWS damage observations.
DATASETS & SOURCE	Before: Quickbird After: Quickbird	Before: Quickbird After: IKONOS	Before: Radarsat I After: Radarsat I	Before: Quickbird After: Quickbird, aerial photographs, VIEWS data
HOW TO ADDRESS OBJECTIVE	Define intact building outlines as objects within the 'before' image. Apply image processing techniques to characterize building collapse. Use reclassification to identify collapsed objects within the scene. Count number of collapsed objects/buildings. Validate results against ground truth observations.	Explore image fusion/integration techniques to combine Quickbird/IKONOS images with different spectral and spatial characteristics. Investigate spectral, textural and edge-based differences using quantitative processing algorithms. Produce damage maps for neighborhood scale. Validate results against ground truth observations.	Calibrate imagery. Develop masks to remove non-urban and non-flood related features. Investigate the performance of change detection techniques including false color composites, thresholding and classification. Validate against independently derived flood extent layers from optical imagery.	Visually identify damage state characteristics for different occupancy types in remote sensing and VIEWS data. Develop observation-based damage scale that is compatible with HAZUS-hurricane. Quantify spectral properties of roof and debris damage. Explore surrogate indicators.
OUTPUT/ PRODUCT	Estimated number of collapsed buildings. Map showing location of collapsed buildings.	Estimated number of collapsed buildings. Map showing location of collapsed buildings.	Robust methodology that works if before and after images are available from different satellites.	HAZUS-compatible damage scale for hurricane. Damage metrics.

Figure 1-4 Logistical Framework Diagram, Summarizing the Overarching Research Aim, Objectives and Methodological Approach Documented in this Report

SECTION 2

LITERATURE REVIEW

2.1 Remote Sensing Research for Post-Disaster Damage Assessment

In the aftermath of catastrophic disasters, the rapid detection of damage within urban areas is an important resilience factor, since it provides critical decision support to help save lives, minimize loss and achieve an efficient response. For example, in the case of government and international emergency response teams, a swift assessment of building damage extent and severity provides a means of gauging an appropriate mobilization effort, and helps direct search and rescue teams to the hardest hit areas where victims may be trapped. For aid agencies, damage information may be used to generate a casualty estimate. It further supports the initial planning of response activities, and the identification of suitable locations for relief and support centers that remain easily accessible. For the re/insurance sector, damage data provides the basis for an initial estimate of losses.

The following sections review prior and ongoing research activities focusing on the development of remote sensing-based methodologies for multi-hazard post-disaster damage assessment. Previous research undertaken at MCEER is highlighted, since it lays the foundation for the activities presented in this report series. Hazard types are addressed in turn, spanning:

1. Earthquake
2. Flood
3. Hurricane windstorm

In each case, key research thrusts are identified, and in so doing, the rationale presented for the research activities featured in Volumes II, III, IV, and V of this report series.

2.2 Earthquake Damage Assessment

Remote sensing technology is increasingly recognized as a valuable post-earthquake damage assessment tool (Adams, 2005; Chiroiu et al., 2006). Recent studies following events including the 2001 Bhuj (India), 2003 Boumerdes (Algeria) and 2003 Bam (Iran) earthquakes have demonstrated that moderate and severe levels of building damage sustained in urban environments can be identified (see, for example, Adams et al. 2003, 2004a, 2004b; Chiroiu and Andre, 2001; Chiroiu et al., 2006; Gusella et al., 2004, 2005a, 2005b; Hutchinson and Chen, 2005; Huyck and Adams, 2004; Huyck et al., 2003a, 2004b, 2005; Rathje and Crawford, 2003; Saito and Spence, 2003, 2004, 2005; Saito et al., 2004; Shirzaei et al., 2006; Vu et al., 2004, 2005a, 2005b, 2006; Woo et al., 2005). The use of remotely sensed data for assessing building damage offers significant advantages over traditional methods of ground-based survey. Where the affected area is extensive and access limited or dangerous, it presents a low-risk, rapid overview of damage across an extended geographic area. For a review of remote sensing systems that are either currently available or planned, see Zhang and Kerle (2008).

As summarized by the literature review diagram in figure 2-1, from a theoretical standpoint, a range of remote sensing-based damage assessment techniques are documented in the literature (see also Chiroiu et al., 2006). These include both *indirect* and *direct* approaches.

2.2.1 Indirect Versus Direct Approaches

In the indirect case, damage is determined using a surrogate indicator. For example, changes in urban nighttime lighting levels have been used to infer disruption and damage within the urban environment (Hayashi et al., 2000; Kohiyama et al., 2004). Hashitera *et al.*, (1999) and Kohiyama *et al*. (2001) compare night-time lighting levels in US Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS) imagery acquired before and after the Marmara and Gujurat earthquakes. In both cases, areas exhibiting the greatest reduction in intensity corresponded with damaged settlements, supporting the hypothesis that fewer lights shine where buildings and accompanying infrastructure are severely damaged. Operating under the cover of darkness, this damage assessment tool is a useful supplement to optically-based methodologies that are limited to daylight hours.

In the direct case, building damage is recorded through its distinctive spectral or reflective signature within satellite or airborne imagery (Yamazaki, 2001). Damage is usually quantified in terms of the extent or density of damaged structures. Direct approaches to building damage assessment, which constitute the focus of this report series, may be categorized as mono- and multi-temporal. *Mono-temporal* analysis detects damage from imagery collected at a single time interval after the disaster has occurred. It is particularly useful when 'before' data is unavailable, and where the characteristics of damage are discernible given the spatial resolution of the imagery, and distinct from the non-damaged case. This thematic methodology (see, for example, Rathje et al., 2006) relies on direct recognition of collapsed structures on high-resolution coverage, through either visual recognition or diagnostic measures. It is most effective for extreme damage states, where buildings have collapsed or are severely damaged (Chiroiu *et al.*, 2002).

Mono-temporal images acquired by both aerial and satellite platforms have been employed for change detection (figure 2-1). In the case of aerial imagery, for a useful review of systems currently available to support disaster response activities, see Kerle et al. (2005a and 2005b). Ogawa and Yamazaki (1999, 2000) and Ogawa *et al.* (1999) employ photo interpretation of mono and stereo aerial photography to determine the damage sustained by wooden and non-wooden structures following the 1995 Kobe earthquake. A 'standard of interpretation' was devised to distinguish between collapsed, partially collapsed, and non-damage structures, based on: the occurrence of debris; level of deformation; and degree of tilt. Success of this methodological approach is judged in terms of correspondence with ground truth observations. Chiroiu and Andre (2001), Chiroiu *et al.* (2002) and Saito *et al*. (2004) use similar criteria to interpret building damage from high-resolution IKONOS satellite imagery of the Indian city of Bhuj, which sustained extensive damage during the 2001 Gujurat earthquake. Chiroiu (2005) and Saito et al. (2005) extend their techniques to assess damage caused by the Bam earthquake, respectively categorizing damage into classes of slight, moderate and heavy based on the observed frequency of building collapse, and finding that the accuracy of damage classification improves when post-event imagery is used. Turker and San (2004) explore shadow mapping on aerial imagery as an alternative source of damage information for the 1999 Marmara earthquake.

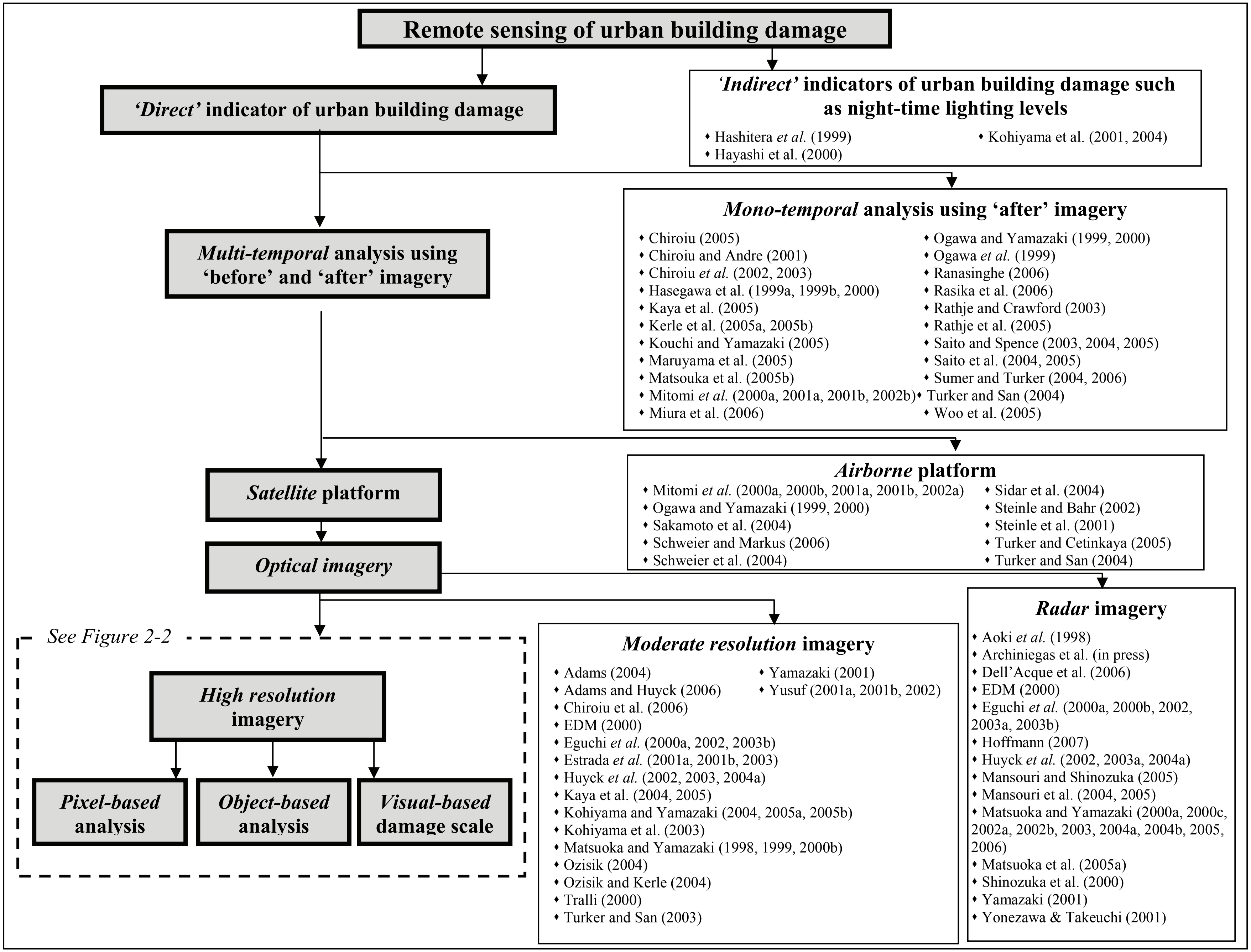


Figure 2-1 Literature Review Diagram, Summarizing Major Research Activities for Direct and Indirect Assessment of Post-Earthquake Building Damage, Using Optical and Radar Imagery

For the more recent Niigata event, Maruyama et al. (2005) successfully employ visually-based inspection of satellite imagery techniques to assess damage.

In addition to standard vertical photography, high speed automated aerial television is also emerging as a useful tool for mono-temporal damage assessment, which offers detailed footage and fairly rapid acquisition. Ogawa *et al.* (1999) and Hasegawa *et al.* (2000) inventory building collapse from visual inspection of HTTV imagery for Kobe. Diagnostic characteristics of debris and structural building damage are expressed quantitatively by Hasegawa *et al.* (1999b) and Mitomi *et al.* (2002a, 2002b). Their basic methodology recognizes collapsed and non-damage scenarios in terms of color, edge and textural information. Multi-level slice and maximum likelihood classifiers determine the spatial distribution of these classes (Mitomi *et al.*, 2001b). Although developed using imagery of Kobe, this methodology has successfully detected collapsed buildings in Golcuk, Chi Chi (Mitomi *et al.*, 2000a, 2000b, 2001b) and Gujurat (Mitomi *et al.*, 2001a; also Yamazaki, 2001). Ranasinghe (2006) and Rasika et al. (2006) also explore object and texture-based segmentation of airborne video data for damage mapping after the 1999 Marmara earthquake.

Thematic image processing techniques using mono-temporal aerial and satellite imagery are also documented. Sumer and Turker (2004) explore shadow characteristics in panchromatic vertical aerial photography for inferring building damage in Turkey, working towards an integrated damage detection system (Sumer and Turker, 2006). Supervised classification techniques have been used to detect damage respectively caused by the 1999 Marmara (Kaya et al., 2005), 2001 Bhuj (Saito and Spence, 2005), 2003 Boumerdes (Rathje and Crawford, 2003; Kouchi and Yamazaki, 2005), 2003 Bam (Matsuoka et al., 2005b; Rathje et al., 2005; Woo et al., 2005) and 2006 Central Java earthquakes (Miura et al., 2006) earthquakes. Saito and Spence (2004) and Rathje et al. (2006) instead employ textural analysis to identify damage caused by the Bam earthquake. Miura et al. (2006) go on to observe that damage assessment accuracies may be improved through comparison with a before image.

Multi-temporal analysis, which is the focus of Volume II, Volume III, and Volume IV of this report series determines the extent of damage from changes between images acquired at several time intervals, typically before and after an extreme event. Change detection-based studies have received some attention in the literature (for a review of general change detection methods see Hall and Hay, 2003), spanning the period before high-resolution satellite imagery became available, through to present date.

Comparatively few studies employ multi-temporal aerial imagery for damage assessment; most instead employ a single post-event scene. While airborne imagery offers a number of advantages compared with satellite coverage (for a review of aerial systems, see Kerle et al., 2005b) including depicting damage with a superior level of detail and the ability to fly below obscuring clouds, the availability or timeliness of archive pre-event footage may be limited (see, for example, Sidar et al., 2004). Sakamoto et al. (2004) explore 2D image matching method where damage is identified in terms of inconsistent areas of adaptive nonlinear mapping, and Turker and Cetinkaya (2005) examine the use of stereo-derived pre- and post-disaster Digital Elevation Models (DEMs) for mapping collapse. Steinle et al. (2001) present a theoretical study using active airborne LIDAR data as an alternative source of height data for modeling earthquake building and road damage (see also Schweier and Markus, 2006; and Schweier et al., 2004).

Satellite platforms offer advantages compared with aerial imagery, including global coverage and competitive imagery pricing. Prior to the launch of high resolution systems, moderate resolution satellites were successfully used to identified broadscale damage characteristics, but could not distinguish the detailed features of individual structures (Zhang and Kerle, 2008). The 1995 Hyogoken-Nanbu (Kobe) earthquake was one of the first events for which a change detection analysis was conducted, in this case using moderate resolution Landsat and ERS imagery collected before and after the event. The results suggested a trend between spectral change and ground truth estimates for the concentration of collapsed buildings (Matsuoka and Yamazaki, 1998; Tralli, 2000; Yamazaki, 2001). Research by Matsuoka and Yamazaki (1998), Chiroiu et al. (2002) and Miura et al. (2006) suggests that collapsed and extensively damaged buildings recorded distinct spectral signatures. However, moderate and minor damage states (for example, damage levels 1 and 2 on the EMS98 scale) are often indistinguishable from non-damage.

Change detection methods including differencing, ratios and correlation were also applied to moderate resolution optical data to evaluate damage in various cities affected by the 1999 Marmara earthquake in Turkey (Adams, 2004; Adams and Huyck, 2006; Adams *et al*., 2004a; Eguchi *et al.*, 2000a, 2000b, 2003b; Estrada et al., 2001b; Huyck et al., 2002, 2004b; Kaya et al., 2004, 2005; Matsuoka and Yamazaki, 2002a; Ozisik and Kerle, 2004; Turker and San, 2003; Yamazaki, 2001). Estrada et al. (2003) and Kohiyama et al. (2003) explore an alternative image fluctuation model method using simulated moderate resolution imagery following the Boumerdes earthquake, which is subsequently applied to Aster imagery after the 2003 Bam earthquake (Kohiyama and Yamazaki, 2005a, 2005b).

In addition to optically-based studies, Aoki et al. (1998), Archiniegas et al. (in press), EDM (2000), Matsuoka and Yamazaki (2002a, 2002b 2003, 2004a, 2004b, 2005, 2006), Mansouri and Shinozuka (2005) and Mansouri et al. (2004, 2005) and successfully apply a range of change detection indices to moderate resolution Synthetic Aperture Radar (SAR) imagery, including difference, correlation, cross-power, self-power and complex coherence, offering the advantage of 24/7, all-weather dam age assessment capabilities. Matsuoka and Yamazaki (2002a, 2003) go on to show consistency in the trend between building collapse and remote sensing measures for the 1993 Hokkaido, 1995 Kobe, 1999 Turkey, and 2001 Gujarat earthquakes. For further details of multi-temporal damage detection following the Gujurat event, readers are referred to Yusuf *et al.* (2001a, 2001b, 2002), Chiroiu *et al.* (2002, 2003) and Chiroiu and Andre (2001). For the 2001 El Salvador earthquake, see Estrada *et al.* (2001a).

Comparatively few studies have attempted to fuse moderate resolution imagery from different sources for multi-temporal damage detection. Huyck et al. (2004a) and Stramondo et al. (2006a, 2006b) explore the potential of integrating optical and SAR imagery for improving accuracies. Huyck et al. (2005) conduct a preliminary study into the integration of high-resolution pre- and post-disaster imagery acquired by different optical sensors.

2.2.2 High-Resolution Optical Imagery

Following the launch of commercial very high-resolution optical satellites such as Quickbird and IKONOS at the beginning of the new millennium, the availability of sub-meter imagery has driven a range of new multi-temporal damage detection activities (for a review, see Adams, 2005; Adams et al., 2004a; for collected studies following the Bam earthquake see Section 3.2 and Eguchi and Mansouri, 2005).

Figure 2-2 summarizes the major research thrusts that have emerged, which include: (1) Pixel-based techniques for rapidly identifying damaged neighborhoods; (2) Object-oriented methods for categorizing the damage state of individual structures; and (3) a remote sensing-based scale for assessing damage severity around the world.

The literature review diagram in figure 2-2 lists pixel-based studies conducted following recent earthquakes. Following the 2001 Bhuj event, Saito et al. (2004) identified collapsed structures through visual inspection. Chiroiu and Andre (2001) investigate false color composites and radiometric profiling for distinguishing damage, but produce inconclusive results. Yamazaki et al. (2004) visually interpret damage from before and after imagery, caused by the 2003 Boumerdes earthquake. Adams et al. (2004a) instead investigate semi-automated analytical approaches, mapping neighborhoods sustaining building collapse as a function of textural changes between the pre- and post-event coverage. Adams et al. (2004a) and Huyck et al. (2004b) go on to successfully apply a similar methodology to assess hard-hit regions within the City of Bam, implementing a combination of textural, edge filters and differencing to highlight significant changes on a neighborhood basis between before and after Quickbird imagery. Woo et al. (2005) also utilize textural variations within Bam, in this instance combined with a correlation change detection function. Shirzaei et al. (2006) evaluate a multi-resolution wavelet transform technique for change detection in Bam, noting promising results compared with manual counts of building collapse.

Returning to the Tiered Reconnaissance concept introduced in Section 1-3, pixel-based activities provide information about damage at a *Tier 2 neighborhood* scale, which from an operational standpoint could be used to direct response teams to the hardest hit areas. However, some barriers to implementation persist. One significant challenge is the timeliness with which reliable damage information is produced. This is primarily a function of the time interval between the disaster and the collection of cloud-free imagery. The rapidity of imagery acquisition after an event may be improved by increasing the number of orbiting sensors. However, this is a longer range solution, over which remote sensing analysts have little control. In the short term, the delivery timescale for damage maps could also be reduced by maximizing the utility of existing systems.

Multi-sensor change detection involves combining pre- and post-disaster images captured by different satellite sensors (such as IKONOS and Quickbird) to produce a damage map. Multi-sensor integration is an attractive methodological solution because it offers “first-come-first served” flexibility. This means that the first available image can be used, rather than having to wait for data to be collected by a given sensor for which pre-disaster archive scenes are available. From a theoretical standpoint, multi-sensor integration has received limited attention

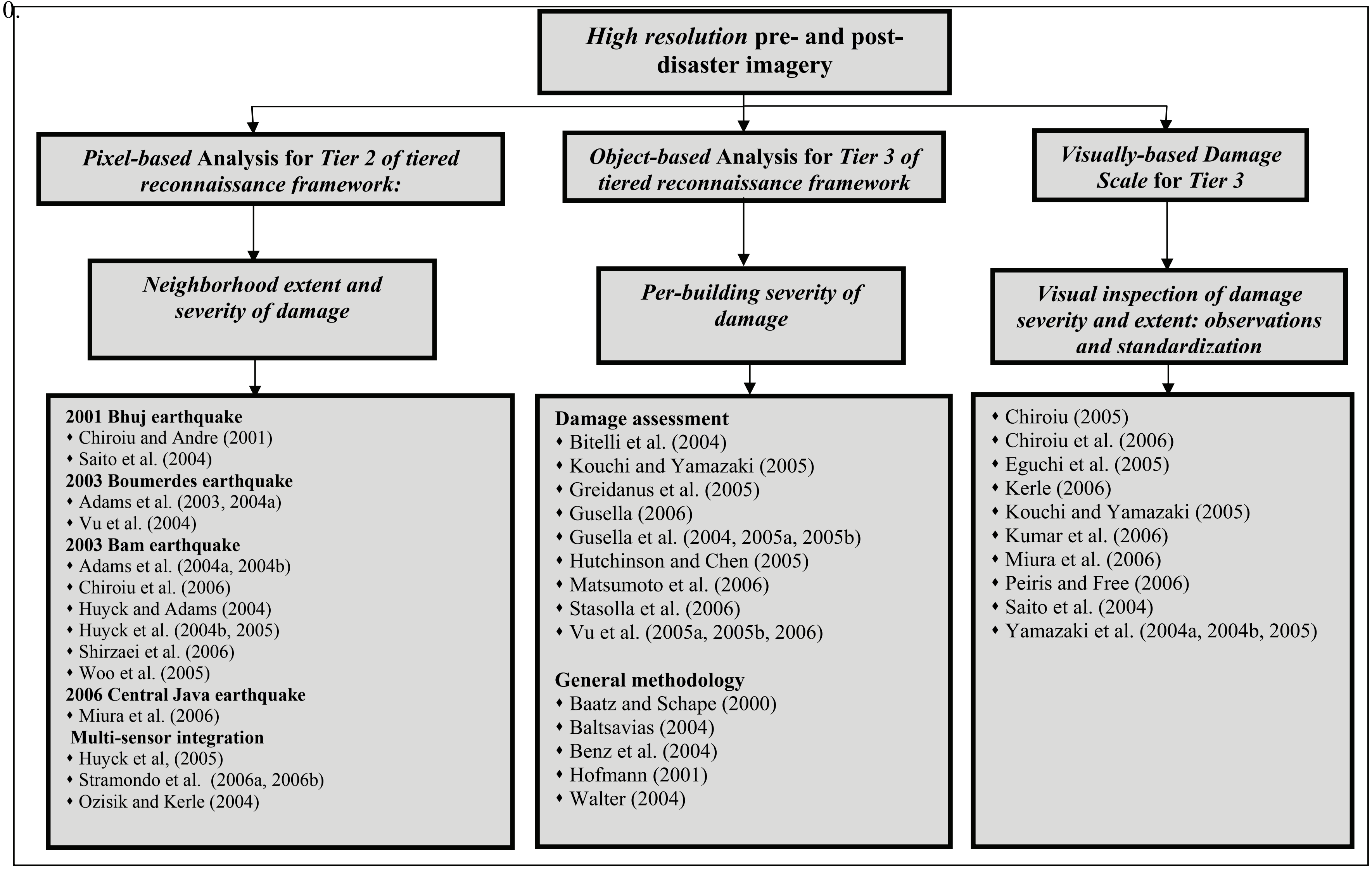


Figure 2-2 Literature Review Diagram, Summarizing Major Research Activities Using High-Resolution Optical Remote Sensing Imagery to Assess Post-Earthquake Damage at Tier 2 and Tier 3 of the Tiered Reconnaissance Framework (Figure 1-3)

in the literature, since it poses a number of challenges; each sensor has a unique and different set of specifications, the combination of which requires detailed consideration. As such, this remains a major research thrust requiring further investigation, which is addressed in Volume III of this report series.

From the literature review diagram in figure 2.2, the development of a remote sensing-based damage scale is also a *Tier 3 Per building* research thrust. This seeks to provide a formal framework for characterizing the different damage states of individual structures based on their visible signatures captured by the imagery. However, this is reserved as a subject for future research.

The literature review diagram in figure 2-2 also identifies 'object-oriented' methods for detecting the damage state of individual structures at a *Tier 3 Per building* scale. Analytically, an object-oriented methodological approach is fundamentally different from traditional 'pixel-based' optical studies. In theoretical terms, a pixel-based approach provides information as a function of the reflectance (spectral) and thematic (textural) characteristics of single pixels within the remote sensing scene (Schowengerdt, 1983). In the case of an object-based analysis, the basic processing unit is instead a *segment*, rather than a single pixel. In real-world terms, as shown in figure 2-3, this may involve treating a building's roof as a single unit, rather than a series of individual pixels, which exhibit differences depending on the roof facet within which they fall, or whether they correspond with a rooftop feature, such as a chimney or roof-mounted air conditioning system. Compared with pixel-based analysis, these additional attributes have the potential to produce more homogenous and accurate mapping of real-world features (Herold et al., 2002).

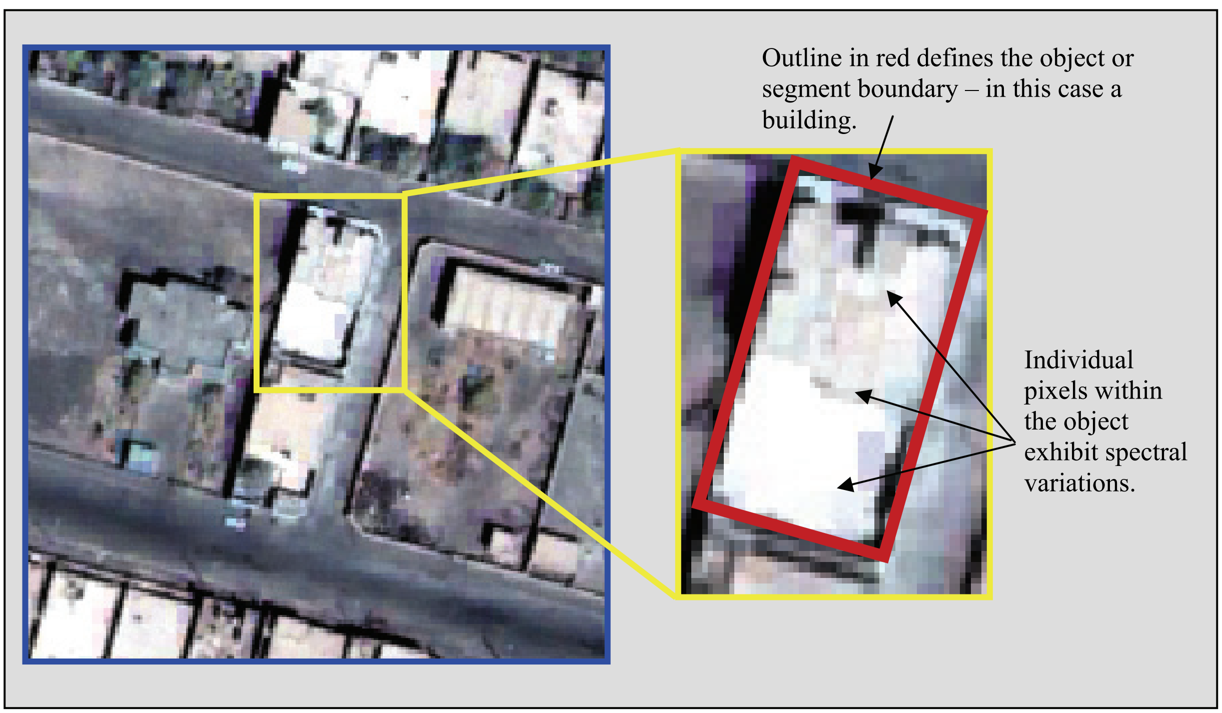


Figure 2-3 For Object-Based Analysis the Basic Processing Unit is a Segment – in this Case a Building. Traditional Image Processing Techniques Instead Analyze Individual Pixels, which may Exhibit Considerable Variability within a given Object.

Object-based studies have the potential to yield important information about the damage characteristics of individual structures. However, a limited number of studies are documented in the literature. Kouchi and Yamazaki (2005) use a single post-event image and Matsumoto et al. (2006) pre- and post-disaster coverage to respectively explore damage caused by the 2003 Boumerdes and 2006 Central Java earthquakes. In addition to direct earthquake damage, Greidanus et al (2005) detect secondary tsunami wave effects caused by the 2004 Sumatra-Andaman earthquake from pre- and post-event radar imagery. Vu et al. (2005a, 2005b, 2006) explore a morphological approach for post-earthquake damage detection in Bam, Iran, and damage mapping in tsunami-affected areas. Although object-oriented analysis offers enormous potential, research has yet to be conducted into its application for post-disaster decision support, specifically producing key statistics such as the number of collapsed or damaged structures, which may be used to infer loss. As such, this remains a major research thrust requiring further investigation, which is addressed in Volume II in this report series.

2.3 Flood Damage Assessment

During the last decade floods have affected more than 1.5 billion people worldwide, which equates to 75% of all people affected by disasters (ESA, 2006). It is predicted that flooding and the resultant impacts on human population is set to increase both because of pressure on populations to live in flood prone areas due to population rise, and climate instability as a consequence of climate change. For situation assessment and emergency response, disaster management agencies, policy makers and Civil Protection Authorities also need to know where to target resources, through an indication of flooding extent on the ground. Flood data is useful for post disaster management, such as gathering data for the insurance and re-insurance industries for insurance premiums, claims and calculating loses. Ultimately flood data will be fed into post-disaster assessment to update risk assessment and flood extent predictions.

2.3.1 Radar Versus Optical Imagery

MCEER researchers at ImageCat. (see Volume IV of this report series, also McMillan et al., in review) provide a useful literature review of prior studies utilizing remote sensing for flood assessment. Efficient flood monitoring and associated damage assessment for urban environments is both important and timely. Remote sensing-based monitoring offers an attractive solution due to its relatively cost-effective nature and widespread coverage for analysis. This is in comparison to stand-alone spatially restrictive ground sampling, semi-qualitative methods such as resident consultation, examination of administrative documents and claims forms, and costly aerial surveys of flooded areas. Flooding in particular can be a very short-lived event, and so it is essential to retrieve a useful satellite derived product quickly. An important consideration in streamlining the flood assessment process is optimizing the imagery specifications, in terms of imagery availability in all weather conditions and specific parameters such as resolution and swath width.

Urban flooding can be a very short-lived event, and so it is essential to retrieve a useful satellite-derived product quickly. To this end, an important consideration in streamlining the flood assessment process is optimizing the imagery specifications. In terms of sensor characteristics, synthetic aperture radar (SAR) imagery offers advantages over optical remote sensing data. A number of flood detection methodologies have used optical satellite imagery to assess flooding extent and damage (e.g. Bryant and Rainey 2002, Brakenridge and Anderson 2005). However, a major limitation to this technique is cloud cover, of particular prevalence in storm-ridden areas. In comparison, using the microwave region of the spectrum bypasses this issue because of its longer wavelength. As radar is an active system (i.e. it creates its own radar pulse) it negates the need for sunlight, so it can be used at night, offering more rapid damage assessment. However, SAR imagery parameters such as spatial resolution and swath width are also an important consideration that may affect the accuracy achieved. Few prior studies have addressed urban flood detection using SAR. It remains for a detailed study of the characteristic flood signature responsible for the obvious flood delineation in Figure 2-4, to be undertaken, and a comparative analysis of different sensor resolutions to be performed.

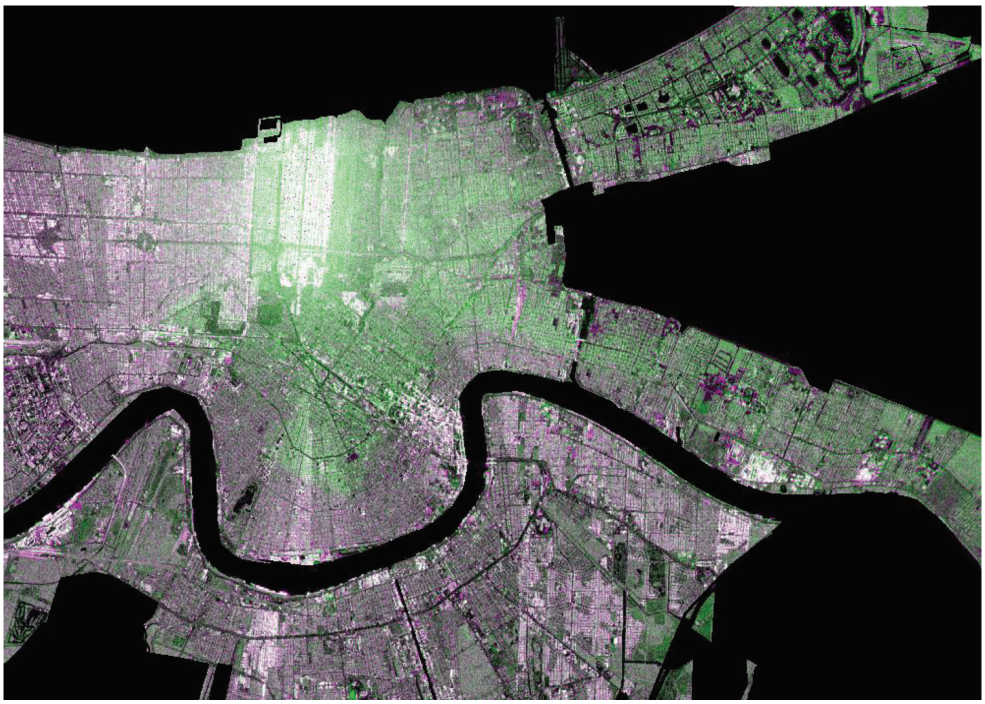


Figure 2-4. Urban flood signature in New Orleans detected after hurricane Katrina using fine beam mode Radarsat I imagery. A false color composite was produced where red = non-flood (13th April 2006), green = flood (9th September 2005), and blue = non-flood.

2.3.2 Flood Assessment in Urban and Non-Urban Environments

Outside the built environment, radar has proved an extremely useful tool for the purpose of flood detection (e.g. Brivio et al. 2002, Tholey et al. 1997, Takeuchi et al. 1999). As it is an active system (i.e. it creates its own radar pulse) it also negates the need for sunlight, so it can be used at night, offering more rapid damage assessment. It has been shown that SAR can potentially be more accurate than certain optical systems, such as Landsat, at delineating flooded areas. Looking at flooding in the Bangladesh monsoon period, Imhoff et al. (1987) showed that SAR (SIR-B) retrieved an accuracy of 85% correctly classified, compared with 64% for Landsat MSS, using a simple density slicing threshold method. The differing backscatter response from water and land means that SAR has the capacity to distinguish sharply between these land cover classes, making it a potentially useful tool for quick response and hazard assessment of flooded areas. It has also been noted that SAR gives higher accuracy flood mapping responses on flat or homogenous floodplain type areas (e.g. Galy and Sanders 2000). However, areas of human population such as urban environments are usually of more interest to hazard managers, as these are the areas where losses are likely to be greatest.

Few previous studies have explored SAR implementation for urban flood detection, due to the complicating beam effects illustrated in Figure 2-5 (see also Kiage et al. 2005, Oberstadler et al. 1997). It also remains for a systematic evaluation to be completed of the various SAR image sets currently available through multi-mode commercial sensors such as Radarsat, in order to identify the optimal imagery specifications for flood detection.

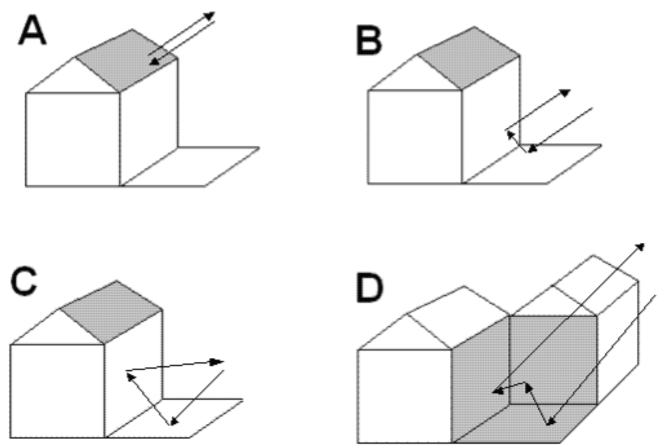


Figure 2-5 - Types of Radar Scattering Encountered in Urban Areas: a) Single Bounce Scattering; b) Double Bounce where Sensor and Feature are Aligned, Increased Backscatter Received Back to Sensor; c) Double Bounce where Flightline and Feature Orientation are not Aligned and Increased Backscatter is not Received at the Sensor; and d) Triple Bounce Scattering
Adapted from Dong et al. (1997)

The response of the surface in urban areas is little described and accounted for, and as regards flood detection, what has been written has often only been preparatory. For instance, Solbø and Solheim (2004) suggest that flood detection can be enhanced in all types of terrain, including urban areas by combining multi-temporal intensity analysis with interferometric coherence data (e.g. Dellepiane et al. 2000, Stabel and Löffler 2003). Although they investigate a range of sensors and beam modes (ERS and Radarsat standard and fine beam mode), it was deemed necessary for operational purposes to focus on the simple case scenario, i.e. open agricultural fields. Therefore these authors did not consider urban and forested regions.

Solbø and Solheim (2004) also describe the design and implementation of the SAR processing part of an operational flood mapping service called the FloodMan project. This focuses on near-real time, unsupervised operational flood mapping. It divides up SAR flooding into three main areas – (1) open agricultural lands, where SAR flood analysis is fairly straightforward using thresholding techniques, (2) forested areas where double bounce causes an enhanced backscatter response and (3) urban areas were examined, consisting of a lot of concrete, steel and corners. They conclude that urban material such as concrete makes it difficult to detect flooding, as there will be no dramatic change in scattering mechanisms for flooded areas.

Oberstadler et al. (1997), using ERS-1 SAR imagery, present qualitative and quantitative analyses (visual interpretation and an automatic classification method). They used evidence-based interpretation of satellite images (EBIS) which involved visual analysis, an automatic classification method, and filtering techniques to classify flooded areas and create a continuous contour. They found that problems occurred in urban areas because of the increased backscatter of buildings overlaying the backscatter from any flooding, and that often no contour lines could be found. Trees, port and embankment constructions in cities also gave increased backscatter. Despite these issues, they conclude that radar has potential, with visual analysis proving useful for delineating the flood boundary in agricultural land and some urban settlements.

In the specific case of flooding in and around New Orleans, Kiage et al. (2005) used Radarsat-1 100m resolution ScanSAR images from the 2nd and 5th September 2005 to look at flooding of the wetlands of Louisiana after Hurricane Katrina. The authors carried out a preliminary study into the performance of ScanSAR imagery for delineating flooding in New Orleans after the hurricane. The ScanSAR imagery had a 50m pixel resolution. They concluded that in this instance SAR was not useful because the corner reflections from urban buildings caused increased backscatter response.

Kiage et al. (2005) further suggest that as optical SPOT imagery has been useful in the response to this event, a combined SAR – SPOT approach should be investigated. Another multi-sensor approach is utilized by Fatone, et al. (2001), who suggest a data fusion technique may be advantageous for looking at detail in urban areas. They employ a segmentation and de-noising regime, fusing SAR for its textural properties with optical imagery for its high resolution properties. However, in terms of fast operational use for post-disaster monitoring, acquiring both SAR and optical data could take considerable time.

While previous studies suggest that radar has considerable potential for flood detection, documented performance within urban environments has been varied, and progress has been limited by methodological challenges such as complicating multi-bounce effects. Before creating elaborate methodologies or conducting advanced data fusion studies, it is necessary to develop a more fundamental understanding of the performance of SAR imagery for urban flood mapping. It is important to examine all types of response from the flooded urban environment, and not to simply assume the specular dark pixel radar response that prior studies have attributed to flooding. Accordingly, Volume IV of this report series extends existing theoretical and methodological bases for extracting flood extent and area in an urban environment using SAR imagery. Specifically, the integration of pre- and post-disaster imagery for a range of different sensor resolutions is explored in both flooded urban and non-urban environments.

2.4 Wind Damage Assessment

Womble (2005) who collaborated with MCEER researchers responding to hurricanes Charley and Katrina (see Volume V of this report series, also Adams et al., 2004c and Womble et al., 2006a, 2007), provides a useful literature review of prior studies utilizing different remote sensing imagery types for windstorm damage assessment, from which the following introduction is drawn. The limited implementation of optical satellite for wind damage assessment is described, together with the more widespread sues of aerial scenes. Figure 2-6 demonstrates optical signatures of hurricane wind damage on high-resolution satellite imagery, which is the

Figure 2-6 Comparison of Pre- and Post-Hurricane 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 and (b) One Day After Hurricane Charley.

focus of Volume V within this report series. These share a number of characteristics with earthquake damage, including the presence of visible roof damage and occurrence of debris for extreme damage states.

2.4.1 Traditional Approaches

Traditional building surveys following major windstorms have yielded significant information about the interaction of severe winds with the built environment. In documenting damage from over 120 windstorms, the Institute for Disaster Research (IDR) and the Wind Science and Engineering (WISE) Center of Texas Tech University (TTU) have compiled the largest database of structural loss information in the country. Significant recent investigations include the Fort Worth, TX tornado of 2000 (Letchford et al., 2000), Oklahoma City tornadoes of 1999 (Gardner et al., 2000), Jefferson County, AL tornado of 1998 (Mehta and Carter, 1999), Jarrell, TX tornado of 1997 (Mehta and Carter, 1998), and Hurricane Andrew in 1992 (Levitan et al., 1993). Several other government, industry, and research organizations have also conducted wind-damage surveys with emphasis on various aspects of windstorm damage. As a result, many guidelines and suggestions have been developed for the implementation of such surveys, as demonstrated by Bunting and Smith (1993), Chiu (1999), Doswell and Brooks (2001), Marshall (2001), MBCI (1998), McDonald et al. (1985), McDonald and Marshall (1984), U.S. Dept. of Commerce (1993), and NAHB/HUD (1993).

Engineering investigations of windstorm-damaged structures involve a number of aspects to determine failure mechanisms for individual buildings, including: exposure (location relative to windstorm paths, other structures, and terrain/ vegetation features) aerodynamic form, material strengths, connection details (load paths), and debris transport (sources, travel paths, and final locations). Collections of such data have typically involved walking surveys, whereby the above factors and the resulting damage states, are recorded by means of photographs, maps, and written or oral (transcribed) notations (McDonald and Marshall, 1984) and more recently by means of portable computers, e.g., personal data assistants (PDA) (He et al. 2005).

In documenting damage with photographs, notes, and maps, Minor (1980) stressed the need to document the location of ground-survey photographs, such as by using serial-number placards visible in the photographs, an early method of photo-georeferencing. Global positioning system (GPS) technology was employed as early 1997 to define the path of the Jarrell, TX tornado from an aerial survey (Phan and Simiu, 1999) and as early as the 1999 Oklahoma City tornadoes to note the position of damaged buildings in a ground survey (Marshall, 2001).

Though prior windstorm damage surveys have contributed greatly to the knowledge of windstorm effects on the built environment, a number of limitations have prevented such surveys from being most helpful. Ideally, investigators would be able to survey and document in detail every building damaged by a windstorm; in reality, this goal is typically not attained due to limited time (prior to cleanup and repairs), manpower, and financial resources, as well as restricted access to damage areas.

Accurate and complete documentation of windstorm damage is highly dependent on the speed with which the documentation can be conducted after a windstorm. Understandably, cleanup and repair efforts commence as quickly as possible following a storm, resulting in the removal or alteration of damage signatures and debris patterns necessary for the proper assessment (quantification) and thorough understanding of the windstorm interaction with the built environment. Typically, a maximum of only 3 to 4 days following a windstorm are available for conducting adequate damage surveys. Even less time is generally available for examining windborne debris transport, and consequently this subject is still not adequately understood. For widespread storm damage such as Hurricane Andrew, it often proves impossible for investigators to thoroughly and methodically cover all areas necessary to suitably document overall damage within the small time window available.

Another barrier to adequate investigation has been the inability to observe the overall extent of damage before arriving at the scene and to judge from this overall view which areas are most promising for subsequent detailed investigation. Often, field teams are dispatched to damage areas where they are not familiar with local geography, demography, and construction practices, and as a result often cannot make the most efficient use of their limited time by documenting the best examples of the various levels of damage in the overall storm area.

2.4.2 Early Use of Remote Sensing

For several decades, aerial photogrammetric and reconnaissance surveys have been used in windstorm damage investigations to obtain a synoptic view of windstorm paths and damage extents. The technique has proved so useful that McDonald and Marshall (1984) and the U.S Department of Commerce (2003) have published guidelines for conducting aerial surveys of tornado damage. Numerous guides for windstorm investigation (e.g., Federal Coordinator, 1997; Fujita and Smith 1993) have also endorsed the technique. Among the windstorms to be investigated with the use of aerial surveys include the 1970 Lubbock, TX tornado (Thompson et al., 1970); the 1974 Xenia, OH tornado (Mehta et al., 1975); thunderstorm downbursts in 1977 and 1978 (Fujita, 1978); the 1980 Kalamazoo, MI tornado (McDonald, 1980); the 1980 Grand Island, NE tornado; Hurricane Andrew in 1992 (FEMA, 1993); Hurricane Fran in 1996 (FEMA, 1997); the 1997 Jarrell, TX tornado (Phan and Simiu, 1999); the 1998 Spencer, SD tornado (Phan and Simiu, 1999); the 1999 Oklahoma City, OK tornadoes (Gardner, et al., 2000); the 2000 Tuscaloosa, AL tornado (Tanner, 2001); and the 2002 Happy, TX tornado (Tanner, 2002). In such investigations, high-quality aerial photographs have enabled researchers to view and map overall damage conditions (e.g., damage paths, damage intensity contours, flow lines, directions of tree fall, and debris patterns) and to strategically plan subsequent ground surveys.

Despite helpful aspects of aerial windstorm surveys in prior decades, McDonald and Marshall (1984) address a number of associated logistical difficulties, including camera stability (aircraft vibration), possible obstruction of view by aircraft wings and windows, a continual need to reload film cameras, the need to trace the flight path on a map for later reference, and the need to make notes for later ground surveys. Minor (1980) found military aircraft useful for aerial reconnaissance but also subject to scheduling and priority adjustments, and thus advised the hiring of private craft for most circumstances. Recent technological advancements have enabled damage surveyors to overcome many of the prior limitations using GPS technology and digital photography. Still present, however, are the needs to locate and hire pilots and aircraft, and the need to plan aerial survey routes, all of which can be costly and time-consuming. At times, flight clearance must also be arranged as portions of a disaster area may be restricted (Marshall, 2001).

Prior to the widespread use of digital cameras, aerial photo surveys utilized conventional film cameras to produce high-spatial-resolution images, though often with only black-and-white film. Black-and-white (grayscale) images hold relatively limited information compared to multispectral images, particularly when implementing computerized change-detection algorithms. Such surveys can be helpful for retrospective studies of windstorms, but do not offer the near-real-time acquisition and transmission capabilities of digital images necessary for rapid, automated, and uniform assessment of damage covering very large regions. Use of the aerial images for computerized change analysis also requires locating both pre- and post-storm imagery of the affected area in a digital format for use by computer.

2.4.3 Modern Use of Remote Sensing

Whereas earlier aerial reconnaissance and photogrammetric surveys provided helpful assistance in the collection of windstorm damage data, the modern field of remote sensing offers significant advancements in the collection, analysis, and use of windstorm damage data. Emerging technologies, including high-resolution remote sensing systems and advanced digital-image analysis techniques, have tremendous potential for the thorough and consistent quantification of windstorm damage. Such technologies enable researchers to freeze "pristine" damage scenarios (including 3-D elevation data and visual imagery) immediately following a windstorm. These frozen damage scenarios can then be used to:

- Observe all areas of damage in current and future studies, without limitations on physical access;
- Consistently quantify damage to buildings and infrastructure throughout an entire region, using damage metrics and automated image-processing algorithms specifically tailored for the unique signatures of windstorm damage;
- Study damage signatures and debris-spread patterns that have previously been impossible to obtain due to rapid cleanup and removal efforts; and
- Replicate the damage scenarios in future physical and numerical models, as well as in the validation of loss-estimation models and disaster simulations.

The use of geo-information technologies for natural-hazard damage detection has been greatly successful in the field of earthquake engineering. As highlighted by Adams et al. (2004a), geo-information technology has enabled engineers and scientists to rapidly detect, classify, and map earthquake damage over widespread areas in a number of recent earthquakes, through the use of change-detection algorithms performed on satellite images obtained before and after an earthquake. This successful implementation of related technologies for earthquake damage assessment suggests great promise for the rapid and automated image-based detection of damage stemming from hurricanes, tornadoes, and severe thunderstorms. Due to major differences in the fundamental nature and appearance of wind and earthquake damage, however, basic research is required to develop systems and methodologies specifically for wind-damage detection and assessment using modern geo-information technologies.

By its very nature (attacking buildings from the outside inward), windstorm damage to buildings is highly visible from the exterior and, in particular, from above, making it extremely well-suited for detection and assessment via remote sensing. Wind damage to low-rise buildings ranges in severity from minor cladding damage (roof covering), to loss of the roof structure, to structural collapse, and finally to complete removal of the building from the foundation. A broad range of windstorm damage is thus visible in the condition of the roof and in the presence of windborne debris. Of the six damage indicators employed in the HAZUS®-Hurricane damage scale for Residential Construction Classes (table 2-1), three descriptors (Roof Cover Failure, Roof Deck, and Roof Structure Failure) pertain to the roof condition and therefore are directly "visible" via remote sensing technology.

Table 2-1 HAZUS$^{\circledR MH}$-Hurricane Damage State Indicators for Residential Buildings

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

Notes: *Occurrence of at least one of the damage descriptors in a shaded cell of this table is sufficient to place a building in the corresponding damage state. Source: FEMA (2003).

While some components of windstorm damage, such as missile impacts and broken doors, windows, and walls, are not directly visible from above; many collateral indicators ("surrogate indices") of these damage mechanisms are generally visible from overhead. For instance, it is possible to make inferences about the Missile Impact damage category through the analysis of windborne debris visible in remote sensing imagery. The presence of windborne debris surrounding a building is an indication of probable missile impacts to the building itself. For remote sensing imagery acquired before cleanup efforts have commenced, the absence of windborne debris near a building serves as a strong indicator that missile impacts have not occurred, though ground-truthing observations by field reconnaissance teams are necessary to validate these assumptions. (It should also be noted that the presence or absence of missile impacts is not mandatory for assignment of any HAZUS damage state.)

For instance, loss of roof decking adjacent to a concrete driveway (both visible from overhead) can indicate a garage-door failure leading to internal pressurization (for a single-story house). Failures of the roof decking adjacent to an external wall opening are common in severe windstorms (Gardner et al., 2000; Marshall, 2001), and can be explained physically by the high correlation of internal and external wind pressures acting to produce a localized large net uplift pressure on the roof (Womble et al., 1998).

Due to the more outwardly visible nature of windstorm damage, modern remote sensing technology offers even greater promise for the detection of the full gamut of windstorm damage than even for earthquake damage. Earthquake damage to buildings ranges in severity from minor cracking of the walls (undetectable from overhead) to total collapse; only the most severe levels of damage can be determined from overhead imagery alone. A common seismic failure mechanism, the so-called "soft-story or "pancake" effect (the collapsing of only a single floor within a building), is difficult to detect from vertical imagery alone. On the contrary, wind damage to low-rise buildings ranges in severity from minor cladding damage (including roofing material), to loss of the roof structure, and to complete removal of the structure from its foundation. Virtually all levels of windstorm damage are therefore visible via remote sensing platforms; as such, an even finer gradation of damage can be accomplished with overhead imagery for windstorm damage than for earthquake damage.

2.4.4 Optical Satellite Images

The availability of satellite imagery is growing at an impressive rate, as are refinements in spatial and spectral resolutions. Since the government-sponsored Landsat satellite series began producing 80-m terrestrial imagery in the early 1970's, satellite-imaging technology has spread into the private sector with image resolutions which now enable the visual recognition of damaged elements of individual buildings. By the time Landsat-5 was launched in 1984, resolution had progressed to 30 m and was sufficient to detect tornado paths, such as for the May 3, 1999 Oklahoma City tornadoes (Mulligan, 2003). The Indian Remote Sensing satellite also provided a 23.5-m image of these tornado tracks, facilitating early work in digital image analysis of tornado tracks (Yuan et al., 2001). The NASA Earth Observing-1 (EO-1) satellite similarly acquired 10-m panchromatic and 30-m multispectral imagery of the La Plata, MD tornado track of April 28, 2002.

Mulligan (2003) analyzed the recent use and effectiveness of satellite imagery for the detection of tornado paths, and found that satellites with "moderate" resolutions of 5-20 m (e.g., SPOT, IRS, and Terra-ASTER) provide a synoptic view of relatively large areas and thus are ideal for detection of tornado path and damage extents at the regional level. Such imagery should be useful to ground survey crews in mapping the nature and extent of tornado damage. The revisit times of the Terra (16 days) and IRS (24 days) satellites may not provide data quickly enough to assist with field surveys. The SPOT satellites offer more timely collections with revisit times of 3 days or less; however, data collection is not continuous, and coordinates for areas to be imaged must be specified in advance, requiring some independent knowledge of tornado paths. For detection of tornado damage to individual buildings, satellite images with resolutions of 1 m or less (IKONOS, Quickbird, and OrbView) are preferred.

The present era of commercial "high-resolution" optical satellite imagery (with spatial resolutions of 1m/pixel or finer) was ushered in by the launch of GeoEye's IKONOS satellite on September 24, 1999, offering 1-m panchromatic and 4-m multispectral imagery. Launch of the DigitalGlobe Corporation's Quickbird satellite on October 18, 2001 brought the highest spatial resolution available today: 61 cm (2 ft) per pixel for a single panchromatic band and 2.44 m (8 ft) per pixel for four multispectral bands (Blue, Green, Red, and Near-Infrared). In addition to IKONOS and Quickbird, the OrbView 3 satellite (OrbImage Corporation), offer resolutions of 1-m panchromatic and 4-m multispectral.

With frequent overpasses of most population centers, commercial satellite companies can readily supply pre-storm archive images at relatively low costs. New, imagery with specific coverage areas and acquisition-time windows can be ordered on a first-come tasking basis for an additional cost. The extremely active 2004 Atlantic hurricane season, however, found satellite imagery companies such as DigitalGlobe acquiring imagery for post-windstorm areas on a speculative basis, making such imagery available at the (lesser) archival price.

At present, archived (pre-storm) satellite imagery is delivered to the user within 24 hours. New (post-storm) imagery is typically delivered to the user within 60 hours of acquisition (DigitalGlobe, 2004b). Acquisitions of post-storm imagery are subject to satellite revisit times (currently 1-3 days for Quickbird and IKONOS), and weather conditions (cloud cover and atmospheric haze). Additionally, it is often possible to acquire oblique (off-nadir) satellite imagery sooner than vertical imagery. The IKONOS and Quickbird systems have off-nadir capabilities of up to ~30° from vertical, enabling potential oblique imaging of an area sooner than scheduled for a vertical (nadir) view. Depending on cloud conditions and satellite orbit positions, post-windstorm images can often be acquired rapidly enough to guide field surveys of windstorm damage, as demonstrated in field studies following Hurricane Charley (see Volume IV).

As satellite imaging technology progresses and as the number of commercial satellites increases in the future, the quality and rapid availability of the images should improve, allowing greater possibilities for utilizing these data in conducting field surveys and emergency management, recovery, and relief efforts. For instance, DigitalGlobe's Next Generation WorldView imaging satellite, launched in 2007 and still undergoing testing, offers an enhanced spatial resolution of less than 50 cm (panchromatic) and an improved revisit time of less than 1 day for 1-m off-nadir imagery (DigitalGlobe, 2004c).

The first-known example of satellite imagery of windstorm damage to individual buildings comes from the Ft. Worth, TX tornado of March 2000. Figure 2-7 shows windstorm damage sustained by a warehouse roof, and demonstrates the present IKONOS spatial resolution (1 m) that is sufficient to detect damaged portions of individual buildings.

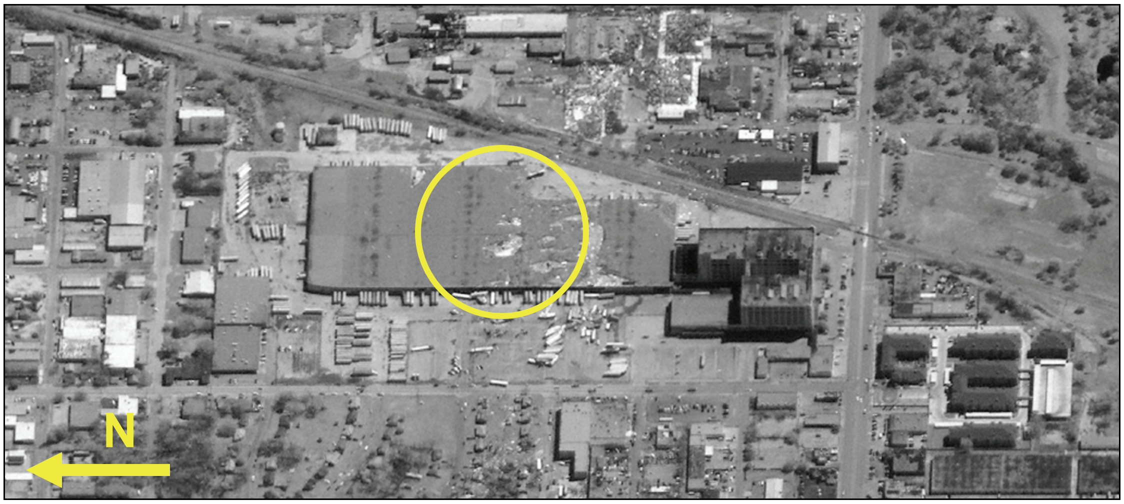


Figure 2-7. IKONOS Panchromatic Image with Sufficiently Fine Spatial Resolution (1 m) to Observe Building Damage from the March 28, 2000, Ft. Worth, TX Tornado. This Image was Acquired March 29, 2000, the Morning Following the Tornado. In Addition to Roof Damage, the Image Shows Damaged and Scattered Semi-Trucks in the Parking Lot. Credit: GeoEye and Mulligan (2003).

Modern high-resolution satellite surveys offer many advantages over their aerial- survey predecessors, most notably:

- Elimination of the need to plan and conduct aerial surveys;
- Speed of acquisition of digital images (without need for developing and printing);
- Rapid delivery of digital images via the internet;
- Availability of multispectral imagery (including near-infrared bands) for use in spectral analysis; and
- For most worldwide population centers, the ability to obtain both before-and-after images in a digital format for use in change-detection algorithms.

Additionally, future technological advances promise to provide finer and finer spatial resolutions for satellite images (rivaling those of traditional film photography), as well as more rapid revisit times to provide timely images for use in damage investigations and emergency-management efforts.

2.4.5 Modern Aerial Imaging

In addition to satellite imagery, a modern version of aerial photogrammetric surveys is also emerging. In the days immediately following landfall (on September 18, 2003) of Hurricane Isabel on the Outer Bank islands of North Carolina, the National Oceanic and Atmospheric Administration (NOAA) acquired aerial images of the barrier islands in the affected area, as part of a research effort for testing and developing standards for airborne digital imagery (NOAA, 2003b,c). Digital images were captured from one to three days (September 19–21) following landfall, at a nominal resolution of 1.2 ft (37 cm) per pixel. “Uncorrected” (non-georeferenced) photos were rapidly posted to the agency's web site and thus made available to interested parties. NOAA collected digital images via aircraft following Hurricane Ivan in September 2004 (NOAA, 2004), and Hurricane Isabel (NOAA, 2003b).

As with the predecessors, modern aerial surveys require significantly more planning and execution than commercial satellite image acquisitions, but do offer the advantage of finer spatial resolutions (at present), the ability to fly beneath a certain amount of cloud cover, the possibility to acquire imagery sooner than a satellite, and the ability to facilitate the 3-D effect of stereo imaging (with the use of overlapping scenes).

2.4.6 Active Remote Sensing Systems

Although high-resolution optical satellite imagery can provide a ready means of detecting and evaluating windstorm damage, its dependence on daylight and cloud-free conditions somewhat limit its capabilities, particularly when immediate damage data are needed in the wake a windstorm. Alternative remote sensing platforms offer possibilities to collect data in all-weather and all-lighting conditions, including such "active" remote sensing platforms as synthetic-aperture radar (SAR) and light ranging and detecting (LIDAR) systems. These systems are termed "active" because they both transmit a signal and receive a return, the properties of which are used to glean information about the geometry of the target. LIDAR systems were used to collect 3-D coastal elevation data (including building elevations) preceding and following Hurricanes Charley and Ivan (Sallenger et al., 2005; Sallenger, 2005; USGS, 2004a,b) and to aid in the recovery efforts following the 2001 World Trade Center attacks (Huyck et al., 2003b). Carter et al. (2000a,b) also demonstrated the use of airborne laser swath mapping (ALSM) and airborne digital photography (ADP) for the pre- and post-hurricane 3-D mapping of coastal areas. This technique employs georeferenced laser data to construct digital terrain models (DTM) of coastal areas. Included in these DTMs are topographic (landform) data, as well as building elevations, the latter of which can be used to detect building collapses.

Initial evaluation of these active remote sensing systems suggests that they have tremendous possibility for quickly pinpointing the most severe levels of windstorm damage associated with significant changes in geometry or elevation (e.g., collapse or removal from foundation), but may not be able to detect lesser states of damage (e.g., loss of shingles) which do not accompany a change in geometry or elevation. Considering these to be advanced applications of remote sensing imagery, Volume V of the present report presents a more elemental evaluation of the potential of optical satellite and aerial imagery to yield damage information spanning multiple building damage states. The use of active systems remains a topic for future research.

SECTION 3

PRIOR AND ONGOING MCEER RESEARCH

At MCEER, prior post-earthquake damage detection research has investigated direct, multi-temporal change detection techniques using both optical (Adams, 2004; Adams and Huyck, 2006; Adams et al., 2004a; Eguchi et al., 2002, 2003b; Huyck et al., 2004a, 2004b, 2005) and SAR imagery (Eguchi et al. 2000a, 2000b, 2003a, 2003b; Mansouri et al., 2004, 2005). A number of field deployments to collect ground-truth data in support of remote sensing and other post-disaster studies have also been conducted.

The 1999 Marmara earthquake was a milestone event that laid the foundations for change detection research. In this case, researchers developed theoretical methods for assessing damage using moderate resolution imagery acquired by optical (Adams, 2004; Adams and Huyck, 2006; Huyck et al., 2004a) and SAR (Eguchi et al., 2000a, 2000b, 2003a, 2003b; Huyck et al., 2002, 2004; Mansouri et al., 2004, 2005) sensors. Researchers also deployed advanced technologies as part of an in-field campaign, to acquire ground truth information for verifying results (Eguchi et al., 2000a, 2000b, 2000c).

Following the launch of the IKONOS and Quickbird high-resolution satellites in 1999 and 2001 respectively, MCEER researchers have investigated a range of resolution-related refinements to their damage detection methodologies. In this case, the 2003 Boumerdes earthquake was the first major urban earthquake for which pre- and post-disaster high-resolution satellite imagery was used to develop pixel-based methods for assessing damage severity at a neighborhood scale (Adams et al., 2003; Adams, 2004; Adams et al., 2004a).

The 2003 Bam earthquake was the second major earthquake where high-resolution imagery was used. Given the extensive damage that was obtained and availability of high-quality imagery, this event has been a major research focus at MCEER, with initial pixel-based studies suggesting that it has the potential to offer significant progress in the development of damage assessment methodologies. Pixel-based analysis using pre- and post-earthquake Quickbird imagery successfully highlighted areas that sustained significant damage, and further distinguished between areas of differing damage severity (Adams et al., 2004a; Chiroiu et al., 2006; Huyck et al., 2004b, 2005). Exploratory investigation of cross-sensor integration combining IKONOS and Quickbird before and after scenes suggests that this is an important methodological development, but refinements to existing methodologies are required to account for inherent variations in spatial and spectral resolution (Huyck et al., 2005). Preliminary object-oriented research further highlighted the potential of high-resolution data to yield damage information at a per building scale (Gusella et al., 2005b). Also at a per building scale, Eguchi et al. (2005) highlight the benefits of a remote sensing-based damage scale, and identify initial steps towards its development.

The Bam earthquake also marked the initial deployment of the VIEWS™ field data collection and visualization system to collect georeferenced ground truth data (Adams et al., 2004b; Adams et al., 2005b). This deployment collected GPS-referenced photographs of damage throughout the city and provided important feedback for continued system development. VIEWS has subsequently been deployed after a range of major disasters (see, for example, Volume V). In the case of earthquake, georeferenced video was captured following the 2004 Niigata, Japan earthquake (Huyck et al., 2006), the 2004 Parkfield, California earthquake and 2004 Sumatra-Andaman earthquake that caused the Indian Ocean tsunami (Ghosh et al., 2005).

Building forwards from these initial damage detection activities, the Bam earthquake is employed here as the basis for developing *advanced methodologies for post-earthquake damage assessment*. Subsequent events such as the 2004 Al Hoceima (Algeria) and 2004 Niigata (Japan) earthquakes were also significant in terms of magnitude. However, the nature and diversity of damage or quality of available imagery has not warranted a similar level of focus.

At MCEER, prior flood-related damage detection research has investigated radar-based methodologies for detecting urban and rural flood damage (McMillan et al., 2006, 2007). Given that few studies provide a detailed assessment of urban SAR flood signatures, as a starting point the research documented in Volume IV *A Study Of Multi-Temporal And Multi-Resolution SAR Imagery For Post-Katrina Flood Monitoring In New Orleans*, explores the fundamental signature of flooding, and the capabilities of different sensing spatial resolutions from 5-30m for detecting floods. Recent high-magnitude flood events are used as case studies, including post-Katrina flooding in New Orleans, and the 2007 UK summer deluges that affected Gloucestershire and Yorkshire (since this work is ongoing, it is not documented in research Volume IV). This research, conducted in collaboration with the Department of Geomatic Engineering at University College London has also resulted in a journal article that is shortly to be published in the International Journal of Remote Sensing (see McMillan et al., in review).

Having successfully identified a characteristic increase in backscatter accompanying urban flooding and decrease within rural areas, research subsequently progressed to unpack urban and urban flood signatures in greater detail (see Oates, 2007; also Oates et al., in preparation). The aim was to investigate the effects of urban texture, such as road orientation, building height and construction materials, with a view to determining if these are responsible for additional variability within flooded scenes.

To date, MCEER's flooding research has employed a range of different radar remote sensing datasets, including Radarsat I fine, standard and wide-beam mode, ENVISAT and ERS imagery. The broad geographic extent offered by satellite SAR imagery satisfies monitoring requirements at Tier 1 of the Tiered Reconnaissance framework. Accordingly, these have offered the benefit of region-wide cloud-free viewing, for a rapid overview of the inundated area. Notably, 2008 marks the launch of a new SAR sensor - Radarsat II, which offers higher revisit periods and increased spatial resolution. This will further enhance the rapidity with which flood monitoring can be undertaken. VIEWS aerial coverage was also collected for the 2007 UK floods, to serve as a detailed validation dataset (ImageCat, 2007). An important lesson learned was the importance of off-nadir imaging for flood. Whereas vertical or 'nadir' coverage is optimal for building roof damage assessment, in the case of flood it is was found to be logistically challenging to fly along a flood boundary. Instead, a spatially offset sideways perspective looking on to the crenulated margin, enables the geographic limit to be delineated in detail (McMillan et al, 2007).

As a precursor to the hurricane research activities described in Volume V of this report series, which were funded by MCEER, the US National Science Foundation SGER program, and the Natural Hazards Research and Information Center, an MCEER Rapid Response Report entitled *Collection of Satellite-Referenced Building Damage in the Aftermath of Hurricane Charley* (Adams et al., 2004c) was published less than one month after the event. This documented data collection during three field deployments conducted within two weeks of Hurricane Charley by MCEER researchers at ImageCat and the Texas Tech Wind Science and Engineering (WISE) Research Center (for details, see Volume V), and outlines preliminary findings.

While hurricane Charley is the first event for which satellite remote sensing-based damage assessment techniques were investigated, subsequent activities have been undertaken by MCEER researchers in the aftermath of events including: hurricane Ivan, hurricane Dennis, hurricane Katrina, hurricane Rita and hurricane Wilma. Table 3-1 summarizes the activities conducted for these events and key publications.

Table 3-1 MCEER Research Team Hurricane Deployments and Related Publications

Hurricane Event	MCEER Data Collection and Research Activities	Publications
Charley	• In-field data collection using VIEWS • Development of remote sensing-based damage scale for wind • Preliminary quantitative assessment of damage characteristics	**Rapid response reports** Adams et al. (2004c) **PhD thesis** Womble (2005) **Conference/journal publications** Womble et al. (2006b, 2007)
Ivan	• In-field data collection using VIEWS • Development of remote sensing-based damage scale for wind • Preliminary quantitative assessment of damage characteristics	**PhD thesis** Womble (2005)
Katrina	• In-field data collection using VIEWS • Rapid airborne damage assessment through PDV • Probabilistic evaluation of windstorm effects based on weather data • Region-scale urban damage assessment using moderate resolution imagery • Aerial evaluation of windstorm damage in Mississippi • Aerial per-scene damage severity ranking • Application of remote sensing-based damage scale for wind • Surge damage assessment • Flood damage assessment	**Reports and journal papers** Womble et al. (2006a) Friedland and Adams (2006) Friedland et al. (2007) McMillan et al. (in review) **Online daily updates** Ghosh and Womble (2005) Ghosh and Hill (2005) **Seminars** MCEER (2006)
Rita	• In-field data collection using VIEWS • Rapid airborne damage assessment through PDV	NIST (2006)
Dennis Wilma	• Rapid airborne damage assessment through PDV	-

These post-hurricane damage assessment activities span all three tiers of the Tiered Reconnaissance framework (see Section 1.3). At a *Tier 1 regional scale*, low resolution weather and moderate resolution optical imagery was used after events such as hurricane Katrina to provide a damage overview. At *Tier 2*, various methodologies have been explored for rapidly assessing *neighborhood scale* damage, including rapid airborne damage assessment through the Post-disaster Damage Verification (PDV) program, and per-scene severity rankings using high-resolution aerial imagery. At *Tier 3*, VIEWS has supported the collection of detailed damage information at a *per-building scale*. A remote sensing-based damage scale has also been developed and implemented operationally, and exploratory research conducted into quantitative damage assessment techniques. In the case of hurricane Charley, exploratory investigations primarily focused on damage assessment at the Tier 3 per building scale.

SECTION 4

CASE STUDY EVENTS

The following section describes the case study events that are documented within this five volume report series. Brief details of the disaster are included, together with a summary of available remote sensing imagery and in-field datasets. Table 4-1 summarizes the datasets that were employed in this research. Details for hurricane Charley and Hurricane Ivan are drawn from Womble (2005).

Table 4-1 Remote Sensing and in-Field Datasets Acquired to Support the Research Activities Documented in Volumes II-V

Event	Timescale	Sensor and Date
Bam Earthquake	Before	Quickbird 9/3/03
	After	Quickbird 1/3/04 IKONOS 12/27/03 VIEWS January 2004
Hurricane Charley	Before	Quickbird 3/23/04;
	After	Quickbird 8/14/04; 8/19/04 Aerial (DMK) 8/29/04 VIEWS 8/18/04 through 8/27/04
Hurricane Ivan	Before	Quickbird 3/12/04
	After	Quickbird 9/21/04 Aerial (NOAA) from 9/17/04 VIEWS 9/21/04 through 9/23/04
Hurricane Katrina	No-flood	Radarsat I 4/13/06; 4/30/06
	Flood	Radarsat I 9/9/05; 9/2/05 VIEWS September 2005

4.1 Bam Earthquake, Iran

The 2003 Bam earthquake struck at 05:26 on December 26, 2003, as a magnitude 6.6 event (USGS, 2004a). Traditional mud-brick and clay homes put up little resistance to the violent shaking, and as walls and roofs crumbled and collapsed, tens of thousands of victims were trapped beneath the rubble. The earthquake was centered approximately 10km to the southwest of Bam (IIEES, 2004), which borders the Dasht-e-Lut desert, in the Iranian province of Kerman. Initial investigations suggest that the event occurred on the Bam fault, and was caused by northward motion of the Arabian plate against the Eurasian plate (USGS, 2004b). A full seismological report is available at USGS (2004a), with seismotectonic background of the Bam area provided by Eshghi and Zare (2003). For a pre-earthquake seismic hazard assessment and bibliography, see Tavakoli and Ghafory-Ashtiany (1999) and ISG (2004). Damage was concentrated in a relatively small area, of roughly 16km radius, around Bam - a tourist destination on the old Silk Road, famed for its 2,500-year old citadel Arg-e-Bam.

In terms of human cost, the Bam earthquake ranks as the worst recorded disaster in Iranian history; a tragic statistic in a nation already ranked as the world’s fourth most disaster prone

country (IFRC, 2004). Reporting of death tolls varied widely from the current accepted statistic of around 25,000 to >40,000. It still remains for a definitive count to be published (BBC, 2004).
Although Bam itself had no prior record of significant earthquake damage, within the surrounding 100km, during the 50-year period from 1948-1998, 14 earthquakes were recorded measuring magnitude 5 or greater on the Richter scale (Eshghi and Zare, 2003). Within the nation as a whole, the 20th century saw 65 major events (magnitude $\geq$6.0), claiming 126,000 Iranian lives (for further details, see Berberian, 2004). According to historic records, earthquakes have razed other cities, including Tabriz, Ray and Nishapur (Berberian, 1997). Such devastation and massive loss of life is largely attributable to poor construction methods in a society where it is traditional for people to build their own homes. According to (F. Naiem, cited in Online NewsHour, 2004), building codes have proved difficult to enforce for modern structures, and are largely absent for older dwellings.

The Bam earthquake is one of the first high-magnitude earthquakes for which high-resolution satellite imagery was available. IKONOS and Quickbird images were rapidly collected after the earthquake hit, on December 27th 2003 and January 3rd 2004. From Figure 4-1, these provide an detailed record of damage sustained. The Bam earthquake also marked the inaugural implementation of the VIEWS system in support of post-earthquake reconnaissance activities in early January 2004 with the EERI reconnaissance team. The data collection system was equipped

(a) Before **(b) After**

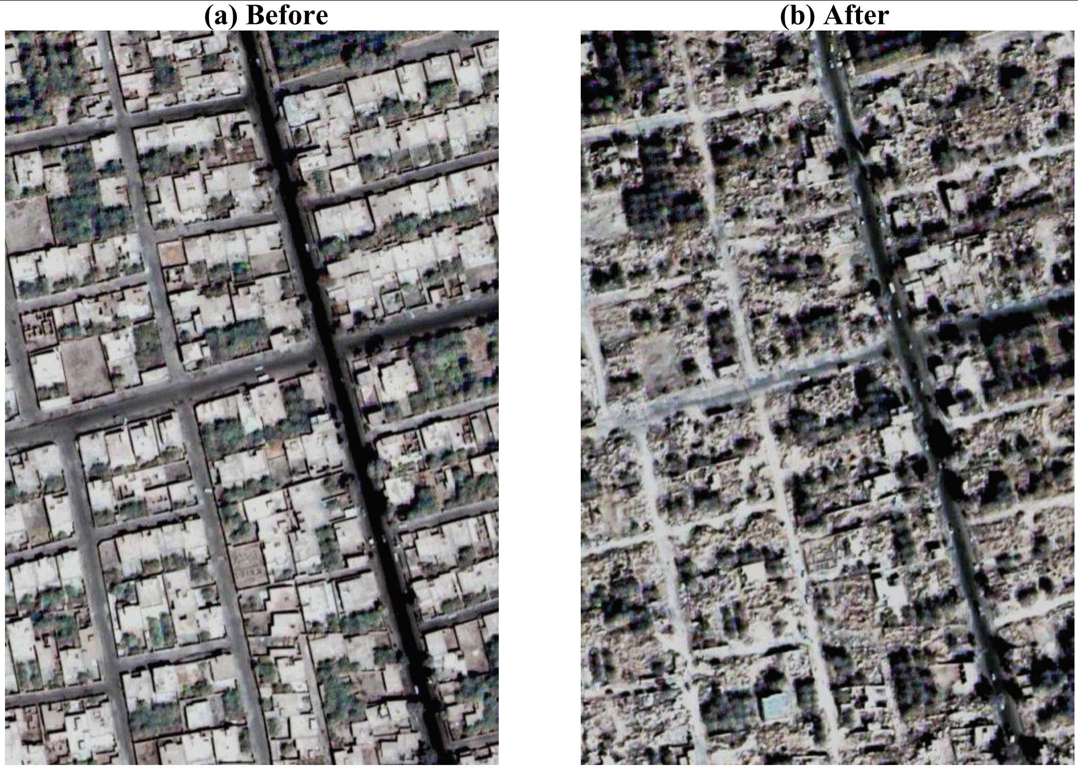


Figure 4-1 Building Damage within Eastern Residential Districts of Bam, Visualized by Comparing the 'Before' and 'After' Quickbird Satellite Imagery. Imagery Courtesy of DigitalGlobe, www.digitalglobe.com

with high resolution optical Quickbird imagery, acquired before (September 30th, 2003) and after the event. To assist the reconnaissance team, a texture-based city-wide damage map (Adams et al., 2004a) and visually-based damage assessment published on-line by USAID (USAID, 2004) were included as additional data layers.

4.2 Hurricane Charley, Florida, USA

Hurricane Charley struck the southwest coast of Florida at Charlotte Harbor on Friday, August 13, 2004 at 4pm ET, (figure 4-2) as a Category 4 storm. Hurricane Charley was the most severe windstorm to strike the US since 1992. 145mph winds devastated the Florida coastal cities of Port Charlotte and Punta Gorda, and 10ft high waves wreaked havoc on nearby barrier islands. In the hours following, a Presidential disaster declaration was issued for twenty-five counties in the impacted region. The event resulted in the loss of at least 27 lives, and caused more than $15.4 billion of damage.

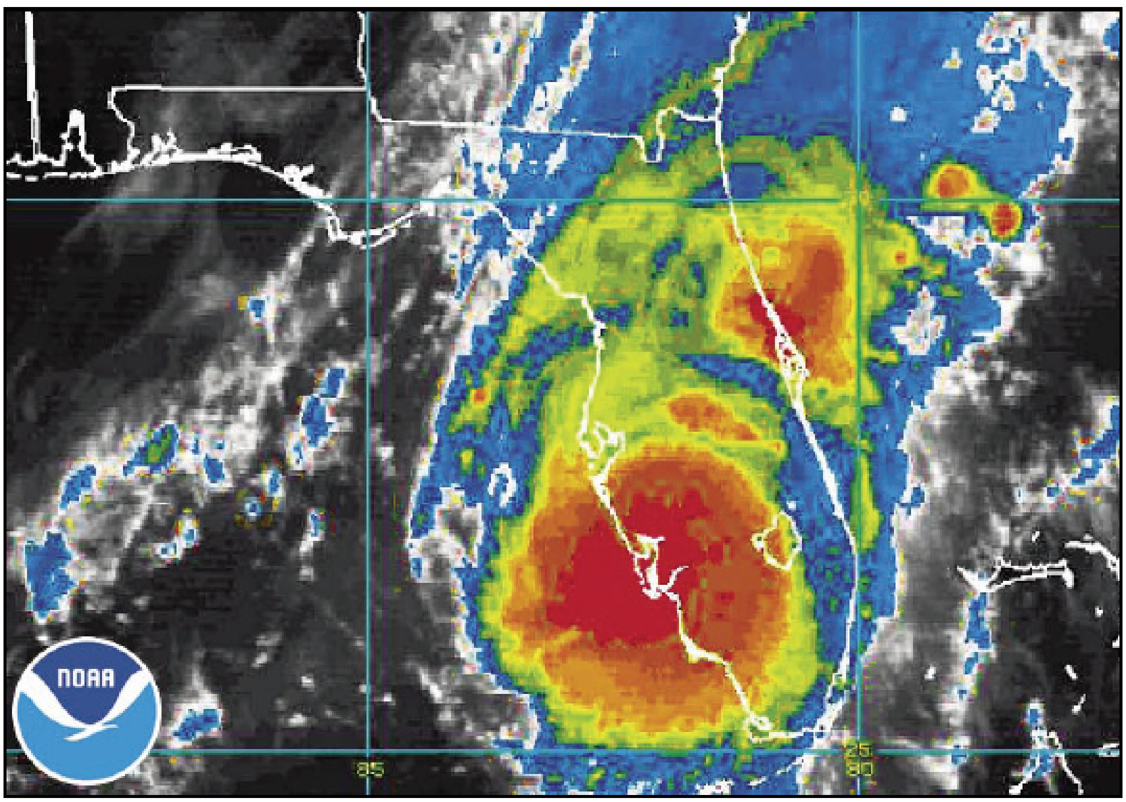


Figure 4-2. NOAA Infrared Weather Satellite Image of Hurricane Charley Centered Over Charlotte Harbor in Southwest Florida. Image Date: August 13, 2004. Courtesy: NOAA and FEMA (2005a).

Hurricane Charley presented the first opportunity to acquire high-resolution satellite images of infrastructure conditions following a major U.S. windstorm, and to thereby preserve the damage scene for future studies. The following day (August 14), the polar orbit of the Quickbird imaging satellite permitted the acquisition of near-vertical (6° off-nadir) imagery of the southwest Florida coast. Though the area was still largely covered with a heavy cloud canopy, the Quickbird acquisition included a small, cloud-free portion of the heavily damaged community of Punta Gorda. This collection of imagery on the day following Hurricane Charley's landfall was fortunate, as it enabled preservation of the post-disaster scene before most critical damage indicators (e.g. debris, roof damage, and fallen trees) could be removed, covered, or repaired.

Pre-hurricane (archival) Quickbird images of the Punta Gorda–Port Charlotte area were available from March 23, 2004. Along with this pre-hurricane imagery, the rapid post-storm image acquisition was extremely helpful for demonstrating the effective use of pre- and post-windstorm satellite imagery in field damage surveys. 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.

During a subsequent orbit on August 19, Quickbird acquired imagery in a southwest-northeast swath, tracing the route of Hurricane Charley across the Florida peninsula. This acquisition included a mostly cloud-free scene of Punta Gorda and neighboring Port Charlotte, imaged at approximately 28° off-nadir and resulting in a nominal spatial resolution of 75 cm. The IKONOS satellite also imaged portions of Punta Gorda and Port Charlotte on August 15, the Port Charlotte area again on August 18, and another nearby area on August 21.

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. 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. Quickbird images were selected for use in this study, as they offer the highest spatial resolution satellite imagery presently available, as well as offering coverage both before and immediately following Hurricane Charley's landfall. The pre- and post-hurricane Quickbird images of Punta Gorda were obtained rapidly enough to employ them in the field survey.

In the two weeks following Hurricane Charley, ground-level field collection of building damage data in Punta Gorda and Port Charlotte was conducted by joint teams from TTU-WISE and ImageCat, Inc., using the available pre- and post-storm Quickbird images. 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 validate visual signatures of damage distinguishable in the satellite imagery. Further details of the field investigations are given by Womble, et al. (2005) and Adams et al. (2004c).

In addition to the satellite imagery, Hurricane Charley, the field teams deployed the VIEWS system to accelerate and streamline the collection of damage data across this broad area, and to produce a permanent visual record of damage sustained by individual structures. Hurricane Charley marked the first non-earthquake deployment of the system. The VIEWS field survey was conducted primarily from a high-profile moving vehicle (SUV) driven at an optimal speed of about 10 mph. 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. The reconnaissance teams focused on temporal changes ("damage") in the before-and-after satellite images to select a wide range of damage levels for the ground-truthing survey. Whereas traditional detailed (forensic) engineering damage surveys

(Section 2.3) have covered approximately 20–100 per day (depending on the level of survey detail), the four-day VIEWS deployment collected a vast volume of field data (including 21 hours of digital video and 930 still photographs) in a limited timeframe, averaging about 2,500 buildings per day. The Hurricane Charley field investigation targeted three main types of building construction: wood-frame-roof construction (including single-family homes and low rise apartment buildings), commercial/industrial buildings (with metal or built-up roofs), and manufactured housing. The field study purposely attempted to capture multiple samples of all damage levels for these various building types.

4.3. Hurricane Ivan

Hurricane Ivan struck the Gulf Shores, AL and Pensacola, FL region (figure 4-3) on September 16, 2004 as a Category 3 hurricane, with sustained winds exceeding 100 mph and gusts of up to 120 mph (FEMA, 2005b). Hurricane Ivan provided a second opportunity for the MCEER/Texas Tech/ImageCat team to obtain high-resolution satellite images before and after a major hurricane, as well as associated field data. Data collected for Hurricane Ivan have made valuable extensions to the data set initiated with Hurricane Charley, largely because of differences in the geography of the affected areas, differences in the affected building inventories, and differences in characteristics of the two hurricanes themselves. Despite having lower windspeeds than Hurricane Charley, Hurricane Ivan's assault on the tall-pine forests of the Florida Panhandle and Alabama coast resulted in significantly more vegetation damage, tree-blocked roadways and treefall damage to buildings. Ironically, the numerous tall trees in the Pensacola area helped to shield nearby buildings from the strong hurricane winds, but inflicted severe secondary damage when the trees themselves fell onto the buildings that they shielded. The large number of warehouses and storage buildings in the Pensacola area also expanded the database of commercial/ industrial buildings. Compared with Hurricane Charley, the larger tidal surge of Hurricane Ivan also resulted in more flood-damaged buildings along the beachfront, street flooding, flood debris, and sand-overwashed roads.

The IKONOS satellite acquired comprehensive images of the landfall area on September 18 (two days after landfall) as well as specific targets during the following weeks. Weather conditions and satellite orbits did not permit imaging of the Mobile – Pensacola area by the Quickbird satellite until September 21 (five days after landfall). As a result, Quickbird satellite images for the area affected by Hurricane Ivan were not obtained until after the ground survey had concluded. The field team was, however, able to confirm with DigitalGlobe the coverage areas for the September 21 collection, to help establish a focus area for a ground (VIEWS) survey (Thomassie, 2004).

Although commercial satellite companies such as DigitalGlobe and GeoEye typically acquire satellite imagery on an advance-tasking basis, high market demand for imagery following Hurricane Charley likely precipitated an effort for the DigitalGlobe Corporation to again acquire images of the affected area, despite a previously tasked order to acquire imagery some distance to the west in Mississippi. To accomplish this feat, DigitalGlobe programmed the Quickbird satellite to acquire imagery in a diagonal northwest-southeast sequence, stretching from Mobile, AL to Pensacola, FL as the satellite's sensors looked eastward during the polar-orbital pass over Mississippi (Thomassie, 2004). The images in this sequence grow progressively off-nadir, to

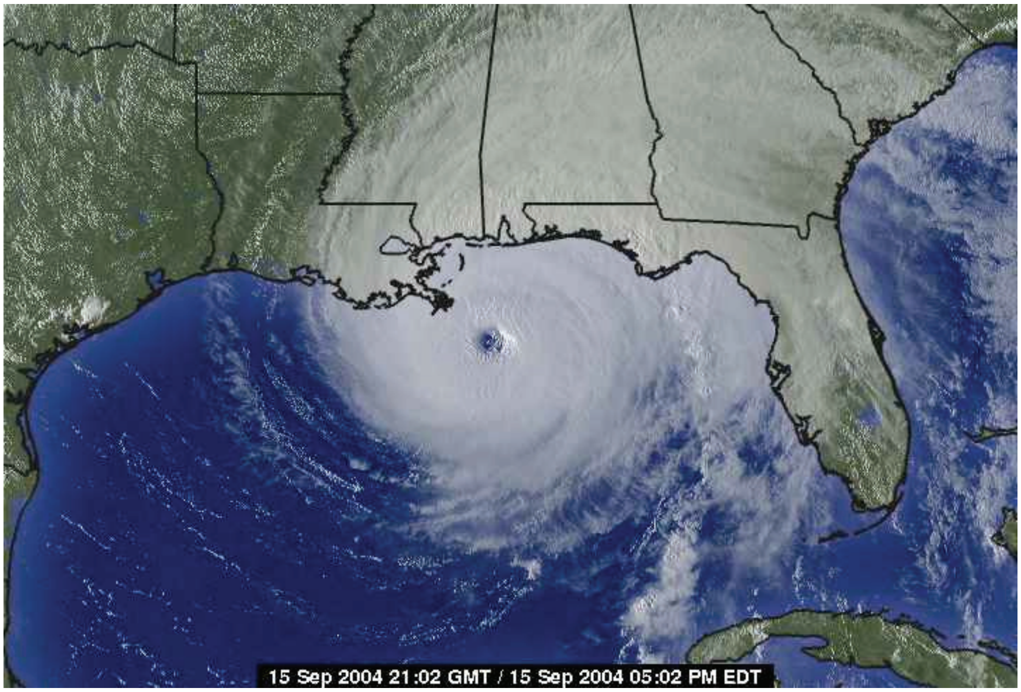


Figure 4-3. Weather Satellite View of Hurricane Ivan Prior to Landfall in Alabama and the Florida Panhandle (September 15, 2004). Credit: NOAA and the Weather Channel <www.weather.com>.

slightly more than 30° for the Pensacola area, resulting in a nominal spatial resolution of approximately 80 cm.

Pre-storm imagery of the Pensacola area was abundant in the Quickbird archives, including a near-vertical, recent view from March 12, 2004. Before-and-after images for the Pensacola area were thus purchased for the present study. Though both images were cloud-free, a great difference in off-nadir angles (and the related spatial resolutions) once again emphasized the need for robust registration and/or extraction procedures to assist in the automated delineation and analysis of buildings in temporal image sequences. The alignment and perspective issues are particularly apparent when viewing the taller buildings in downtown Pensacola; ground-level alignment of the building bases alone does not result in proper alignment of building roofs.

In continuing a research effort begun with Hurricane Isabel the previous year (NOAA, 2003b,c), NOAA's Remote Sensing Division acquired 2000 digital aerial images of coastal areas affected by Hurricane Ivan, ranging from Gulf Port, MS to Fort Walton Beach, FL. These images included coastal areas of Pensacola and the Pensacola Naval Air Station (NAS). The aerial 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, 2004b). Such images can be extremely helpful for ground-survey operations; however, the Hurricane Ivan field team experienced severe limitations on high-speed internet access in the field, and therefore found retrieval of numerous large images to be impractical.

Acquired from an elevation of 7500 ft, the NOAA images have a nominal spatial resolution of 37 cm, significantly finer than currently available satellite images. The difference in spatial resolution provides a basis for qualitative comparison of the NOAA aerial images and the Quickbird satellite images of the same post-storm areas. As with standard photogrammetric surveys, adjacent images have a forward overlap (approximately 60%), making them suitable for stereo imaging and 3-D feature extraction. These large images are stored and transmitted in a compressed JPG format (resulting in file sizes of about 4 MB each), leading to possible loss of image information due to compression. In comparison to the multispectral satellite images, the NOAA images are natural-color (red-green-blue bands) only, and thus do not have a near-infrared component. Additionally, lack of georeferencing information for the online images requires additional pre-preprocessing of the information for use in a GIS environment (e.g. VIEWS).

The NOAA aerial survey demonstrated the ability of modern aerial-survey to, in some instances, collect remote-sensing imagery sooner than the high-resolution satellites. However, such surveys require significant planning and time for execution. And unless additional measures are taken to conduct an aerial survey preceding a windstorm (where exact locations are generally difficult to pinpoint in advance), pre-storm images may not be available in the same format for temporal change-detection comparisons. In such instances, a comparison of pre-storm archival satellite images with post-storm aerial images may be warranted.

An MCEER/Texas Tech/ImageCat reconnaissance team was made to collect building damage data in the wake of Hurricane Ivan at Gulf Shores, AL, Orange Beach, AL, and Pensacola, FL. This ground-truthing survey was conducted September 21-23, 2004, and thus Quickbird post-storm images and NOAA aerial images were not available prior to deployment. Poor electronic communications in the field also prohibited the transmission of large image data to the field team. The survey team found the lack of a synoptic view of the damage scene to be a frustration in attempting to rapidly locate ground-truthing samples for various damage states. Cellular telephone communications between the field teams and DigitalGlobe (Thomassie, 2004) were, however, successful in confirming which cloud-free areas had been imaged by the Quickbird satellite on September 21 and would thus be targeted for field investigation on the final day of the field deployment.

Ground-truthing data (including 12 hours of georeferenced digital video and 1200 georeferenced digital still images) were again acquired using the VIEWS system, deployed from a moving vehicle. Despite the lack of post-storm imagery for the base map, VIEWS remained a valuable tool for tracking the progress of the ground investigation and for linking photographs and video sequences to their corresponding locations for subsequent analysis via the VIEWS® Visualization mode once the post-storm Quickbird images had been acquired.

The experience of the field-survey team in Hurricane Ivan in particular stressed the merit of remote sensing in windstorm damage assessment and emphasized the need to rapidly acquire remote-sensing data for assistance with strategic planning for field surveys. Compared to Hurricane Charley, the field team experienced more obstacles in accessing damaged areas. In addition to a 7:00 pm curfew and road closures due to treefall, flooding, and sand deposits, the ground team found access to several areas prohibited by law-enforcement officials. Particularly inaccessible were the severely damaged beachfront areas of Orange Beach, AL, the barrier island of Perdido Key, FL, and the heavily damaged Pensacola Naval Air Station. Ironically, it can be noted that initial limitations on access to such areas may, in turn, delay cleanup efforts and allow longer time windows for capturing the damage scene with satellite or aerial imagery.

4.4 Hurricane Katrina, Louisiana/Mississippi, USA

On the 29th of August 2005, Hurricane Katrina made landfall as a Category 4 storm in Plaquemines Parish, Louisiana (USGS, 2005). Due to the hurricane, storm surges affected large areas of coastlines along Louisiana, Mississippi and Alabama, and also the hydrological system associated with Lake Pontchartrain in close proximity to New Orleans. The storm surge caused by Hurricane Katrina breached a number of the levees on canals linked to Lake Pontchartrain, causing extensive flooding throughout the city, estimated at 80% (USGS, 2005). Because of the extent of the flooding through the urban environment, Katrina is thought to have been the costliest natural disaster in US history with insurance claims and damage estimates still being revised at the time of press. Eroding levees along the Mississippi, the Mississippi River Gulf Outlet (MR-GO) and the Mississippi Sound caused major flooding in St Bernard's Parish and the Lower Ninth Ward. A second surge flowed Westward through the Gulf Intracoastal Waterway further contributing to flooding in this area. More breaches occurred along Lake Pontchartrain, the London Avenue Canal and the 17th Street Canal causing flooding in Eastern and Western New Orleans. By September 1st, the flood water is thought to have equalized to around three feet above sea level (NOVA, 2006).

In the aftermath of Hurricane Katrina, remote-sensing data from satellite and airborne platforms were collected rapidly and made available to support post-disaster situation assessment and response activities in Mississippi and Louisiana. While weather satellites provided constant monitoring of the storm track, given the limited ground access due to surge inundation and flooding, remote-sensing imagery constituted one of the first-available sources of information on damage conditions. Womble et al. (2006a) presents a full review of remote sensing imagery captured in the days and weeks after Katrina. Specifically, Radarsat I captured moderate-resolution radar coverage of New Orleans using different imaging 'modes'. The images collected include ”fine” (8 m nominal resolution), ”standard” (25 m), and ”wide” (30 m). Radarsat captured early imagery of the hurricane system on August 28, as it approached land. The first post-hurricane Radarsat coverage for New Orleans was also acquired on September 2, with subsequent collections on September 5 and September 9 (see figure 4-4). Given the extensive nature of flooding within New Orleans city and timely acquisition of multi-resolution SAR imagery, New Orleans is a useful case study for exploring optimal imagery specifications for the monitoring of urban flood events. The hardest hit communities were in the county of Orleans, Louisiana, namely the city of New Orleans, St Bernard's, Plaquemines and Jefferson parishes.

A VIEWS damage survey of impacted areas in New Orleans was conducted by a four-member MCEER team, from a moving vehicle driven at 25-30 mph. In general, access to the various residential neighborhoods did not prove to be a significant limitation. On occasion, admittance to heavily damaged institutional buildings and university campuses required special authorization. Accordingly, some of these sites proved inaccessible for damage documentation. Vehicular access to the levee breach sites was limited, so damage data collection in those areas was primarily conducted on foot. Sixteen hours of georeferenced HDV footage were recorded along the reconnaissance survey route. From the HDV footage, a library of approximately 27,000 georeferenced HD photographs was extracted.

Figure 4-4. Radarsat-1 SAR Image (Fine Beam – 8m resolution) of Downtown New Orleans Acquired on September 9, 2005 (Courtesy of Canadian Space Agency http://www.space.gc.ca/asc/eng/satellites/radarsat1/featured_north_america.asp and MDA Corporation http://gs.mdacorporation.com).

SECTION 5

CONCLUSIONS

Concluding this first volume of the five volume damage detection series, the four cases studies serve as a segway for readers from introductory information about the background of remote sensing for post-disaster damage detection, to the technical methodological descriptions, results and key findings. These are contained in four separate volumes:

- II: Counting the Number of Collapsed Buildings Using an Object-Oriented Analysis: Case Study of the 2008 Bam Earthquake
- III: Multi-Sensor Image Fusion Techniques for Robust Neighborhood-Scale Urban Damage Assessment
- IV: A Study of Multi-Temporal and Multi-Resolution SAR Imagery for Post-Katrina Flood Monitoring in New Orleans
- V: Integration of Remote Sensing Imagery and VIEWS™ Filed Data For Post-Hurricane Charley Building Damage Assessment

It is intended that at this juncture, readers have a provisional understanding of both the technology push (high-resolution optical imagery, radar data, VIEWS) and user pull (improved resilience, rapid and resourceful damage assessment and loss estimation) driving the implementation of remote sensing for post-disaster damage assessment. The prior activities and outstanding research requirements that provide context for this work should also be apparent. Together with acknowledgement for with the leadership role that MCEER and MCEER's new Remote Sensing Institute are playing in advancing multi-hazard disaster management and response activities.

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