Imagery Interpretation Guide

Assessing Wind Disaster Damage To Structures

Harvard Humanitarian Initative

Signal Program on Human Security and Technology

About This Project

The methodology was developed by the Signal Program to specifically address gaps in current practice identified by the World Bank. The World Bank communicated its need for this methodology to the Signal Program after financing a Unmanned Aerial Vehical (UAV) damage assessment of the impact of Cyclone Pam on Vanuatu in 2015.

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The Signal Program on Human Security and Technology

The Signal Program on Human Security and Technology (Signal Program) was founded by the Harvard Humanitarian Initiative in 2012. Signal Program staff, fellows, and partners work to advance the safe, ethical, and effective use of information technologies by communities of practice during humanitarian and human rights emergencies.

The program addresses critical gaps in research and practice that HHI encountered while designing and managing the pilot phase of the Satellite Sentinel Project (SSP) from December 2010 to the summer of 2012. As part of SSP, HHI analyzed satellite imagery and open source reports from Sudan and South Sudan to assess the human security status of civilians.

The program's ongoing research and scholarship focuses on the following three areas:

- *Tools and Methods:* Design and scientifically test tools and methods that remotely collect and analyze data about humanitarian emergencies;
- *Standards and Ethics*: Lead the development of technical standards and professional ethics for the responsible use of technology to assist disaster-affected populations; and
- *Mass Atrocity Remote Sensing:* Conduct retrospective analysis of satellite imagery and other related data to identify remotely observable forensic evidence of alleged mass atrocities.

The Harvard Humanitarian Initiative

HHI is a university-wide center involving multiple entities within the Harvard community that provide expertise in public health, medicine, social science, management, and other disciplines to promote evidence-based approaches to humanitarian assistance. The mission of HHI is to relieve human suffering in war and disaster by advancing the science and practice of humanitarian response worldwide.

HHI fosters interdisciplinary collaboration in order to:

- Improve the effectiveness of humanitarian strategies for relief, protection and prevention;
- Instill human rights principles and practices in these strategies; and
- Educate and train the next generation of humanitarian leaders.

Table of Contents

Ray Shirkhodai

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Foreword

It was not very long ago that hazards were viewed as inevitable furies of nature, and disasters as the tragic outcomes, countered only by transfer of the risk through insurance and statistical loss estimation. Then came those committed to changing that helpless narrative, arguing that disasters – defined as the intersection of hazard forces destructively impacting the human-built environment and overwhelming the related systems – can be reduced by minimizing the intersection of hazards and human systems. Through their efforts, Disaster Risk Reduction (DRR) was coined and disaster management entered a new era.

Today, DRR research and practices encompass a wide array of activities: hazard avoidance, increasing coping capacities, and improving recovery capabilities. Yet, try as we may to reduce risks, we cannot entirely eliminate the destructive impacts of all hazards for all exposed communities. And, when destruction does occur, every second saved in assessing the damage and obtaining accurate and actionable information could literally translate into lives saved.

As critical as rapid damage assessment is to effective relief and response operations, to-date it relies heavily on eye-witness, on-the-ground reports from the responders. This is very problematic, not only because remote locations, where damage may be most extensive, are hard to reach; but also because it presumes responders' knowledge of and ability to quickly reach the hardest-hit areas and appropriately communicate what they see. Even so, uniformly mapping the reports and sharing the results take additional valuable time. At the same time, various methodologies for assessing damage remotely require obtaining and maintaining large volumes and inventories of pre-impact data, which again is neither practical nor scalable. Finally, ad hoc methodologies used for remote assessments lack standardization, chain-of-custody, and a common baseline necessary for wide sharing of the information among the participating communities.

The authors of this study at the Harvard Humanitarian Initiative (HHI) considered means of addressing these challenges by offering a uniform approach, using commonly available high-resolution imagery, spatial analytical tools, and a standard visualization system that does not demand high proficiency in a specific language or jargon. Even though focused on wind damage assessment, the approach described here could well serve as a means of establishing a common baseline for rapid damage assessment regardless of the hazard type, and may begin to establish standards for all such remote assessments.

Since 1996, Pacific Disaster Center has been looked upon as an important innovator in applying scientific methods and emerging technologies toward disaster management, and a contributing partner in the DRR efforts worldwide. Our colleagues at HHI may just have given us all another important innovation: a fresh look at technologies used toward a common, scalable, and practical approach to remote damage assessment.

This proposed HHI approach has the potential to contribute significantly to DRR as a whole, but more importantly, may lead to valuable, actionable information for decision makers, precisely at the point when every second matters the most.

Ray Shirkhodai

Executive Director, Pacific Disaster Center

Chapter 1: Standardizing Remote Assessments of Wind Disaster Damage

1A. Introduction

The ability to rapidly assess wind disaster* damage to structures is a critical necessity for responding agencies. However, the assessment process is complicated by the lack of common standards and scalable methodologies for the use of remote sensing in damage assessments. At present, accepted methodologies for wind disaster damage assessments rely almost exclusively on responders having ground access to the affected area to document damage to housing structures.[1]

This approach to rapid needs assessments in these scenarios can prove time consuming and inefficient, particularly in the critical period immediately following a storm's impact when this data is potentially most useful. Geospatially-based damage assessments may provide actionable information to responding agencies about hard-to-reach, often non-permissive environments.

Agencies are increasingly using geospatial technologies to conduct wind disaster damage assessments of structures without agreed methodologies for doing so. The primary problem facing these agencies is the absence of a "theory of actionability" for how and why the provision of geospatial data to responding agencies can enhance ground operations.

The absence of a common theory of actionability has created a significant gap in the current practice of geospatial analysis-supported ground operations. This gap in current practice has real implications for humanitarian agencies that can operationally manifest themselves in some of the following ways:

- *Conflicting counts of damaged structures:* Without a common methodology, different analysts can come to different and conflicting counts of how many structures have been visibly damaged by a wind disaster event;
- *Varying damage scales:* The severity of damage assigned to one structure may vary between assessments of the same structure by different analysts, or teams of analysts, due to the lack of a common method for agreeing damage scales; and
- *Slower response and reduced actionability:* Lacking common, agreed standards for what information is most required, what formats and metrics are most actionable, and without a shared basis for understanding how this information should be used by ground responders may slow response and reduce the ability of non-geospatial experts to operationally apply information gained from these assessments. Additionally, the absence of these guidelines can lead to conflicting or duplicated information, further hindering the response.

The goal of this guide is to address these gaps by providing the foundation of a common approach for conducting geospatially-based damage assessments of the impact of wind disasters on structures. The guide is aimed at institutional analysts, voluntary technical organizations (VTOs), and affected communities who may be utilizing geospatially-derived data to support ground operations in the initial phase of a wind disaster response through seeking to improve situational awareness for responding agencies and communities.

The method presented in this guide is the "Baker, Achkar, Raymond" methodology (hereafter, "BAR"). It was developed by the Signal Program on Human Security and Technology (Signal Program) at the Harvard Humanitarian Initiative (HHI) at the request of the World Bank to standardize the categorization of structures visible in geospatial data and create a common severity scale for assessing apparently visible damage to these objects.

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* Wind disasters can include cyclones, typhoons, hurricanes, tornadoes, and other similar phenomena.

Satellite and UAV imagery of the aftermath of Cyclone Pam, which hit the island of Vanuatu in March 2015, is utilized as a case study for demonstrating the potential application of the BAR methodology. While each wind disaster event will differ in terms of context and impact, the aim of the BAR methodology is to provide the first common, scalable approach for conducting these assessments through geospatial data across contexts and varying types of wind disasters.

1B. Current State of the Art

The Signal Program surveyed all available literature related to remote and ground-based assessments of damage to structures caused by wind disasters in preparing to conduct the research presented in this guide. The goal of the survey was to identify any relevant approaches for guiding geospatially-based damage assessments of areas affected by these types of disaster events.** No method specific to remote assessment of damage to structures caused by wind disasters was found in this review.

However, two major ground-based methodologies - Economic Community for Latin and America and the Caribbean (ECLAC) assessment and the Enhanced Fujita Scale (EF) - appear to be the most commonly used at various points as part of some geospatially-based assessments. The Signal Program finds, though, that these two models do not provide a methodological approach sufficient to comprehensively document damage to structures using data produced by geospatial and remote sensing-based approaches.

Moreover, the literature on damage assessment shows a general absence of a common theory and corresponding methodology for assessing storm damage to structures that is scalable across contexts and geographic regions. As mentioned previously, these methodologies are fundamentally designed for ground-based assessments, and thus are not intentionally tailored to be used with geospatial data.

ECLAC Handbook for Disaster Assessment
The ECLAC approach focuses broadly on determining the socio-economic impacts of damage inflicted by a natural disaster. ECLAC-based data may provide some useful insights when conducting a damage assessment specifically focusing on the monetary cost of damage to housing stock. A well-established pre-disaster event baseline of data about existing types and common conditions of regionally specific dwellings and structures, which is often not available in many contexts, is required to conduct an accurate and actionable assessment. [2]

The ECLAC approach categorizes different housing units by distinct types to indicate the extent of damage to specific classes of housing units. The ECLAC assessment methodology focuses on ascertaining the estimated costs of event's damage to inform post-disaster needs assessments as part of reconstruction efforts. While useful for medium and long term reconstruction activities, this approach does not adequately support initial rapid needs assessment activities.

There are multiple reasons why ECLAC is not a strong "tool-to-task" match for rapid needs assessments, regardless of the involvement of geospatial data. The method is time consuming and requires pre-existing, in-depth data on a region's specific housing infrastructure, market prices, and income of occupants. Additionally, ECLAC relies heavily on ground-based visits which are often not permissible or cost-effective in the immediate aftermath of a disaster.

Enhanced Fujita Scale
The EF Scale is the most widely used method for assessing the severity of a wind disaster event, and it was developed specifically to assess damage caused by tornadoes. The EF Scale was developed to fill the gaps that existed in the previous model, known as the Fujita Scale.[3] The authors of the revised 2006 assessment noted that the limitations to the Fujita Scale "are a lack of damage indicators, no account of construction quality and variability and no definitive correlation between damage and wind speed." [4]

** "Geospatially-based damage assessments" are defined in the context of this document as efforts to ascertain the number and severity of structures damaged by a wind disaster based initially on imagery derived from earth orbiting satellites and/or UAVs, as opposed to efforts to corroborate a ground-based assessment of wind disaster damage to structures.

The new model established 28 damage indicators (DIs) ranging from structures, to trees, and telecommunications poles; each of which can possess various degrees of damage (DODs) based on the identified DIs.[5] Both Fujita models were created to determine wind speeds and therefore accurately assess the strength of a tornado based on the damage occurred to the identifiable DIs.

The EF model provides useful steps to creating a wind-related damage assessment model in terms of providing a detailed list of DIs and DODs. While valuable in certain scenarios, the model is largely reliant on responders having the ground access necessary to assess damage for the explicit purpose of estimating wind speed and tornado strength, rather than to provide a comprehensive overview of the total degree of damage to an area.

The enhanced model improves upon the previous Fujita Scale as a ground-based assessment tool, but it does not provide a directly transferrable metric and method for geospatially-based analysis of the total scope of damage present in wind disaster affected areas. Regardless, EF has been used in some remote sensing-based assessments of wind damage, most notably crowdsourced assessments of tornado damage in the United States.[6, 7]

1C. Gaps in Current Practice

The Signal Program's analysis of the current state of the art in this field indicates that there is no common methodology for performing this specific task intentionally with a remote sensor. The following are the three most urgent gaps the Signal Program has identified that illustrate this problem, which the method presented in this guide seeks to address:

- *No Common Damage Scale:* There does not exist a method specific to assessing the severity of damage to structures through remote sensing data during the initial "rapid assessment phase" with the aim of intentionally supporting critical decision making by ground responders.
- *No Common Structure Categorization System:* No common categorization system for broadly categorizing types of structures and levels of damage repeatedly observed across these categories appears to exist.
- *No Agreed Imagery Annotation Approach:* In the absence of a common structure type and damage level classification system, there are no shared standards for annotating imagery data of disaster affected areas, which prevents generating aggregated data sets from different assessments over time and across contexts, significantly limiting the potential actionable value of this data.

Addressing these gaps is critical because NGOs, governments, and researchers are increasingly using remote sensing to perform initial damage assessments after wind disasters. The rise in the use of this technology can likely be anecdotally attributed to ongoing improvement to technical and market access to geospatial data and related platforms.[8]

However, as evidenced by the Signal Program's survey of the literature, this work is being done without common methods and standards for data capture, analysis, and presentation. This lack of accepted methods and standards for wind disaster damage assessments appears to have resulted in no clear theory of expected impact for why, when, where, and how these assessments are performed.

Chapter 2: Applying the BAR Methodology

2A. Overview of the BAR Methodology

The BAR method proposed by the Signal Program provides a standardized and replicable approach to damage assessment of wind disasters through the analysis of geospatial data. As part of this methodology, assessments, outputs, notation and presentations of the data collected and analyzed are standardized to support responders by delivering information in a common format that is believed to be most actionable in the rapid needs assessment phase.

The proposed methodology is not meant to eliminate the need for ground-based assessment - rather it provides a complementary approach to support humanitarian operators simultaneous to the deployment of ground assessment teams. Ideally, assessments conducted using the BAR methodology will help target ground assessment teams, speeding the completion and cross-corroboration of their assessments.

BAR is based on two preconditions to be deployed: First, baseline data (e.g. imagery captured prior to the wind disaster event occurring) must be available to compare post-event imagery against to determine the pre-disaster disposition of apparently affected structures; and second, analysts and digital volunteers deploying BAR must have basic fluency in commonly available software platforms and methods of imagery comparison analysis. For the first criteria, it is important to note that high resolution baseline satellite imagery does not necessarily have to be acquired commercially, and can often be found for no cost on online digital platforms, such as GoogleEarth.

The core components of the BAR methodology in the order that they should be applied are as follows

1) **Setting Parameters:** First, an alphanumeric grid frame is overlaid on satellite imagery of the Area of Interest (AOI) with software which can include ArcGIS or InDesign. The grid will serve to guide the imagery analysis of the image(s) by the analyst(s). Though an important part of the process, the absence of the grid should not impede the users application of the methodology. (See *Appendix I*)

2) **Assigning Structure Categories:** Second, all potential structure types apparently visible in the imagery, regardless of region and contexts, are sorted into three categories: A) Light strength structures (the most vulnerable); B) Medium strength structures (moderately vulnerable); and C) Heavy strength structures (usually the least vulnerable). Each analyst or group of analysts performing a damage assessment through the BAR Methodology must agree what constitutes light, moderate and heavy structures in their specific operational context. (See *Section 2B* below)

3) **Assigning Damage Scale:** Each object in every structure class is assigned a specific color that corresponds to the damage scale. The damage scale is a point based scoring system that ranges from 0 to 3. These classifications remain the same for each structure class and are used to assess the damage of each building to give it a point ranking. The point system is as follows: 0 = no visible damage to the structure; 1 = visible partial roof damage while; 2 = the roof has suffered significant damage or is completely off, but the walls remain standing; and 3 = the walls and the roofs are down and the structure integrity is completely compromised.

4) **Calculate Point Totals:** The point total for each object and for each structure category are aggregated together into a total score for each grid square and the entire AOI. The aggregated results of BAR are a points based damage score that can be visualized as either a numeric chart or a map. The long-term goal of this point total system is to eventually support the creation of computer supervised classification algorithms.

2B. Assigning Structure Categories

Establishing set criterions in order to classify observed structures into three categories is a critical first step that will allow the user to appropriately deploy the methodology. A poorly established categorization will negatively impact the viability and accuracy of the assessment conducted. Categorizing structures allows analysts to provide a rapid assessment of damage caused by wind-related disasters to the areas observed. Through categorization and classification, analyst(s) can provide a snapshot of damages relating to specific type of infrastructures and establish a preliminary understanding of areas most vulnerable and in need of immediate help. Categorization has an added benefit of assessing the strength of the disaster based on damage done to structures that are considered structurally stable and not vulnerable.

The characteristics of types of structures defined below will help users classify observable structures into the categories that are best suited. In each situation this methodology is applied, the defined characteristics and parameters will help users easily classify structures into three defined categories: light, medium and heavy. It is expected that structure classification will differ across countries and regions due to infrastructure and socio-economic differences from one area to the other.

Cultural differences and regional dynamics will affect defining parameters for each of the classes established below. These differences will be especially impactful in regards to the light structures definition as this class is the most sensitive to these differences and is often dominated by traditional methods of construction in the regions observed. Understanding cultural preferences and techniques in construction is therefore a necessary task to undertake in order to properly categorize the different structures. As part of any study, the team will need to clearly articulate which structures fits into the different categories and provide a rationale for doing so prior to starting any imagery analysis. When applying the BAR methodology, analysts should document and publish the criteria they choose for assigning each category.

- ∆ *Light Structures:* This category, annotated with a triangle, encompasses structures that are built predominantly from light material or locally sourced materials. These structures may be mobile or possess no real hard roof, in some cases, roofs are made of metal or light material; they are often small in size. As such, these structures are likely to be the most vulnerable structures in any impacted region. Examples of these types of structures can include huts, tukuls or mobile trailers.
- ○ *Medium Structures:* This category, annotated with a circle, encompasses structures that are built from semi-hard materials or mixed products. These structures have solid frames built using wood, steel or cement. These type of structures are fixed and possess hardened walls and roofs which can be made out of wood or cement. Unlike light structures, these types of structures are able to withstand moderate level of wind, with no to little damage, while maintaining their structural integrity. These types of structures can be individual or multi family houses, small stores, places of worship and similar structures.
- □ *Heavy Structures*: This category, annotated with a square, encompasses structures that are built from hard materials such as reinforced cement and steel. Infrastructure of this type is the least structurally vulnerable in any observed region. These structures are designed to withstand high level winds without receiving heavy damage or endangering the structural integrity of the structure. In many areas, these may include multiple story buildings, strip malls, hospital buildings, or public utilities.

2C. Assigning Damage Scale

The Signal Program BAR Methodology applies a color-coded damage scale across all structure types based on repeating, visible damage patterns. Damage in the BAR scale is classified in 4 distinct categories: Green, Yellow, Orange and Red.

- *No Visible Damage*: This category, classified by the color green, signifies no visible damage to the structures. In these cases, the roof is virtually undamaged and the walls, in effect, remain standing. The structure appears to have complete structural integrity and does not appear to need repair.
- *Minimal Visible Damage*: This category, classified by the color yellow, signifies that some minimal visible damage has been sustained. In these structures, the roof remains largely intact, but presents partial damage to the roof's surface, with minimal exposure beneath. In oblique aerial and satellite imagery, minimal damage may be able to be observed within the structure and to the exterior walls. The structure appears to have general structural integrity but needs minor repairs.
- *Significant Visible Damage*: This category, classified by the color orange, signifies that partial but extensive visible damage has been sustained. In these structures, the roof is entirely damaged or missing. The walls of the structure remain upright. However, the interior wall partitions can be partially damaged. Debris inside the structure can also potentially be visible. The structure does not appear to have complete structural integrity and is in need of significant repair.
- *Critical Visible Damage*: This category, classified by the color red, signifies severe visible damage has been sustained. In these structures, the roof is completely destroyed or missing, and the walls have been destroyed or collapsed. The support structures are completely leveled, and interior objects have also suffered visibly heavy damage or destruction. The structure does not appear to have any structural integrity and requires comprehensive reconstruction or demolition of the entire structure.

2D. Limitations and Variables

Certain limitations and variables can impact remote sensing based damage assessments, whether these assessments use the BAR or any other methodology. Chief among these limitations and variables are the following:

- Lack of access to either high-resolution satellite imagery captured soon after the wind disaster event occurred and/or pre-event baseline imagery captured prior to the event;
- UAV imagery captured may not be georeferenced, which would require time and further resources to orient the analysts. Additionally, this limits some of the functionality of a georeferenced image such as measuring and precise coordinates which are often critical in conducting an accurate damage assessment;
- Cloud coverage and other phenomena can affect the quality of satellite imagery, though is a less of a limiting factor for UAVs;
- Reconstruction efforts may begin before satellites are able to image an area therefore reducing the numbers of apparently visible damaged structures present in the imagery. In some cases, reconstruction of light structures can occur within 48-72 hours following the event;
- In areas that are hit repeatedly by multiple disasters, assessing damage done by the specific event may be complicated by the fact that reconstructions efforts were not completed following the previous disasters. In these cases, it is crucial to have baseline imagery available as close to the date of the specific event examined as possible;
- The presence of standing water after a flood that obscures walls and interiors of a structure, hindering the analysts abilities to assess the damage
- Analysts are often unable to assess potential damage done to the interior of structures through the use of remote sensing platforms exclusively; and
- Every type of remote sensing data has its own potential dynamics that may distort the image in both repeating and isolated ways.

Chapter 3: Case Study: Applying BAR to Cyclone Pam's Impact on Vanuatu

3A. Background

The Republic of Vanuatu is an archipelago made up of close to 80 islands in the South Pacific Ocean. It has an estimated population of 270,000. According to available data, two thirds of the population make their living from small scale agriculture.[9] The United Nations World Risk Index 2014 ranks Vanuatu as the topmost exposed country to natural disasters. Additionally, Vanuatu has poor disaster preparations and response mechanisms.[10]

Cyclone Pam was a category 5 cyclone that swept throughVanuatu and neighboring countries in March of 2015. The cyclone caused serious damage to the infrastructure of the country and affected the lives of tens of thousands of people.[11] According to the government of Vanuatu, close to 170,000 people were displaced by the cyclone - nearly 60% of the total population of the country. 320 km/h winds led to widespread destruction across the islands.[12] The cyclone wiped out food production across Vanuatu, with 96% of food crops reportedly destroyed. The damage to the agricultural sector will have significant financial and economic impacts.[13]

Traditional dwellings on Vanuatu utilize long-standing methods of construction and materials that are easily accessible in the area such as timber, bamboo and "natangura leaf (thatch) roof."[14] These traditional dwellings remain popular, as they are both inexpensive and easy to build. The roofs of these dwelling are generally triangular or spherical in nature, allowing water to slide off the sides and reducing tension on the roof. Traditional dwellings vary between different villages and across the islands due to the availability of resources, but their fundamentals remain the same across different areas.

Impact of Cyclone Pam

Along the path of Cyclone Pam, UNOSAT-UNITAR reported that the percentage of affected buildings in damaged zones ranged from 50% on the main island of Efate where the capital Port Vila is located to 100% on the island of Buninga.[15] The death toll, analysts estimate, would have been higher but for the traditional housing structures, or huts, that are commonly used in rural villages. The composition of these structures resulted, in part, in a death toll that was realtively low. The early warning SMS system activated by the Government of Vanuatu played a vital role in limiting the potential death toll, as citizens were warned about the approaching cyclone.[16] Traditional houses are easy to produce and use locally available resources to build.[17] Rebuilding efforts were documented a few days following the cyclone.[18]

3B. Imagery Data

The imagery data analyzed for this guide consisted of two types: very high resolution (VHR) satellite imagery and oblique aerial imagery. The satellite imagery was open source data downloaded directly from Google Earth Pro. Several images were collected over Vanuatu immediately following the landfall of Cyclone Pam in March of 2015. The oblique aerial imagery was collected by an Unmanned Aerial Vehicle (UAV) operated by users on the ground in Vanuatu, as part of the World Bank's UAVs for Resilience Program. This imagery was shared electronically with the Signal Program for the purposes of this report.

The satellite imagery used for analysis from Google Earth Pro was selected based on the sharpest resolution and the least amount of cloud obfuscation. A satellite image, which predates the cyclone landfall, was also used as a baseline image for damage assessment comparison. This imagery was used for a broader overall damage assessment of structures in a particular area. The aerial imagery, which has a greater resolution than the satellite imagery analyzed, was used to get a more granular assessment of the level of damage sustained by the structures present.

Prior to analysis, the downloaded imagery from Google Earth Pro was georeferenced in ArcMap so that it could be analyzed with remote sensing software. The baseline and post-event imagery was then uploaded into the remote sensing program ERDAS Imagine, where they were presented in two concurrent and geospatially synchronized windows. A manual before-and-after analysis was conducted by comparing specific structures between the two images. The program's 'count feature' tool was then used to annotate structures and log the visible damage according to the scale developed by the Signal Program.

The aerial imagery was then used to verify and amend the assessments made by the satellite imagery analysis. The aerial imagery also helped flag damaged structures that may have been missed in the initial analysis. Because the aerial imagery was not georeferenced, Signal Program analysts oriented themselves by cross-referencing key landmarks within the aerial imagery to match with the satellite imagery. Through this approach, analysts were able to better validate satellite imagery analysis with the oblique aerial imagery to accomplish a more accurate assessment of the damaged structures.

3C. Criteria for Assigning Structure Categories and Applying Damage Scale

Structure Category Criteria

Structures were assigned to the three categories used in the BAR methodology based on the criteria in the bullets below. The three categories encompass all visible structures observed in imagery of Vanuatu analyzed for this case study.

As per the BAR methodology, the criteria that the Signal Program used for assigning the three structure categories are as follows:

- The light structures category is assigned to traditional structures built using, cinder blocks, bricks, organic or locally sourced material with the roof built using thatch.
- The medium structures category is assigned to single-level, small to medium sized structures built using cement walls with roofs made out of metal or prefabricated material.
- The heavy structures category is assigned to multi-level and/or large structures built using cement walls or prefabricated material with a metal or prefabricated roofs.

Damage Scale Criteria

The Signal Program assigned damage levels to structures observed in the imagery according to the damage scale of the BAR methodology. The context-specific criteria an analyst uses for assigning the damage scale should be documented and made public with every use of the BAR methodology. In this case, the damage observed in the imagery of Vanuatu was applied based on the criteria below:

- The "No Visible Damage" category was applied to structure that appear virtually undamaged with no identifiable damage to the roof or the walls.
- The "Minimal Damage" category was applied to the structures that appear to have sustained limited damage with only parts of the roof appearing to be either damaged or missing.
- The "Significant Damage" category was applied to structures that appear to have sustained damage with large parts of the roof damaged or missing. These structures, however, remain standing with the walls appearing largely intact
- The "Critical Damage" category was applied to structures that have completely lost their roofs and have sustained heavy damage to their walls. These structures have sustained massive damage to their structural integrity and have largely or completely collapsed.

3E. Damage Examples

Figure 3.1: Green Triangle

Imagery shows a light structure with thatched roof and wooden walls. In imagery collected after the event, the roof appears to be completely intact and the walls appear to remain upright, showing no visible signs of damage.

Light structure with no visible damage

Figure 3.1

Baselayer Satellite Image
19 November 2014
Mele, Vanuatu

Post-Event Satellite Image
15 March 2015
Mele, Vanuatu

Post-Event UAV Image
02 April 2015
Mele, Vanuatu

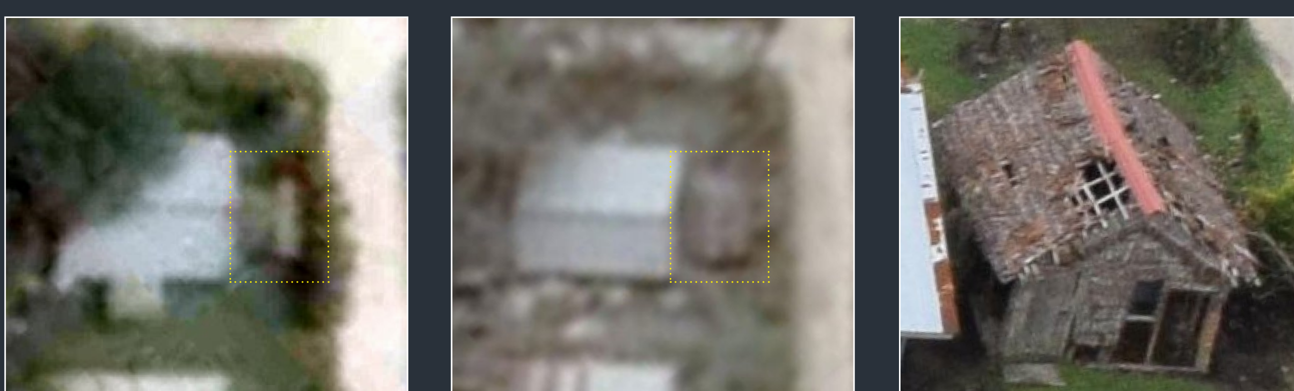
Latitiude/Longitude: 17.688239 S, 168.269392 E

Figure 3.2: Yellow Triangle

Imagery shows a light structure with thatch on the roof that is partially removed with scaffolding that is visible underneath. No internal damage is apparent.

Light structure with minimal visible damage

Figure 3.2



Baselayer Satellite Image
19 November 2014
Mele, Vanuatu

Post-Event Satellite Image
15 March 2015
Mele, Vanuatu

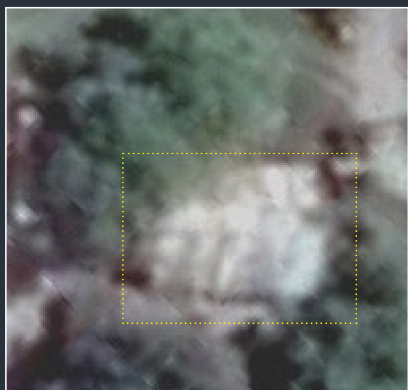
Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.688941 S, 168.270919 E

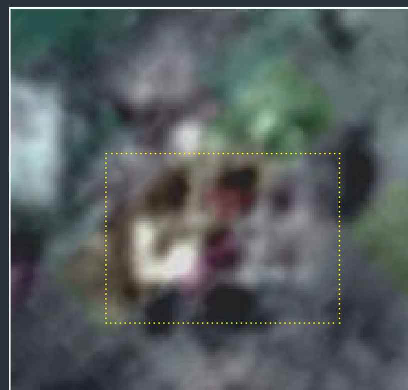
Figure 3.3: Orange Triangle
Imagery shows a light structure with cinder block walls and a roof that is completely destroyed or has been removed. There is no apparent damage sustained by the outer walls or the interior partitions.

Light structure with partial but extensive damage

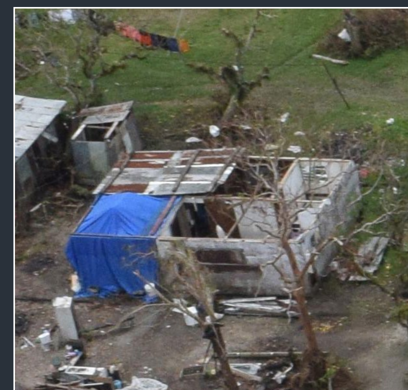
Figure 3.3



Baselayer Satellite Image
19 November 2014
Mele, Vanuatu



Post-Event Satellite Image
15 March 2015
Mele, Vanuatu



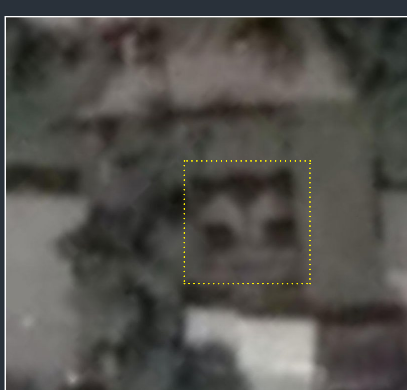
Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.686299 S, 168.270826 E

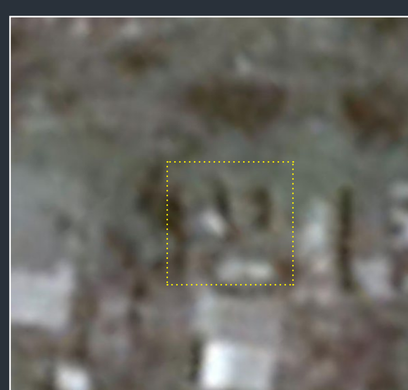
Figure 3.4: Red Triangle
Imagery shows a light structure with brick walls that is almost entirely destroyed along with the roof collapsed. Considerable amount of debris can be seen in the southwestern portion of the structure.

Light structure with complete visible damage

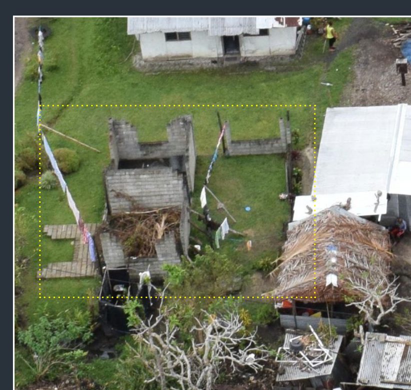
Figure 3.4



Baselayer Satellite Image
19 November 2014
Mele, Vanuatu



Post-Event Satellite Image
15 March 2015
Mele, Vanuatu



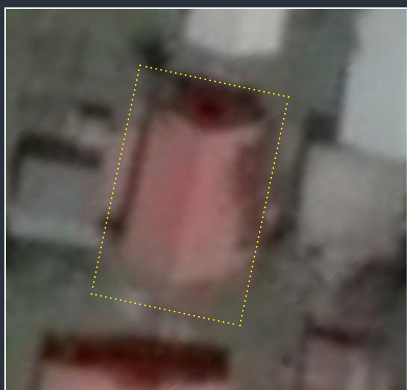
Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.686320 S, 168.271056 E

Figure 3.5: Green Circle
Imagery shows a building with concrete walls with metal roof that is consistent with medium type structures showing no apparent damage to the roof or visible walls.

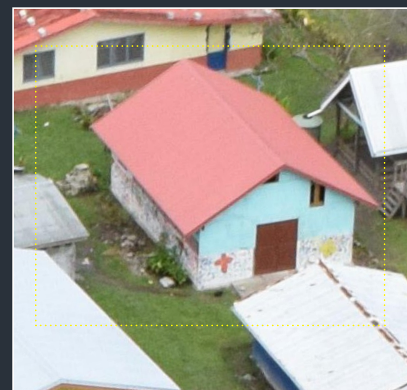
Medium structure with no visible damage

Figure 3.5



Baselayer Satellite Image
19 November 2014
Mele, Vanuatu

Post-Event Satellite Image
15 March 2015
Mele, Vanuatu



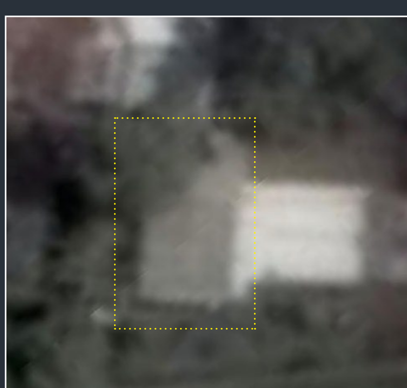
Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.689767 S, 168.269971 E

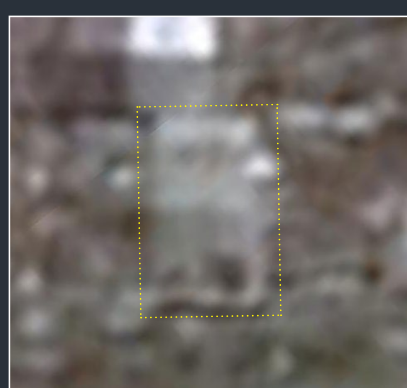
Figure 3.6: Yellow Circle
In the imagery, a medium structure with concrete walls and a metal roof has apparently sustained partial damage to the roof, with no apparent damage to the outer walls. A portion of the interior is exposed, but no apparent signs of extensive damage are present.

Medium structure with minimal visible damage

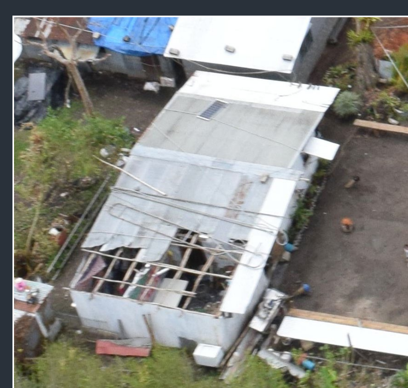
Figure 3.6



Baselayer Satellite Image
19 November 2014
Mele, Vanuatu



Post-Event Satellite Image
15 March 2015
Mele, Vanuatu



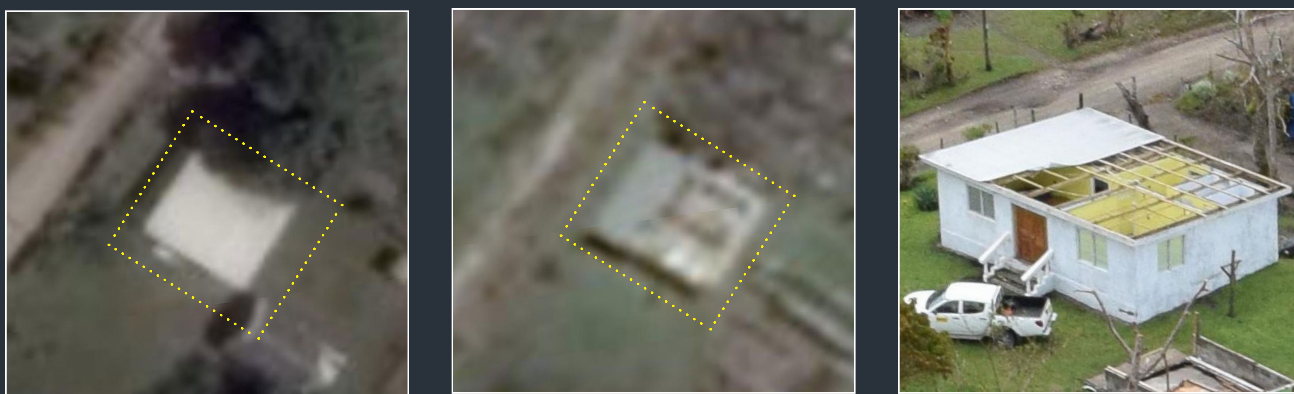
Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.688690 S, 168.270321 E

Figure 3.7: Orange Circle
Imagery shows a medium structure with walls and roof built from fabricated materials. The roof with sustained substantial damage, with no apparent damage to the walls or interior are visible.

Medium structure with partial but extensive damage

Figure 3.7



Baselayer Satellite Image
19 November 2014
Baofatu, Vanuatu

Post-Event Satellite Image
15 March 2015
Baofatu, Vanuatu

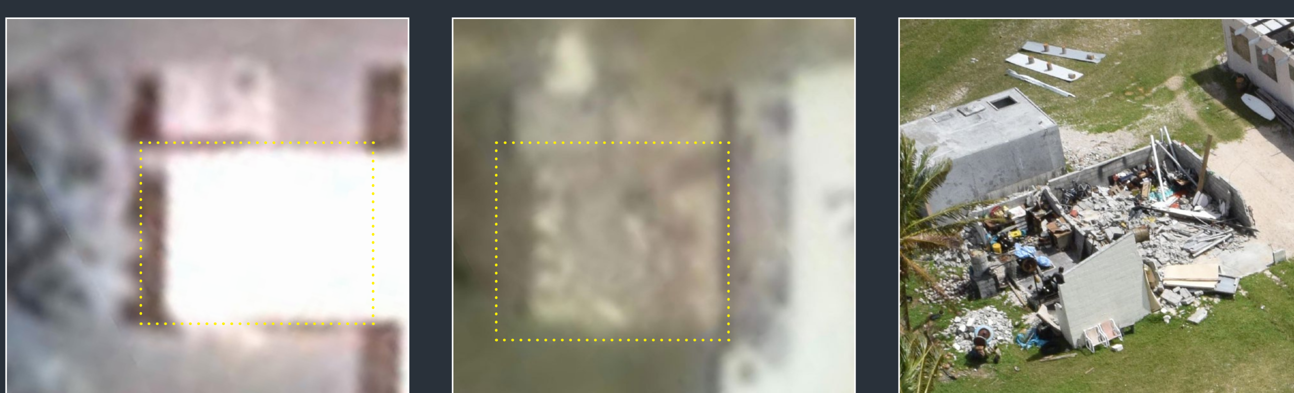
Post-Event UAV Image
02 April 2015
Baofatu, Vanuatu

Latitiude/Longitude: 17.687990 S, 168.269727 E

Figure 3.8: Red Circle
In the imagery, a medium structure with concrete walls and roof made out of prefabricated material has sustained heavy damage resulting in the collapse of the entire structure. Extensive amount of debris is apparent in the interior.

Medium structure with complete visible damage

Figure 3.8



Baselayer Satellite Image
19 November 2014
Baofatu Vanuatu

Post-Event Satellite Image
15 March 2015
Baofatu, Vanuatu

Post-Event UAV Image
07 April 2015
Baofatu, Vanuatu

Latitiude/Longitude: 17.535971 S, 168.449820 E

Figure 3.9: Green Square
Imagery shows a multi-level, heavy structure constructed with what appears to be pre-fabricated material. The imagery does not indicate any damage sustained by the structure following the event.

Heavy structure with no visible damage

Figure 3.9

Baselayer Satellite Image
19 November 2014
Mele, Vanuatu

Post-Event Satellite Image
15 March 2015
Mele, Vanuatu

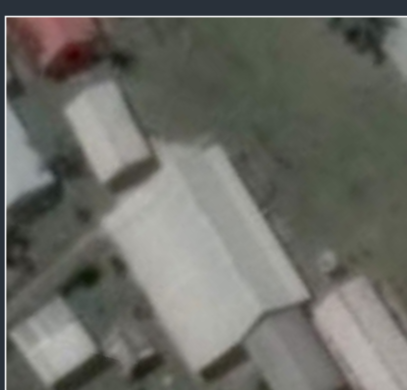
Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.743313 S, 168.316151 E

Figure 3.10: Yellow Square
Imagery shows a heavy structure with concrete walls and metal roof. The imagery indicates partial damage sustained to the roof with no clear apparent damage to the interior.

Heavy structure with minimal visible damage

Figure 3.10



Baselayer Satellite Image
19 November 2014
Mele, Vanuatu

Post-Event Satellite Image
15 March 2015
Mele, Vanuatu

Post-Event UAV Image
02 April 2015
Mele, Vanuatu

Latitiude/Longitude: 17.689551 S, 168.269695 E

Figure 3.11: Orange Square

Imagery shows a large structure with walls and roof made from fabricated materials. Structure sustained substantial, extensive damage to the roof as well as the walls, and visible debris is apparent in the interior.

Heavy structure with partial but extensive damage

Figure 3.11

Baselayer Satellite Image
11 June 2014
Baofatu, Vanuatu

Post-Event Satellite Image
15 March 2015
Baofatu, Vanuatu

Post-Event UAV Image
02 April 2015
Baofatu, Vanuatu

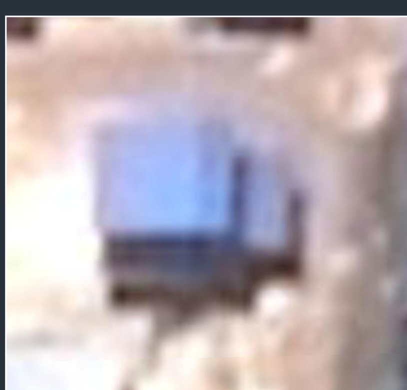
Latitiude/Longitude: 17.536119 S, 168.449663 E

Figure 3.12: Red Square

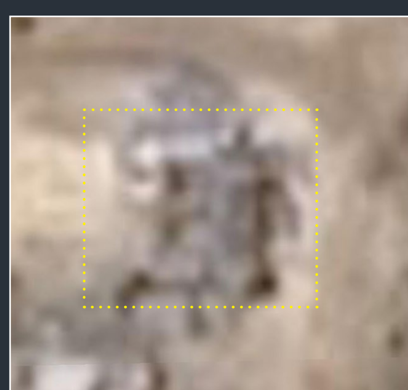
Satellite imagery shows a heavy, multi-level structure with walls and roof built from fabricated materials. In post-event imagery, the walls and roof of the structure has been destroyed, with some of the foundation of the structure remaining.

Heavy structure with complete visible damage

Figure 3.12



Baselayer Satellite Image
29 January 2014
Port Vila, Vanuatu



Post-Event Satellite Image
15 March 2015
Port Vila, Vanuatu

Latitiude/Longitude: 17.743324 S, 168.316134 E

Results

In this grid AOI, 358 structures are identified. The structures identified are divided into the three distinct categories: 144 light structures, 190 medium structures and 24 heavy structures. (See *Appendix I*)

An analysis of the damage sustained by these structures utilizing the BAR methodology revealed that 56.70% of all structures, or 203 structures, examined have sustained some level of damage. The damage to each category of structure is as follows:

- Light Structures: 49 structures sustained no visible damage, 35 structures sustained minimal damage, 29 structures sustained significant damage and 31 structures sustained critical damage
- Medium Structures: 83 structures sustained no visible damage, 81 structures sustained minimal damage, 14 structures have sustained significant damage and 12 structures sustained critical damage.
- Heavy structures: 23 structures sustained no visible damage, 1 structure appear to have sustained minimal damage and no structure appear to have sustained significant or critical damage in the grid analyzed.

A deeper analysis of results indicate that 65.97% of light structures sustained some level of damage; 56.32% of medium structures sustained some level of damage; and 4.17% of heavy structures sustained some level of damage.

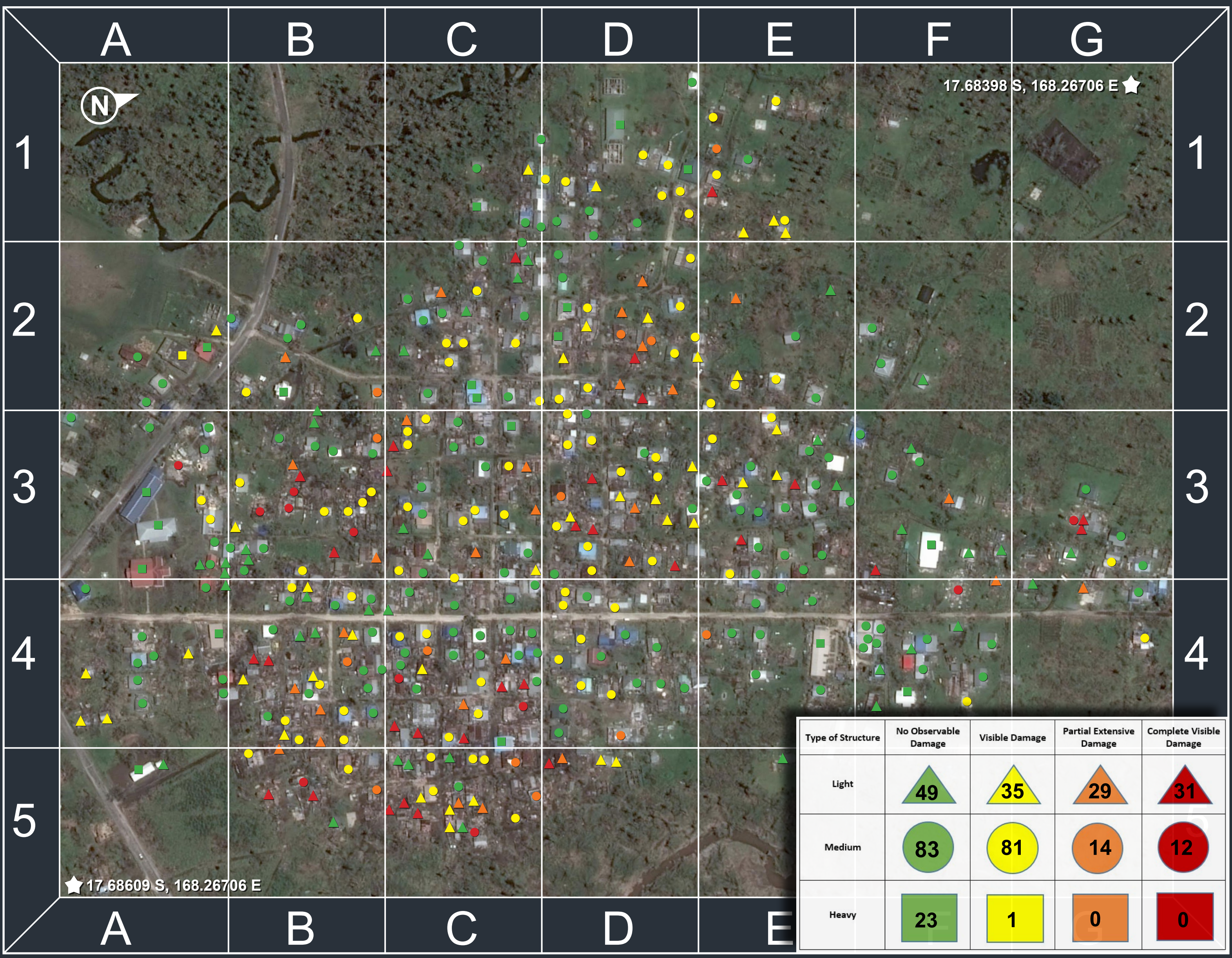
This AOI sustained 332 total damage points out of a possible 1074 damage points. In other words, 30.91% of total potential damage to structures possible was inflicted by the cyclone. Light structures sustained 186 damage points out of potential 432 points, representing 43.06% of total potential damage points for this category. Medium structures sustained 145 damage points out of a potential 570 points, representing 25.90% of total potential damage points for this category. Heavy structures sustained 1 damage point out of a potential 72 points, which represents 1.39% of total potential damage points for this category. (See *Appendix II*)

Appendix I: Analysis of Structural Damage from Cyclone Pam

Pre-Event Image
19 November 2014
Mele, Vanuatu

Post-Event Image
15 March 2015
Mele, Vanuatu

GRID Application and Damage Assessment of Structure Types



Type of Structure	No Observable Damage	Visible Damage	Partial Extensive Damage	Complete Visible Damage
Light	49	35	29	31
Medium	83	81	14	12
Heavy	23	1	0	0

Comparison of Satellite and UAV Imagery View of Quadrant B-4

Satellite Image

UAV Image

Appendix II: Data Metrics

Impact Report Card

Types of Structures	Number of observed structures	Damage Scale			
		No Visible Damage	**Minimal Damage**	**Significant Damage**	**Critical Damage**
Damage Points		0	1	2	3
Light	144	49	35	29	31
Medium	190	83	81	14	12
Heavy	24	23	1	0	0
Total amount of structures	358	155	117	43	43
Total Number of Structures Damaged	203				
Percentage of Total Damaged Structures	56.70%				

Damage By Structure Type

	Percentage of Structures Damaged	**Damage Points Accumulated Per Structures**	**Percentage of Total Potential Points**
Light Structures	65.97%	186	43.06%
Medium Structures	56.32%	145	25.44%
Heavy Structures	4.17%	1	1.39%

Damage Impact

Potential of Total Accumulated Damage Points	1074
Total Damage Points Accumulated	332
Percentage of Total Potential Damage Having Occurred	30.91%

Total Damage Points accumulated by Damage Level

		Percentage of Total Damage Points
No Visible Damage	0	0.00%
Minimal Damage	117	35.24%
Significant Damage	86	25.90%
Critical Damage	129	38.86%

Damage Breakdown by Type

	No Visible Damage	**Minimal Damage**	**Significant Damage**	**Critical Damage**
Light	34.03%	24.31%	20.14%	21.53%
Medium	43.68%	42.63%	7.37%	6.32%
Heavy	95.83%	4.17%	0.00%	0.00%

Structure Type	No Visible Damage	Minimal Damage	Significant Damage	Critical Damage
Light	49	35	29	31
Medium	83	81	14	12
Heavy	23	1	0	0

Endnotes

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