ASSESSING MODERN CONFLICT TO MONITOR HUMAN RIGHTS WITH REMOTE SENSING:

RUSSIA’S WAR IN UKRAINE

by

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This work is dedicated to the innocent civilians of Russia’s war in Ukraine

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Abbreviations

AOI	Area of Interest
ASF	Alaska Satellite Facility
DN	Digital Number
ESA	European Space Agency
GIS	Geographic Information System
MARS	Mass Atrocity Remote Sensing
NGO	Non-Governmental Organization
RTC	Radiometric Terrain Correction
SAR	Synthetic Aperture Radar
UN	United Nations
UN OHCHR	United Nations Office of the High Commissioner for Human Rights
UNOSAT	United Nations Satellite Centre
VHR	Very High-Resolution

Abstract

Russia's unprovoked attack on Ukraine on February 24, 2022, sparked the largest armed conflict in Europe since World War II. As war in Ukraine continues, widespread reports of violations of human rights and international humanitarian law accompany extensive civilian casualties. Satellite imagery has provided unprecedented awareness of Russia's war to corroborate testimonial evidence of human rights violations. While the use of satellite imagery is now commonplace to aid such efforts, human rights groups need improved remote sensing methods in active war zones. The objective of this study is to evaluate the suitability of freely accessible medium-resolution synthetic aperture radar (SAR) imagery from the European Space Agency's (ESA) Sentinel-1 satellite versus expensive very high-resolution (VHR) optical imagery for the purpose of detecting war-induced building damage. The study area is the Ukrainian city of Mariupol, which was seized by Russia in May 2022. The study assesses building damage using backscatter intensity changes between images over time. Detected damage in conjunction with reports of civilian casualties may indicate potential violations of international humanitarian law. This study's results indicate cumulative building damage in both extent and magnitude comparable to a United Nations damage assessment that relied on VHR optical imagery. Statistics estimate 27% damage from February 2022 to May 2022, which is lower than the 32% damage estimate by the UN for the same study area. While SAR imagery may provide less accurate results compared to VHR optical imagery, the increased timeliness, accessibility, and adaptability it offers may render SAR imagery analysis as a more feasible option for some human rights practitioners.

Chapter 1 Introduction

The international human rights community needs improved remote sensing methods to detect violations of human rights and international humanitarian law in conflict situations promptly and safely. Russia's full-scale invasion of Ukraine on February 24, 2022 sparked the largest armed conflict in Europe since World War II (RAND 2022). Since the war's onset, multiple sources report Russia is conducting indiscriminate attacks on civilian areas in violation of international humanitarian laws and human rights and with concomitant loss of life and damage to civilian infrastructure. As the war continues, the need for timely detection and assessment of these violations is vital. This thesis investigates the use of imagery from Synthetic Aperture Radar (SAR) satellites to detect damage from Russian attacks. SAR imagery can be taken day or night and is all-weather capable and cloud-penetrable, so it offers the possibility for change detection in a greater range of conditions than optical imagery. The purpose of this study is to investigate the feasibility of using SAR imagery for mass atrocity monitoring by the international human rights community. This chapter introduces the research objective, motivation, study area, and research constraints.

1.1 Motivation

On February 24, 2022, Russia conducted an unprovoked full-scale invasion of Ukraine from multiple fronts to overthrow Ukraine's Western-aligned government and bring it under Russian control (Bowen 2023). The ongoing war has created a humanitarian crisis affecting millions of civilians, spurring global food and energy crises, and shocking the global economy (Levi and Molnar 2022; Margesson and Mix 2022; Torkington 2023; UN SDG 2022). Evidence shows Russian violations of international human rights law and international humanitarian law.

Many of these actions amount to war crimes, including willful killings and attacks on civilians (UN OHCHR 2023b). Shortly after Russia's invasion, the UN Human Rights Council established an Independent International Commission of Inquiry to examine allegations of human rights abuses, international humanitarian law violations, and crimes relating to Russia's aggression against Ukraine (UN OHCHR 2023b).

Identifying and verifying violations of humanitarian law is extremely challenging and often requires on-the-ground situational awareness not always possible in active war zones. Remote sensing data can aid in damage and destruction assessments to better evaluate Russian attacks in Ukraine. These assessments can corroborate other evidence of possible war crimes in International Criminal Court. The goal of this thesis is to evaluate the use of Sentinel-1 SAR imagery as an alternative to costly high-fidelity imagery to detect war-induced infrastructure damage from Russian attacks. This analysis will promote work in pursuit of justice and accountability of civilian targeting and international law violations.

1.1.1 History of the Russia-Ukraine Conflict

Tensions between Russia and Ukraine are rooted in deep historic and ethnic ties fueling Russia's reluctance to accept Ukraine's independence. Since Ukraine's independence from the Soviet Union in 1991, Russia has negatively perceived Ukraine's motions to align with Western-style democracy, including the European Union and the North Atlantic Treaty Organization (Masters 2022). These tensions are especially evident in Ukraine's southern region of Crimea and in the eastern Donbas. The Donbas region in eastern Ukraine consists of the Donetsk and Luhansk regions called oblasts and is home to the highest proportion of ethnic Russians and Russian-speaking population of any Ukrainian region except Crimea (Welt 2021; Yekelchyk 2015). Figure 1 illustrates the ethnic affinity in Crimea and Donbas.

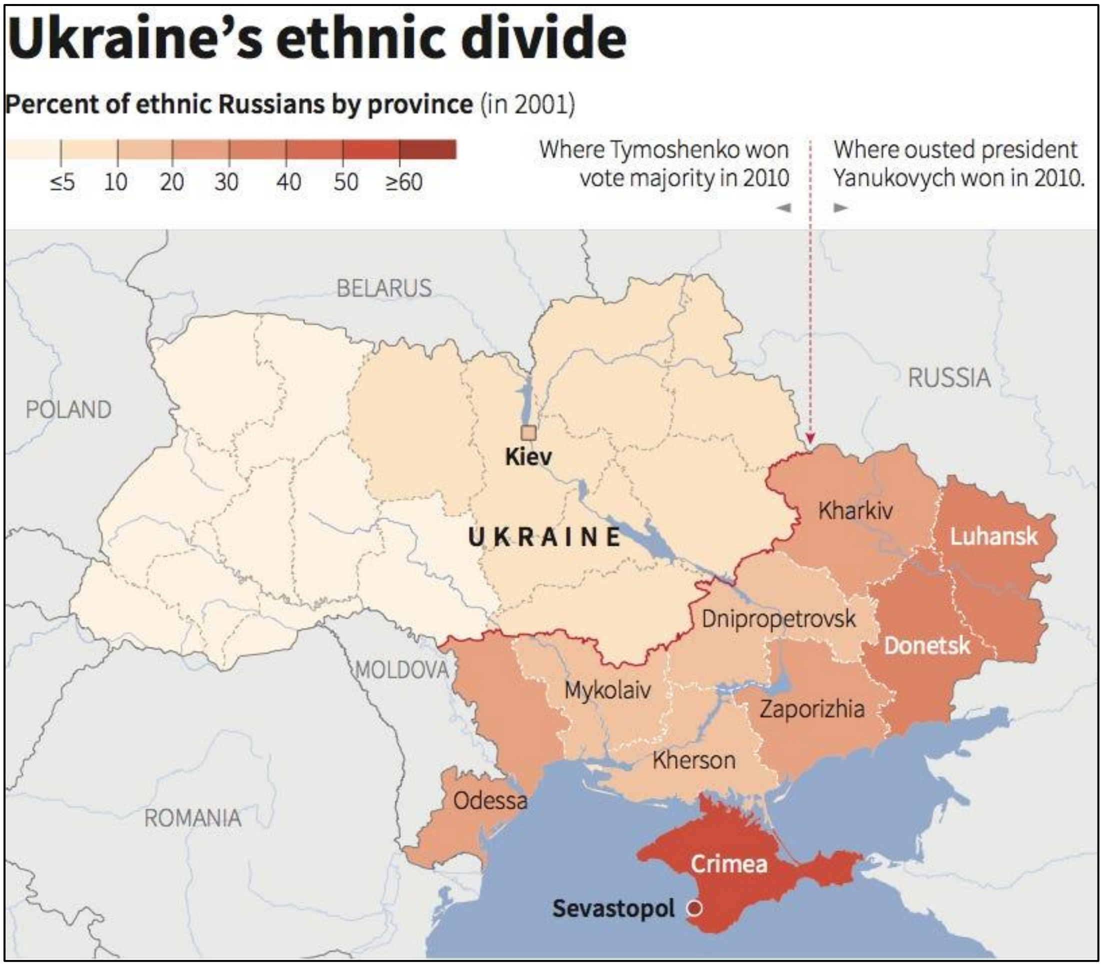

Figure 1. Ukraine's ethnic composition (Source: Inton 2014)

While the majority Russian speakers are located in eastern Ukraine, the majority population of Donbas identifies as ethnic Ukrainian (Yekelchyk 2015). The ethnic divide is further juxtaposed by the language composition. According to the same 2001 census, the majority of the population in Donbas claimed Russian as their native language (Yekelchyk 2015). Figure 2 illustrates the linguistic affinity in Crimea and Donbas.

Figure 2. Russian language affinity in Ukraine (Source: Washington Post 2022)

While most of the population in Donbas claim Russian as their native language, the majority also identifies as ethnic Ukrainians. This incongruity between ethnicity and language is symbolic of the cultural assimilation of Ukrainians during the late Soviet period resulting in a hybrid identity (Yekelchyk 2015).

Ukraine's heavily industrialized eastern Donbas region maintained close economic ties with Russia after independence from the Soviet Union. These ties fueled conflict in 2014, when Russia annexed Crimea and armed Russian separatists in Donbas, justifying its actions with claims of protecting Russian-speaking people in the east (Masters 2022). Donbas has been a hot spot for civilian deaths, injuries, and infrastructure damage and destruction since 2014 hostilities. Fighting culminated in Russia's February 2022 "special military operation" claiming to protect the civilian population, part of a long disinformation campaign reinforcing Russian false narratives (U.S. State Department 2022). Since the invasion, devastation in Ukraine includes war crimes, human rights abuses, and violations of international humanitarian law (UN OHCHR 2023a).

1.1.2 Human Rights Violations and International Humanitarian Law

The international community alleges Russia is guilty of violating international law and committing war crimes and crimes against humanity (Mulligan 2023). Additionally, international leaders including the UN Secretary General and the U.S. Secretary of State assert that the conflict in Ukraine has led to human rights violations (Mulligan 2023). Evidence of these atrocity crimes can assist prosecution of aggressors during international tribunals, including the International Court of Justice, International Criminal Court, and European Court of Human Rights (Mulligan 2023).

Law of war in the context of international law is often used interchangeably with the law of armed conflict and international humanitarian law (Mulligan 2022). This paper uses these terms interchangeably. Law of war regulates the initiation of use of force, conduct of conflict, and protection of war victims (Mulligan 2022). The Hague Conventions of 1899 and 1907 and the four Geneva Conventions of 1949 address methods of warfare regulation and protections for non-combatants. Under these treaties, parties in conflict must adhere to engage legitimate military targets and cannot direct attacks at civilians or protected objects (Mulligan 2022). Evidence of breaches of the Geneva Conventions can constitute war crimes prosecuted in International Criminal Court (Mulligan 2022). Human rights are universal laws protecting individuals and groups against actions that impede fundamental freedoms and human dignity (UN OHCHR 2001). International human rights law is distinct from international humanitarian law but holds complimentary principles concerning protection of life, health, and dignity of all human beings (ICRC 2010). The Universal Declaration of Human Rights adopted by the UN General Assembly in 1948 is the main legal instrument of international human rights law (UN n.d.) In armed conflict situations, human rights law reinforces International Humanitarian Law (ICRC 2010).

Before the widely accepted use of satellite imagery, witness testimony, photography, forensic evidence, and human rights researcher reporting were used as evidence in various national and international courts (Hasian 2016; Herscher 2014). Reliance on witness testimony came with various challenges, including reluctant observers or few surviving eyewitnesses. International criminal court proceedings used satellite imagery for the first time following genocidal massacre during the Bosnian War in the late 1990s (Kroker 2015; Lee et al. 1998). During a UN Security Council meeting, Madeline Albright, in her role as U.S. ambassador to the UN, presented photographic evidence of the Srebrenica and Zepa atrocities (Hasian 2016; Rohde 1995; Rotberg 2010). These “before” and “after” aerial and satellite photos revealed sites of mass graves where an estimated 6,000 to 8,000 civilians were buried (Lee 1998; Rohde 1995). This led Tribunal investigators to alleged massacre sites to collect evidence corroborating witness accounts used for prosecution of war crimes (Rotberg 2010; United Nations International Criminal Tribunal for the former Yugoslavia n.d.). This event marked a shift by legitimizing remote sensing technologies used to investigate war crimes and human rights violations.

1.1.3 Human Rights Violations in Ukraine

Russia’s war in Ukraine has had devastating impacts on the civilian population. As of February 15, 2023, the United Nations Office of the High Commissioner for Human Rights (UN OHCHR) recorded 8,006 civilian deaths, 13,287 civilians injured, 8 million refugees, and 5.4

million internally displaced people. Widespread reports of violations of human rights and international humanitarian law accompany extensive civilian casualties. Alleged crimes include indiscriminate and mass killings, shelling of humanitarian corridors, and filtration operations (forced interrogation and separation) of civilians and noncombatants from Russian-controlled areas (Bowen 2023; UN 2023a).

The UN estimates nearly 18 million people in Ukraine need humanitarian assistance and demands continue to rise rapidly. Massive damage and destruction to human infrastructure have left hundreds of thousands of Ukrainians homeless while many are living in damaged homes or in buildings ill-suited to provide protection during winter season in life-threatening sub-zero temperatures (UNHCR 2022). Shelling from heavy artillery strikes, launch rocket systems, and missile and air strikes are the cause of most of the civilian casualties reported by the UN OHCHR (2023b). UN OHCHR (2023a) estimates over 90% of civilian casualties are caused by explosive weapons with wide area effects used in populated areas. These attacks have damaged or destroyed thousands of residential buildings, over 3,000 educational institutions, and more than 600 medical facilities. Casualties are likely underestimated due to delayed reporting and pending verification. Most attacks likely initiated by Russian armed forces have been determined as indiscriminate, lacking specific military objective therefore violating international humanitarian law (UN OHCHR 2023a).

Many countries have condemned Russia's invasion of Ukraine as a violation of international law governing the use of force and have identified examples of potential Russian war crimes and human rights violations (Bowen 2023; Mulligan 2022). Evidence of violations of international humanitarian law include indiscriminate attacks in densely populated areas (Amnesty International 2022), attacks and mining of humanitarian corridors (Lister 2022), and airstrikes on hospitals (Cullison 2022). However, the process of identifying, gathering information, and proving international humanitarian law violations requires detailed fact-finding for on-the-ground truth and can be extremely challenging to prove (Mulligan 2022). To address some of these challenges, satellite remote sensing offers a means to document necessary evidence within inaccessible active war zones. The scope of this study does not investigate individual violation claims. Rather, it utilizes remote sensing methods to identify potential areas of human rights violations. As war continues, remote sensing applications and geospatial analysis can provide a more compressive understanding of the evolving ground situation to assist the international human rights community.

1.2 Study Area

The study area is the coastal city of Mariupol, Ukraine located in the southern Donetsk oblast. Figure 3 shows a map of Ukraine and highlights the Donbas region, comprised of Luhansk and Donetsk, bordering western Russia.

Figure 3. Map of Ukraine highlighting Crimea and Donbas regions (Source: CRS 2021)

Figure 4 depicts the area of interest (AOI) of Mariupol, Ukraine comprised of two districts. The two outlined zones, the Zhovtnevyi District (left side of AOI) and Livoberezhnyi District (right side of AOI), make up some of the most heavily damaged civilian residential areas. The study timeframe is February 16, 2022 (pre-Russian invasion) to May 23, 2022 (post-capture of Mariupol). This study uses imagery collected on a 12-day revisit rate corresponding to the temporal resolution of the Sentinel-1 satellite. Imagery provides a time-series of the same satellite footprint of a consistent area of interest, including satellite imagery acquisitions with the same path and frame.

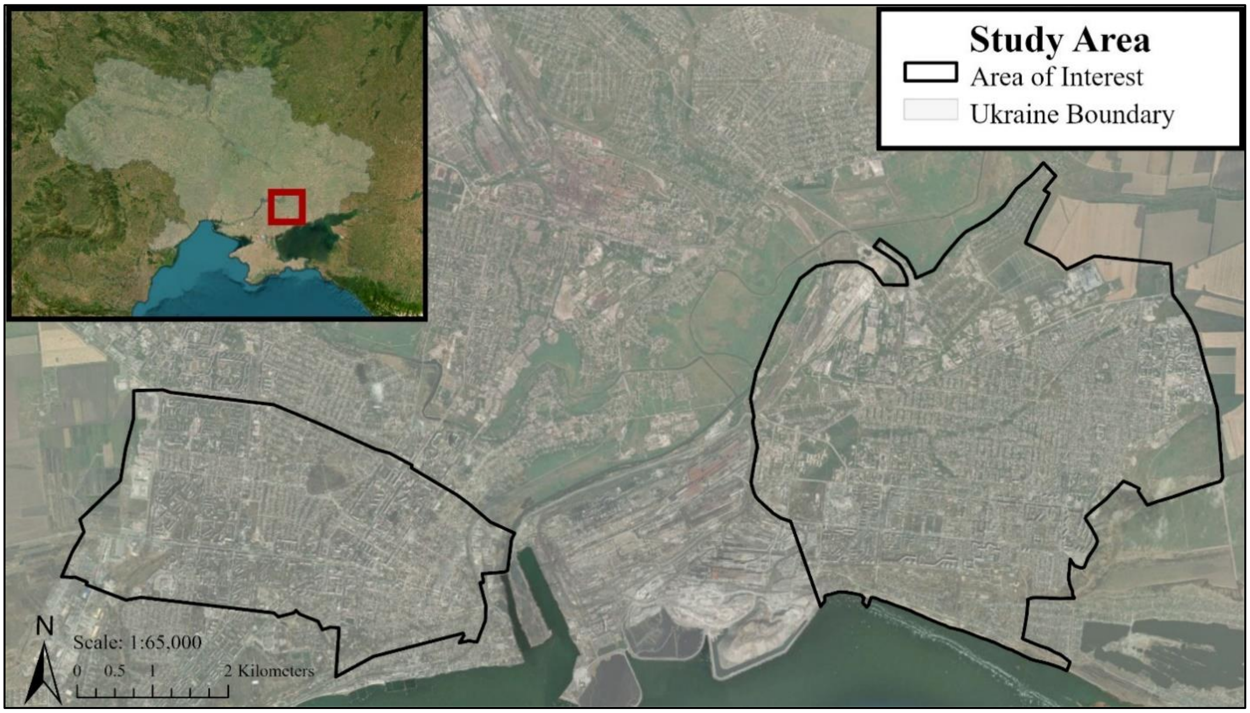

Figure 4. Study area of Mariupol, Ukraine

1.2.1 Significance of Study Area

Mariupol was a key Russian military objective since the early stages of Russia's invasion (Bowen 2023). Mariupol is strategically important because of its location between Russian-annexed Crimea in the south and separatist-controlled areas in Donbas. Analysts assessed capture of the city could create a corridor between Russia and forcefully occupied Ukrainian territories including Donbas and Crimea in addition to control of the Sea of Azov (Gardner 2022; Ghaedi 2022; Parker et al. 2022; Vohra 2022). Figure 5 illustrates Mariupol's geographic strategic importance.

Figure 5. Mariupol's significance during Russia's war in Ukraine (Source: DW)

As a result of Russia's objectives, Mariupol was one of the most devastated cities suffering thousands of causalities and significant destruction (UN 2023a). Reports of constant shelling and explosive weapons striking civilian buildings from Mariupol are included in the Independent International Commission of Inquiry on Ukraine (UN OHCHR 2023a). Investigated examples of human rights violations and international law violations include the indiscriminate attacks on the Mariupol drama theatre that killed and injured many civilians, and the attack on the Mariupol Maternity Ward No. 3 that resulted in at least two deaths (UN OHCHR 2023a). After weeks of fighting, Russia announced seizure of Mariupol in late April 2022, followed by Mariupol's surrender in mid-May 2022 (Bowen 2023). Without access to the Donetsk region, including Mariupol, the Commission has yet to make a sufficient determination of whether the attacks and seizure of Mariupol constitute crimes against humanity. Remote sensing offers a means to corroborate imagery with other sources, such as eyewitness testimony, in the absence of direct access to Mariupol for investigative purposes. This research will map where potential damage has occurred to corroborate human rights violations allegations.

1.3 Project Overview

The objective of this research is to evaluate the use of medium-resolution SAR imagery to detect damage in the civilian residential areas of Mariupol, Ukraine due to Russian attacks from February through May 2022. Final analysis is compared to the United Nations Satellite Centre (UNOSAT) Rapid Damage Assessment results based on very high-resolution (VHR) optical imagery. The overall goal is to assess the feasibility of using medium-resolution SAR imagery in human rights contexts where use of more expensive, high-resolution optical imagery may be less accessible. This research will recommend practical methods to aid human rights efforts during Russia's war in Ukraine. Data includes Sentinel-1 SAR imagery from the Alaska Satellite Facility (ASF), geographic boundary data from UNOSAT, and building damage points from UNOSAT. SAR backscattering intensity analysis is used to determine changes between images representing potential war-induced damage. This research is tailored to human rights practitioners in need of timely detection during conflict to record, assess, and prosecute potential violations of human rights and international humanitarian law.

1.3.1 Constraints

Human rights practitioners investigating human rights violations in Ukraine require timeliness, sufficient accuracy, low cost, and simplicity. These needs are evident during natural or anthropogenic disasters where timely detection for emergency response is critical. Human rights practitioners need access to reliable data in denied territories such as active war zones and methods for quick detection of potential human rights and international humanitarian law violations to document incidents promptly. While the highest fidelity imagery and most robust methods are desirable, they are not always practical due to constraints which vary depending on crisis. The data and methods of this project are chosen with this real-world context in mind.

Timely detection of potential human rights violations is prioritized over 100% accuracy for the purposes of this research. Timely detection – defined herein as detection within hours or days – allows researchers to identify focus areas, determine impacted populations, and work with other organizations such as private research groups with access to higher fidelity imagery and methods to refine analyses. Another constraint is sufficient accuracy. The cost of highly accurate data can render it inaccessible to many human rights organizations, delaying detection and assessment. For example, a review of the current state of satellite monitoring of armed conflicts determines that commercial sub-meter WorldView-4 imagery from Maxar costs $22.50/km, totaling US $13.6 million for the country of Ukraine (Bennet et al. 2022). Therefore, coarse yet publicly accessible data is used in this project to test its suitability for providing information to the international human rights community. Finally, this project prioritizes simplicity in its methodology as its workflow should be reproducible by non-imagery experts in the field.

1.3.2 Data and Methods

This research employs the principle of SAR backscatter intensity changes to assess war-induced damages and human rights violations. A SAR log intensity change method is adapted from similar methods applied to studies of natural and anthropogenic disasters, including earthquake and war-induced destruction (Aimaiti et. al 2022, Braun 2018, Matsuoka and Yamazaki 2004). Data includes freely accessible Sentinel-1 SAR imagery through ASF, AOI boundary data from UNOSAT, and geolocated building damage points derived from VHR optical imagery from UNOSAT. All analysis is run in ArcGIS Pro using an imported Python toolbox and various ArcGIS Pro geospatial analysis tools. Resulting cumulative damage assessments from Sentinel-1 SAR imagery are compared to the UN damage assessment using VHR optical imagery. Finally, relationships between UN damage points and Sentinel-1 SAR damage pixels are examined.

1.4 Thesis Overview

This thesis includes the literature review, methodology, results, and discussion informing the use of SAR imagery to assess potential human rights violations in active war zones. Chapter 2 provides a literature review expanding on the benefits and applications of SAR imagery as well as methods for detecting building damage in the environmental studies and humanitarian fields. Chapter 3 provides a description of the data and employed methodology, including imagery preparation and analysis. Results are presented in Chapter 4, followed by a discussion in Chapter 5 on limitations, challenges, and proposed improvements for future studies.

Chapter 2 Literature Review

The purpose of this thesis is to evaluate the use of satellite remote sensing data to assess war-induced building damage. This chapter introduces satellite remote sensing techniques used to detect building damage followed by satellite remote sensing applications used for human rights violations investigations. This literature review provides insights on existing methods and challenges in the field of remote sensing for the detection of human rights violations.

2.1 Remote Sensing of Building Damage

Satellite remote sensing is used extensively for damage mapping and damage assessments after natural disasters, where in-person data collection is often dangerous or impossible. Such satellite-derived assessments assist damage extent surveys, search and rescue operations, and reconstruction planning. A common imagery analysis method following natural disasters utilizes pre- and post- event images for change detection (Dong and Shan 2013; Korkmaz and Abualkibash 2018; Romaniello et al. 2017). While new methods for building damage assessments in natural or anthropogenic disaster contexts continue to develop, extensive limitations persist (Bennet et al. 2022; Dong and Shan 2013). The following sections provide an overview of satellite remote sensing, SAR, and remote sensing science principles used for building damage detection.

2.1.1 Satellite Remote Sensing Overview

Remote sensing refers to any technology that provides detection of physical phenomena on Earth's surface, such as destroyed buildings due to natural or anthropogenic disasters. Platforms include, but are not limited to, manned aircraft, unmanned aerial systems, and satellites. Satellite remote sensing involves measuring reflected and emitted electromagnetic energy from a surface at a distance to detect physical characteristics (NASA n.d.a). There are two kinds of satellite remote sensors: active and passive. An active sensor is a radar instrument that transmits signals and measures reflected, refracted, or scattered signals from a surface (NASA n.d.a). A passive sensor uses optical instruments and records electromagnetic waves emitted by the sun and reflected from the Earth. A passive sensor example is an optical satellite, which provides imagery easily interpreted by the human eye. Both active and passive sensors can make valuable observations in inaccessible environments such as active war zones. This thesis utilizes imagery from the European Space Agency (ESA) Sentinel-1 SAR satellite, an active sensor. The benefits of low-risk acquisition, wide coverage area, and high temporal resolution are discussed further in the following section.

2.1.2 Synthetic Aperture Radar Overview

SAR is a unique type of remote sensing technology that provides all-weather, all-day imagery used to detect changes in the Earth's surface after natural or human disturbance. SAR satellites have active sensors that transmit electromagnetic energy and record reflected energy called backscatter (ASF n.d.b). SAR uses microwave wavelengths, with most radar applications operating within the 3mm to 30 cm range. These longer wavelengths give radar sensors the unique capability to penetrate clouds, making SAR imagery an optimal choice during unreliable weather conditions. The name is derived from the practice of combining a sequence of imagery acquisitions from a shorter satellite antenna to provide higher resolution imagery (NASA n.d.b). A unique feature of SAR instruments is a side-looking sensor, which differs from other satellites that look straight down (nadir). This feature enables the SAR sensor to identify the location of received waves on the ground and differentiate between features equidistant from the sensor on opposite sides (ArcGIS Pro n.d.a). SAR satellites record backscatter in phase and amplitude to render a 2D image. Phase provides information on distance between a sensor and target, and amplitude indicates amount of sent signal that returns to the sensor. The digital number (DN) for the amplitude of a SAR imagery pixel represents backscatter. A high DN corresponds to a strong backscatter, while a low DN represents a weak backscatter. The amplitude strength of the measured backscatter is used to discern features on the ground (ArcGIS Pro n.d.a). Many factors influence backscatter returned to a SAR sensor, including sensor wavelength, surface roughness, and a phenomenon known as the double bounce effect, explained in the next section (ASF n.d.b). Because SAR is an active type of satellite sensor, it is not dependent on time of day because it does not require sunlight to illuminate a target. SAR sensors offer the benefit of 24-hour, all-weather capability. SAR offers benefits over its optical counterpart, which can be ineffective at night or in the presence of clouds or smoke (Brown and Hogan 2020). This research utilizes SAR satellite imagery over optical imagery due to these benefits, greatly reducing dependency on optimal imaging conditions.

2.1.3 Building Damage Detection

SAR technology can be used as a powerful remote sensing tool to detect changes in the Earth's surface, including natural or human disturbance (ASF n.d.e). Changes in the Earth's surface, such as war-induced infrastructure damage, can be detected by radar reflections called backscatter. The principle of SAR intensity (backscattering) change detection for building damage assessment is based on weak reflection from collapsed buildings. Pioneers in the field of SAR imagery, Matsuoka and Yamazaki (2004) investigate use of SAR intensity to detect building damages after the devastating 1995 earthquake in Kobe, Japan. Their research reveals significantly lower backscattering coefficient values and intensity correlation in pre- and post-event images in severely damaged areas (Figure 6).

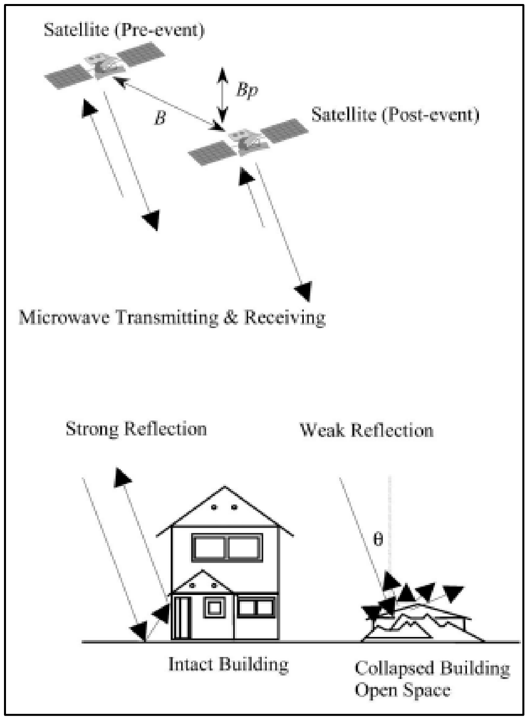

Figure 6. Satellite observation and backscattering of ground objects (Source: Matsuoka and Yamazaki 2004)

Using coarse 30 m spatial resolution imagery, their study demonstrates the challenge of identifying backscattering characteristics of individual buildings. Instead, the study proves the possibility of detecting groups of damaged buildings. Previous studies evaluating backscatter in the 1995 Kobe earthquake by Aoki et al. (1998) and Matsuoka and Yamazaki (2004) show that man-made structures such as urban buildings exhibit high reflection. This is due to multiple reflections, known as the cardinal effect. Normally, a non-collapsed building exhibits strong backscatter effect caused by corner reflectors between intact structures and the ground. This phenomenon is commonly referred to in literature as the double bounce effect, illustrated in Figure 7. In contrast, open spaces and damaged buildings exhibit low reflectance when microwaves are scattered in multiple directions (Figure 6). Changes in backscattering can be indicative of changes due to destruction.

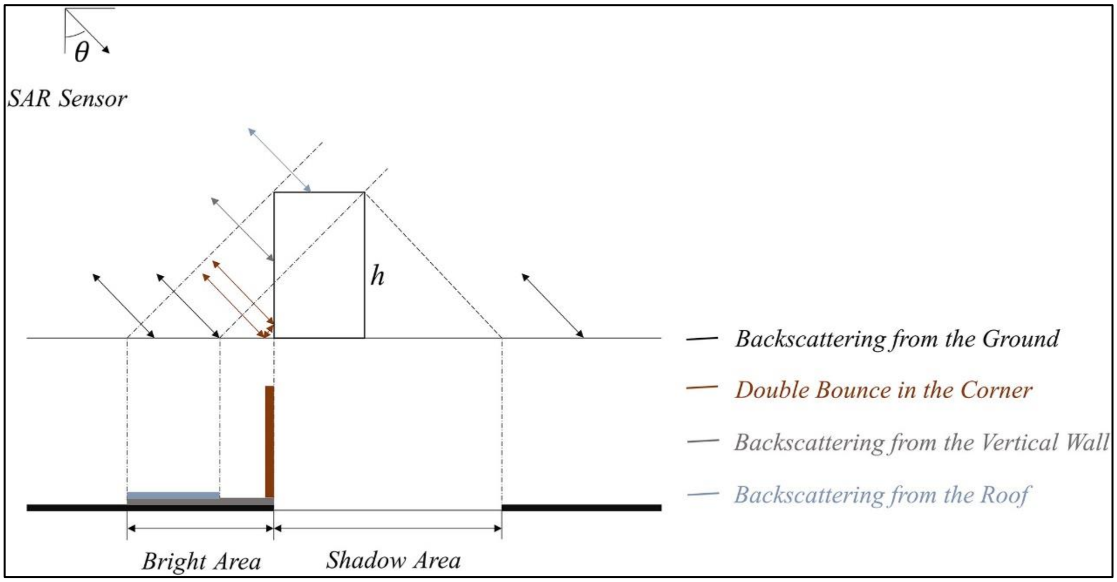

Figure 7. Double bounce effect from intact buildings (Source: Ge et al. 2020)

A key assumption for this thesis is that a damaged building will result in a significant backscattering intensity change. Intensity change values can be positive or negative depending on the geometry of the building and the nature of collapse (van Heyningen 2018). Figure 8 demonstrates this dependency. The left-hand side of Figure 8 demonstrates the following scenario. A radar signal hitting the corner of an intact building returns a strong backscatter signal. However, after a wall collapse, rubble forms a corner reflector and causes an increase in backscatter signal. On the right-hand side of Figure 8, a radar signal hits an intact wall and ground resulting in a double bounce (strong signal). Debris resulting from damage disperses subsequent radar signals, resulting in decreased backscatter intensity.

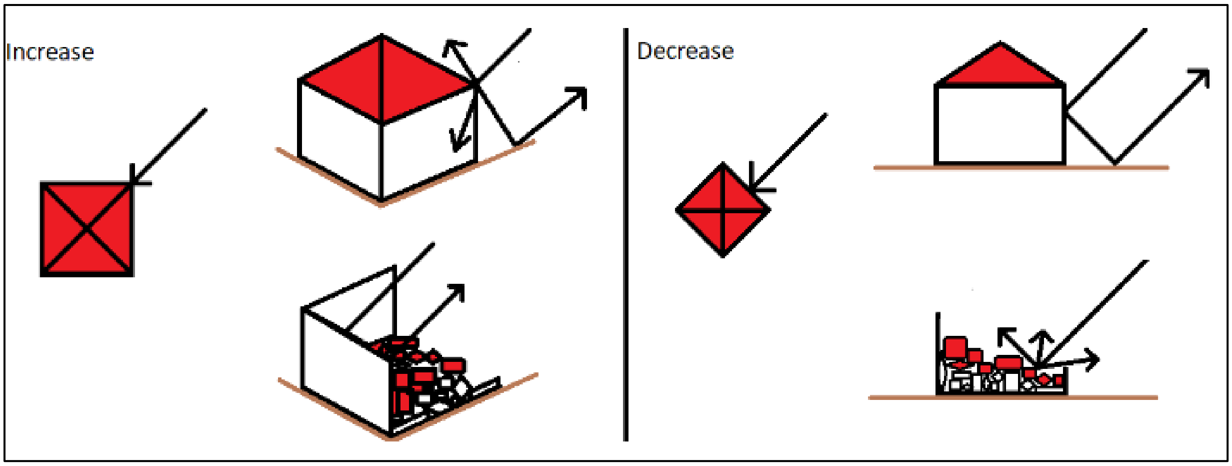

Figure 8. Increased (L) and decreased (R) backscatter intensity after building damage (Source: van Heyningen 2018)

While SAR imagery is not as easily interpreted by the human eye as its optical counterpart, SAR backscatter intensity analysis offers valuable insights for potential infrastructure damage. Figure 9 shows examples of intensity characteristics of high-resolution SAR images in intact and collapsed building areas. Image a) shows post-event optical image of intact buildings; b) post-event SAR image of intact buildings; c) pre-event optical image of collapsed buildings; d) post-event optical image of collapsed building; e) post-event SAR image of collapsed buildings (Cui et. al 2018).

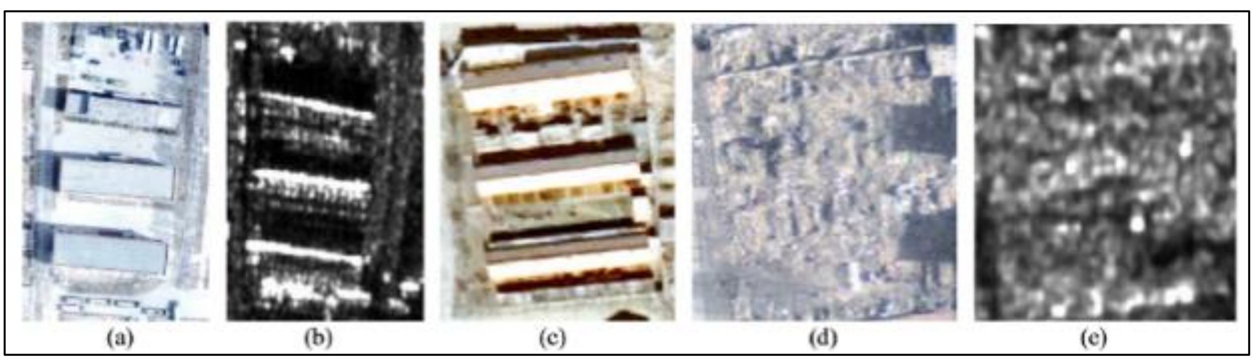

Figure 9. Examples of SAR image intensity (Source: Cui et al. 2018)

The SAR intensity image of an intact building shows regular shadow and layover zones and building features can be coarsely interpreted (b). In contrast, the SAR intensity image of a damaged building shows random pixel distribution and identification of physical features is extremely challenging (e). These "before" and "after" SAR images demonstrate the need for SAR backscatter intensity change analysis to detect damages.

2.2 Remote Sensing for Human Rights

The increased use of satellite remote sensing came after the Gulf War in the early 1990s when satellite technology introduced the 'first space war' (Anson and Cummings 1991; Witmer 2015) offering first-ever on-demand war coverage to the public (Datta 2022). This trend expanded within the humanitarian realm, where satellite remote sensing was used to monitor the 2003 Darfur conflict in Sudan (Amnesty International 2004; Prins 2008; Witmer 2015). Satellite imagery is a valuable alternative to other remote sensing platforms for situations demanding large study areas, short acquisition and analysis timelines, or in remote areas or dangerous conflict zones. Despite these benefits, limitations may include variable spatial resolution, weather-related constraints, and high costs. Furthermore, while the number of commercial satellite providers increases, privatization of satellite imagery may limit data accessibility for humanitarian actors. The following sections review satellite remote sensing methods used for human rights violation monitoring and SAR methods to detect war-induced damage.

2.2.1 Satellite Remote Sensing Applications for Human Rights Monitoring

Satellite imagery is increasingly used to identify crimes against humanity by documenting the scale and method of human rights abuses and affected areas (Rotberg 2010). This is primarily done with very high spatial resolution optical images (≤1 m), which enables individual building scale analysis (Witmer 2015). Human rights abuse in conflict settings analyses are conducted by non-government organizations such as Human Rights Watch and Amnesty International, and intergovernmental organizations, such as the UN. Example satellite imagery applications include detection of troop activity and village destruction in Sudan and South Sudan (Harvard Humanitarian Initiative 2012), unlawful airstrike evaluation in Libya (Human Rights Watch 2012b), identification of mass graves (Amnesty International 2016), and fire detection of destroyed villages from conflict (UNOSAT 2011). While these organizations can use satellite imagery as complimentary evidence to corroborate eyewitness testimony, lack of new methods has contributed to slow progress in the field.

A standardized, universal forensic approach using satellite imagery to detect and document human rights atrocities does not exist and is likely impractical (Raymond et al. 2014). Every conflict varies in study area, affected populations, type of warfare, research objectives, and imagery requirements. While this study cannot address the needs of every conflict, it applies existing methods suited for constraints of the war in Ukraine. Spatiotemporal analysis will help international aid workers identify humanitarian needs and assist human rights groups with documenting impacts of violent conflict.

Although the number of organizations engaged in the use of remote sensing within the humanitarian space is growing, efforts to professionalize and standardize the practice for mass atrocities monitoring lags behind other fields (Marx 2013; Raymond et al. 2014; Witmer 2015). Furthermore, lack of technical knowledge and training required to analyze remote sensing imagery presents a challenge for non-imagery experts in the conflict research field (Witmer 2015). As a result of scarce documented practice, humanitarian practitioners are operating without accepted forensic standards specific to confirming mass atrocity events. Aware of this shortfall, Raymond et al. (2014) identifies the need for a standard forensic approach for high-resolution satellite imagery used to document mass atrocities as its own discipline, referred to as Mass Atrocity Remote Sensing (MARS). An object-based remote sensing method is proposed in which activity patterns are categorized by observable phenomena to identify activity consistent with mass atrocities. An example indicator of interest is intentional targeting of civilian populations and forced displacement. This alleged action is observable by destroyed structures consistent with civilian dwellings and facilities (observable object indicators). This observable object indicator framework is applicable to human rights violations investigations for Russia's ongoing war in Ukraine.

MARS research differs from other disciplines using remote sensing due to the unique operational challenges and requirements of monitoring conflict, including data availability and technology (Raymond et al. 2014). Human rights remote sensing researchers adopt a general approach using a standard sequence of steps. Researchers 1) identify desired violation, 2) select remotely sensed phenomenon associated with the violation, and 3) select an appropriate sensor that will detect the phenomenon (Marouf 2016; Marx and Goward 2013). Several studies by Marx investigate damage detection methods using this framework for village burnings in Myanmar and in Darfur (Marx and Loboda 2013; Marx et. al 2019) and bombings and missile attacks against civilian neighborhoods in Syria (Marx 2016). These studies address shortfalls of costly and labor-intensive methods with Earth-observing satellites to detect potential human rights violations (Marx and Goward 2013; Marx and Loboda 2013). Table 1 summarizes potential human rights violations that can be identified indirectly by specific signals characteristics detected by various satellite sensors. Following the approach by Marx and Goward (2013), this thesis aims to investigate human rights violations in the form of indiscriminate Russian attacks on Ukrainian residential areas evidenced by building damage detected by changes in SAR backscatter intensity from Sentinel-1 SAR imagery.

Table 1. Examples of remotely sensed human rights violations

Violation	Phenomenon	Signal Analysis	Sensor	Revisit	Source
Artillery near civilians	Artillery, bomb craters	Identification of craters near civilians	WorldView 1 (0.5 meters)	2 weeks	UNOSAT 2009
Mass execution	Creation of mass graves	Detection of disturbed earth, earthmovers	U-2 (unknown)	n/a	NYT 1995
Homes targeted by ethnicity	Destruction of individual houses	Destruction of destroyed roofs	DigitalGlobe (2 meters)	6 months	AAAS 2008
Civilian buildings targeted	Damage to public buildings	Identification of destroyed buildings	WorldView 1 (0.5 meters)	n/a	UNOSAT 2008
Political prison camps	Expansion of prisons	Detection of changes in the size of prisons	Digital Globe (2 meters)	10 years	AI 2011
Civilian buildings targeted	Destruction of forests, fields, and villages	Detection of changes in land cover classification	Landsat 5 (30 meters)	4 years	De Vos 2008
Civilian population removed	Abandonment of agricultural land	Detection of changes in agricultural fields	Landsat 5 (30 meters)	~4 years	Witmer 2008
Villages attacked	Burning of arid villages	Detection of fires by Moderate Resolution Imaging Spectroradiometer	MODIS (250 meters)	Annual	Bromley 2010

Source: Marx and Goward 2013

MARS phenomena detection is dependent on factors including spatial resolution, temporal resolution, and scale (localized or regional). Witmer (2015) summarizes the current state of remote sensing conflict research and organizes observable phenomena based on detection time. War-induced structural damage from bombs or fires is generally detectable from satellites within minutes to hours; environmental damage takes hours to days, population movement takes days to months, and land-cover and land-use change takes months to years. Applying this observation timeline to the war in Ukraine, imagery capable of detecting war-induced structural damage within minutes to hours is needed. Based on the current capabilities of satellite sensors, Witmer (2015) suggests fine resolution imagery (1-10 m) for detecting destroyed buildings and structures, with visual photointerpretation offering the easiest and most accurate identification technique for small study areas. Manual inspection of 1-10 m resolution imagery is one option for analysis in Ukraine but requires accessible data. The majority of MARS related imagery analysis employ optical (visible spectrum) and near-infrared sensors (**Error! Reference source not found.**). The current state of MARS research does not include extensive use of SAR imagery.

Table 2. Analysis methods for conflict-induced effects

Category/effect	Analysis method	Sensors(s)	Citation
Bomb impacts, destroyed bridges, oil spills, destroyed oil tanks	Visual ID	IRS, Landsat	UNEP 1999
Bomb damage	Visual ID	QuickBird, IKONOS	UNEP 2003
Damaged structures	Visual ID, OO, MM & PCD	IKONOS	Al-Khudhairy, Caravaggi, and Giada 2005
Destroyed and rebuilt structures	Support Vector Machine classification	IKONOS	Pagot and Peraresi 2008
Village burned	Drop in village albedo	Landsat	Prins 2008
Village burned	Detection of fires	MODIS	Bromley 2010
Huts burned	Classification & MM to identify huts	QuickBird	Sulik and Edwards 2010
Village burned	Near-infrared reflectance decrease	Landsat	Marx and Loboda 2013

Source: Witmer 2015

2.2.2 Synthetic Aperture Radar Applications for Human Rights Monitoring

Two types of remote sensing technologies applied to assess disaster-induced building damage are optical and SAR sensors. Optical sensors provide images that can be easily interpreted by the human eye. High spatial resolution optical satellite imagery is the most frequently used Earth observation medium for post-natural disaster mapping. However, optical satellite sensors require sun illumination and cannot image through clouds, greatly limiting use as an emergency response tool (Ge et al. 2020). In contrast, SAR is not dependent on sun illumination or impacted by clouds but is challenging to interpret and limited by speckle noise. Due to its day/night and all-weather capabilities, SAR imagery is usually available earlier than optical imagery. The flexibility and reliability of SAR appeals to conflict researchers seeking assessment of building damage available for detection within minutes to hours (Ge et al. 2020; Witmer 2015). SAR offers advantages over its optical counterpart making it a suitable sensor choice for study of Russia's war in Ukraine.

Various approaches must be considered for SAR-based building analysis, including change detection approach, change detection method, and spatial scale. These options make it difficult if not impossible to recommend a single approach for SAR-based building damage assessment (Joyce et al. 2009). This research addresses the need for remote sensing solutions to produce timely and accurate human rights violations by proposing a SAR framework for the war in Ukraine. While scientific literature covering SAR-based building damage detection due to environmental disasters offer insights (Dong and Shan 2013; Matsuoka and Yamazaki 2004), few publications specifically address the remote sensing needs of conflict researchers and organizations monitoring human rights violations. This thesis addresses these gaps by adapting SAR-based building damage assessments for natural disasters and applying them to assess war-induced damage.

Two types of SAR-based building damage detection approaches are change detection (using both pre- and post-event data) and assessment (using only post-event data). Since imagery from pre-Russian invasion and post-Russian invasion of Ukraine are available, this study will use a change detection approach comparing pre- and post- event imagery.

Damage detection studies use two different scales of analysis: block unit or single building level. Block unit change detection was first developed during the 1990s in the SAR-based building damage assessment field due to image resolution limitations (Dong and Shan 2013; Ge et. al 2020). There are three types of block level building damage assessment: pixel-based (or grid) analysis (Matsuoka and Yamazaki 2004), irregular blocks separated by urban boundaries (Zhai and Huang 2016), and irregular blocks based on homogenous features (Gokon et al. 2017). Other similar studies using block level SAR-based building damage assessments from natural disasters use medium-resolution SAR imagery ranging from 8-30m and coarser (Chini et al. 2009; Chini et al. 2013; Matsuoka and Yamazaki 1999). This study uses the 10 m pixel size of Sentinel-1 imagery as the scale.

Three methods of change detection used in building damage assessment are intensity-based, coherence-based, or polarimetry-based analysis. Coherence-based analysis and polarimetry-based analysis are not considered for the scope of this study. Intensity-based analysis can be used in any SAR satellite operating mode and exploits the amplitude information of the backscattering from ground targets received by a SAR sensor. Intensity changes can indicate ground changes caused by a disaster event. Generally, built-up structures exhibit high backscatter values due to double bounce effects (building wall to ground). Some of the first published investigations of SAR amplitude data analysis used for building damage assessments found relationships between backscatter changes from ground targets using pre- and post-event imagery (Matsuoka and Yamazaki 1999; Shinozuka and Loh 2004). In Matsuoka and Yamazaki's (1999) SAR-based study of the 1995 Hyogoken-Nanbu earthquake in Japan, SAR backscatter values decrease with increasing damage. This principle is utilized extensively in remote sensing for disaster management literature, and more recently by researchers applying methods for detection of conflict-related damage due to the Syrian Civil War (Braun 2018) and Russia's War in Ukraine (Aimaiti et. al 2022).

While SAR imagery is used more commonly to assess building damages from natural disasters, studies also use SAR to explore damages from armed conflict. Braun (2018) uses time-series of Sentinel-1 radar imagery to identify building damage resulting from civil war from

2014-2017 in the city of Raqqa, Syria. Scattering mechanisms of built-up structures including corner reflection, building materials, and orientation toward the sensor influence radar amplitudes in urban areas. The study uses these principles to identify building presence and identify changes probably caused by war. Results show that Sentinel-1 data can indicate heavy damage, but is limited due to low spatial resolution inhibiting detection of moderate damages. Finally, a UNOSAT dataset consisting of points representing damaged structures is used for validation and shows Sentinel-1 analysis strongly underestimates changes indicative of damage. Despite this shortfall, Braun (2018) concludes Sentinel-1 data is a highly suitable indicator for severe damage in urban areas. With these limitations in mind, this thesis utilizes SAR imagery and UNOSAT data to investigate potential for damage assessment due to war in Ukraine.

To the author's knowledge, research by Aimaiti et. al (2022) is the only publication as of March 2023 using SAR backscattering intensity change analysis as part of a building damage assessment due to war in Ukraine. While the strong backscatter from damaged buildings usually decreases or disappears when a building collapses due to a disaster, an overall increased backscattering intensity can also result from a strong double bounce effect formed from partially collapsed buildings and resulting corner reflectors (Matsuoka and Yamazaki 2004; Matsuoka and Nobuoto 2010). Using these principles captured in a SAR log ratio of intensity for Sentinel-1 imagery, Aimaiti's results classify 58% of damaged buildings correctly when compared with UNOSAT damage assessment derived from very high-resolution optical imagery.

This study utilizes the SAR log ratio of intensity between images to detect and assess war-induced damage in Mariupol, Ukraine (1):

$$I_{ratio} = 10log_{10}\left(\frac{I_N}{I_{N+1}}\right) \tag{1}$$

where I_N is pre-event image and I_{N+1} is post-event image. Calculating the log difference between two images can identify areas of significant changes in backscatter over time (ASF 2020).

Building damage analysis evaluates the humanitarian cost of Russia's war in Ukraine and offers further insights of impacted civilian communities based on temporal and spatial characteristics of damage. The next chapter describes methods used to assess war-induced building damage due to Russia's war in Ukraine applying concepts, approaches, and methodology gaps described in this literature review.

Chapter 3 Methods

The goal of this study is to assess the use of medium-resolution, publicly available SAR imagery to detect war-induced building damage in Mariupol, Ukraine due to the ongoing Russia-Ukraine conflict. This chapter provides a methods overview for SAR imagery analysis attributing backscatter intensity change to Russian attacks. Data and methods were selected to address the needs of the international human rights and humanitarian law communities for timely and accurate detection of mass atrocities. Results were compared to the UNOSAT Rapid Damage Assessment and data derived from very VHR optical imagery. Final analysis provides spatial insights for the war in Ukraine and expands research in SAR imagery used to support human rights violations monitoring efforts.

3.1 Data

This study used Sentinel-1 SAR imagery from ASF and geospatial data from the UN Rapid Damage Assessment. These sources are described in Tables 3 and 4. One of the key benefits of Sentinel-1 satellite SAR imagery data is its accessibility from the ASF. However, its large file size (65 GB) demanded several hours for data downloading and imagery pre-processing. UN data is also freely available and easily accessible from UNOSAT and requires less storage space and download times compared to the Sentinel-1 imagery. While Sentinel-1 SAR images and UNOSAT geolocated point data derived from VHR imagery do not exactly align, both cover appropriate temporal timescales for fair comparison for this study. Table 3 and Table 4 highlight key data attributes.

Table 3. Sentinel-1 SAR imagery

Date	Event	Data Type	Purpose	Spatial Resolution	Temporal Resolution	Size on Disk	Availability
02/16/2022	Pre-Russian invasion	GeoTiff raster	Change detection	10 m	12-day revisit rate	65 GB	Freely available at https://search.asf.alaska.edu
02/28/2022	Post-Russian invasion						
03/12/2022	Conflict						
03/24/2022	Conflict						
04/05/2022	Conflict						
04/17/2022	Conflict						
04/29/2022	Conflict						
05/11/2022	Conflict						
05/23/2022	Post-Russian seizure of Mariupol						

Table 4. UNOSAT rapid damage assessment

Data	Date	Data Type	Purpose	Spatial Resolution	Size on Disk	Availability
AOI of Mariupol residential area	2022	Polygon vector	Study area boundary	N/A	23 MB, 13.3 MB	Freely available at https://unosat.org/products/3300
Rapid Damage Assessment Map	06/21/2021, 03/14/2022, 05/7/2022, 05/08/2022, 05/12/2022	Point vector with damage scale attribute information	Validation	30 cm WorldView-3 imagery, 50 cm WorldView-2 imagery		

3.1.1 Sentinel-1 SAR Imagery

ESA's Sentinel-1 satellite mission is to provide continuous radar mapping of the Earth by providing enhanced revisit frequency, coverage, and timeliness for Earth science and emergency response applications (Sentinel n.d.b). ASF provides an accessible graphical interface for creating imagery searches and downloading remote sensing data from its archive. Imagery is available within three days of acquisition to any user free of charge, making it suitable for NGOs and human rights organizations lacking special licenses or funding (ASF n.d.c). An alternative source, ESA, was also considered. ESA is the owning agency of the Sentinel-1 satellite and delivers Sentinel data within 24 hours or within one hour of reception for near real-time emergency monitoring (Sentinel n.d.a). While both ASF and ESA offer accessible imagery, ASF was chosen as the source for this study because of its online Radiometrically Terrain Corrected (RTC) imagery conversion tool providing RTC data for download. ASF was selected for its user-friendly platform and ArcGIS Pro compatible geoprocessing tools, making it a user-friendly data source for non-imagery experts. 10 m resolution, C-band, ground range detected (GRD) SAR imagery was downloaded from the ASF Data Search Vertex with the creation of an account.

ASF provides new imagery every 12 days corresponding to the Sentinel-1 satellite's 12-day imaging rate (Kristenson 2020). Images between February 16, 2022, and May 23, 2022, are used for this study. These dates align with pre-Russian invasion and post-seizure of Mariupol. Figure 10 is an example of RTC SAR imagery.

Figure 10. Sentinel-1 SAR image from February 28, 2022

SAR images are not always easily interpreted due to the non-intuitive, side-looking geometry of the sensor (ASF n.d.a). Surfaces, slope, and man-made structures can affect backscattering and therefore brightness in an image (ASF n.d.a). These white and black images at coarse 10 m resolution do not reveal clearly discernable buildings to determine damage and therefore identify potential violations of human rights. Methods for using this imagery for damage analysis are explained in the workflow section.

This study considered other potential imagery sources but identified limiting factors for consideration. Cost and accessibility are the two greatest limitations when choosing an appropriate SAR data source. At the time of this study, very few civil and commercial companies capture SAR data, limiting sources for researchers. Many commercial companies require contracts for access, contributing to the low prevalence of SAR research in the human rights community. ESA's TerraSAR-X and TanDEM-X Earth observation SAR imagery are only offered to users located in the territory of ESA member states in the European Commission Member States and in Africa. These accessibility restrictions make it an unreliable source for human rights practitioners working worldwide in often unpredictable locations. In the commercial sector, Airbus imagery resellers quoted an academic price for high-resolution SAR imagery at $156.25 - $568.75 for 25 sq km of coverage. Furthermore, at the time of this study, Airbus was restricting sale of SAR data collected over Ukraine during ongoing war for security purposes.

Optical imagery was also investigated as a potential validation source but was not selected accessibility restrictions. At the time of this study, Planet and Maxar are two leading commercial imagery companies offering VHR optical imagery. While both offer some of the best available imagery to date, Planet's Education and Research Program for students only offers free optical imagery up to 3 m resolution, unsuitable for building-level damage assessment. Maxar only offers select archive imagery from natural disaster events which did not include the war in Ukraine at the time of this study. Medium-resolution Sentinel-1 SAR imagery does not have these accessibility restrictions. Rather, it offers the most suitable coverage, accessibility, cost, and practicality for this study. These characteristics make Sentinel-1 SAR imagery a suitable source for human rights practitioners.

3.1.2 UNOSAT Rapid Damage Assessment

UN data was used for geospatial analysis and compared to Sentinel-1 SAR damage analysis. UNOSAT produces damage assessment maps using VHR satellite data of areas affected by disaster, complex emergencies, and conflict. The UNOSAT shapefile included a study area polygon of the AOI in the residential area of Mariupol. UN geolocated point data representing damaged buildings identified from 30 cm optical WorldView-3 and 50 cm optical WorldView-2 imagery were used to compare imagery analysis results from 10 m SAR Sentintel-1 imagery. Figure 11 displays the Mariupol AOI boundary and damaged building points from UNOSAT.

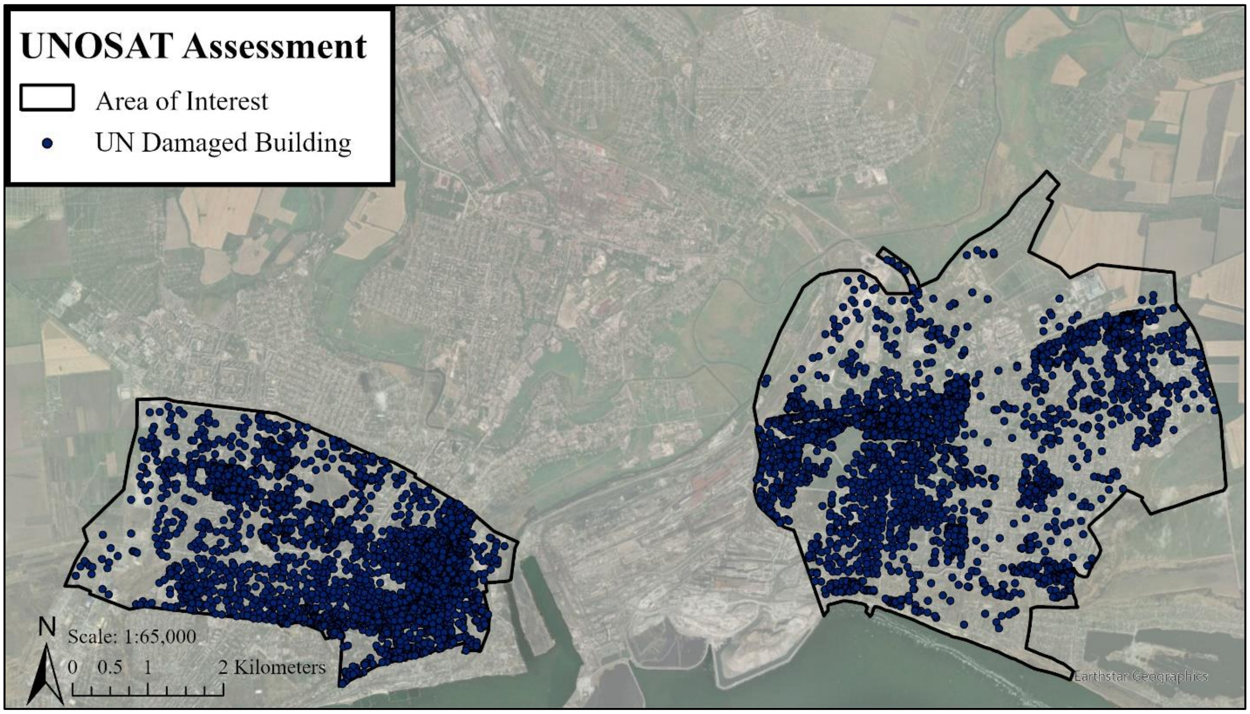

Figure 11. UNOSAT rapid damage assessment

While UN point data are classified into four degrees of damage (destroyed, severe damage, moderate damage, and medium damage), UNOSAT warns results have not been validated in the field due to lack of access to an ongoing war zone. Although UNOSAT point data derived from VHR Worldview imagery has not been validated in the field due to denied access during ongoing war, it is the best validation source at the time of this study due to the data's accessibility, usability, and high fidelity. Due to the coarse spatial resolution of the Sentinel-1 SAR imagery used in this study, classifying individual building degrees of damage is beyond the scope of this study and all UN point data used for verification are assumed to indicate damaged or destroyed buildings.

UN point data representing damaged buildings generally align with buildings from ArcGIS World Imagery base map. Distance rings in Figure 12 show buffers at 5, 10, 20, and 30 meters around each UN damage point to visualize proximity of damaged buildings to other sites.

Figure 12. Distance rings for UN points representing damaged buildings

Distance rings in Figure 12 show that damage points can possibly be associated with damages detected by SAR imagery in this project. Chapter 4.2.2 includes further details comparing UNOSAT rapid damage assessment points with SAR damage detection.

3.2 Workflow

Figure 13 provides the SAR imagery analysis and spatial statistics workflow used in this study. This workflow generated damage assessment raster images every 12 days using SAR imagery pairs between February 16, 2022, and May 23, 2022. Light blue boxes are data from Table 3 and Table 4, yellow boxes are ArcGIS Pro geoprocessing tools, and green boxes are products. The Calculate Log Difference tool used in this study is not an ArcGIS Pro native tool. The ArcGIS Python Toolbox designed by ASF includes the Calculate Log Difference tool designed for Sentinel-1 RTC SAR datasets necessary to complete this workflow. The resulting products of this analysis are the damage assessment map clipped to the Mariupol AOI and corresponding damage statistics.

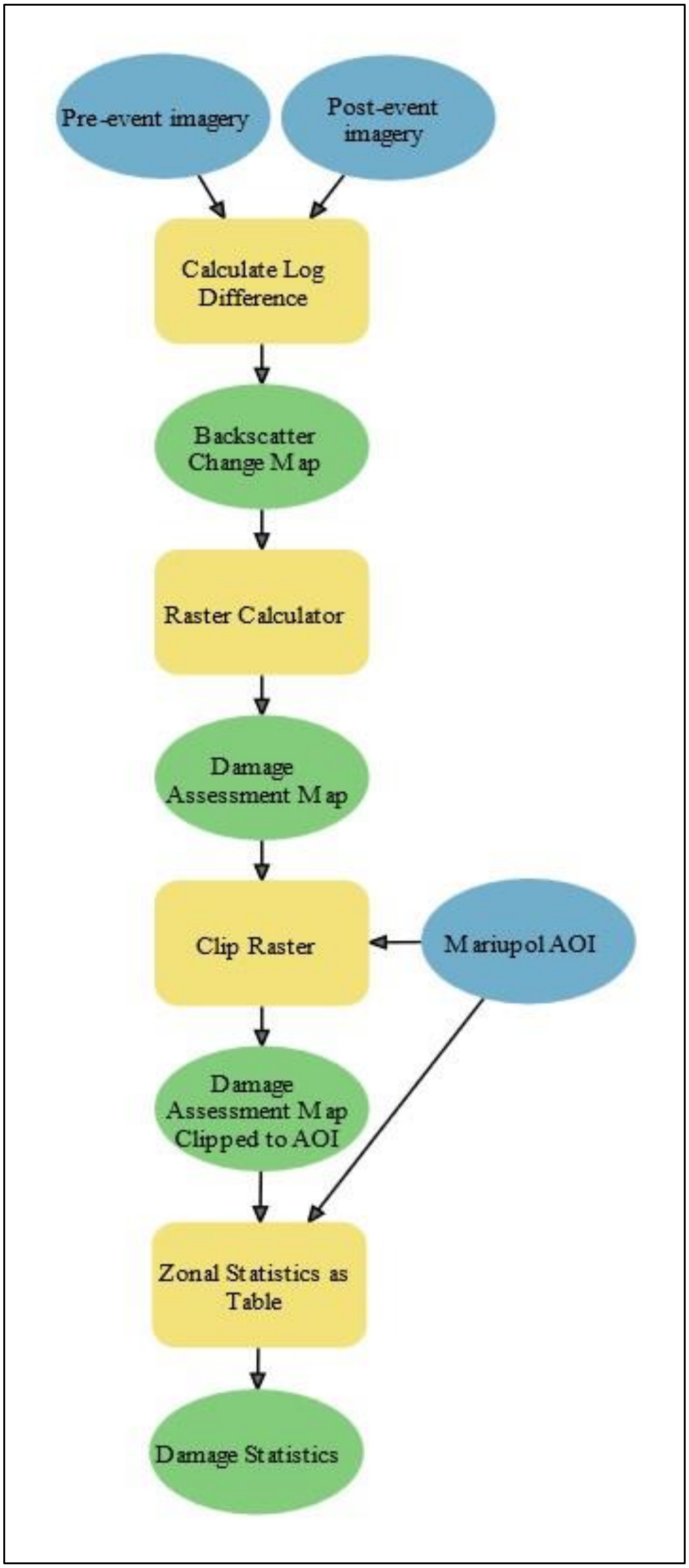

Figure 13. Workflow for Sentienl-1 SAR damage assessment

Figure 14 provides the geospatial analysis and accuracy assessment between Sentinel-1 SAR and UNOSAT. This workflow generated a summation of UNOSAT damage points that lie within SAR damage polygons, providing an accuracy evaluation. Blue boxes include the Sentinel-1 SAR cumulative damage raster resulting from analysis in Figure 13 and UNOSAT damage points from Table 4. Yellow boxes are ArcGIS Pro geoprocessing tools and green boxes are results.

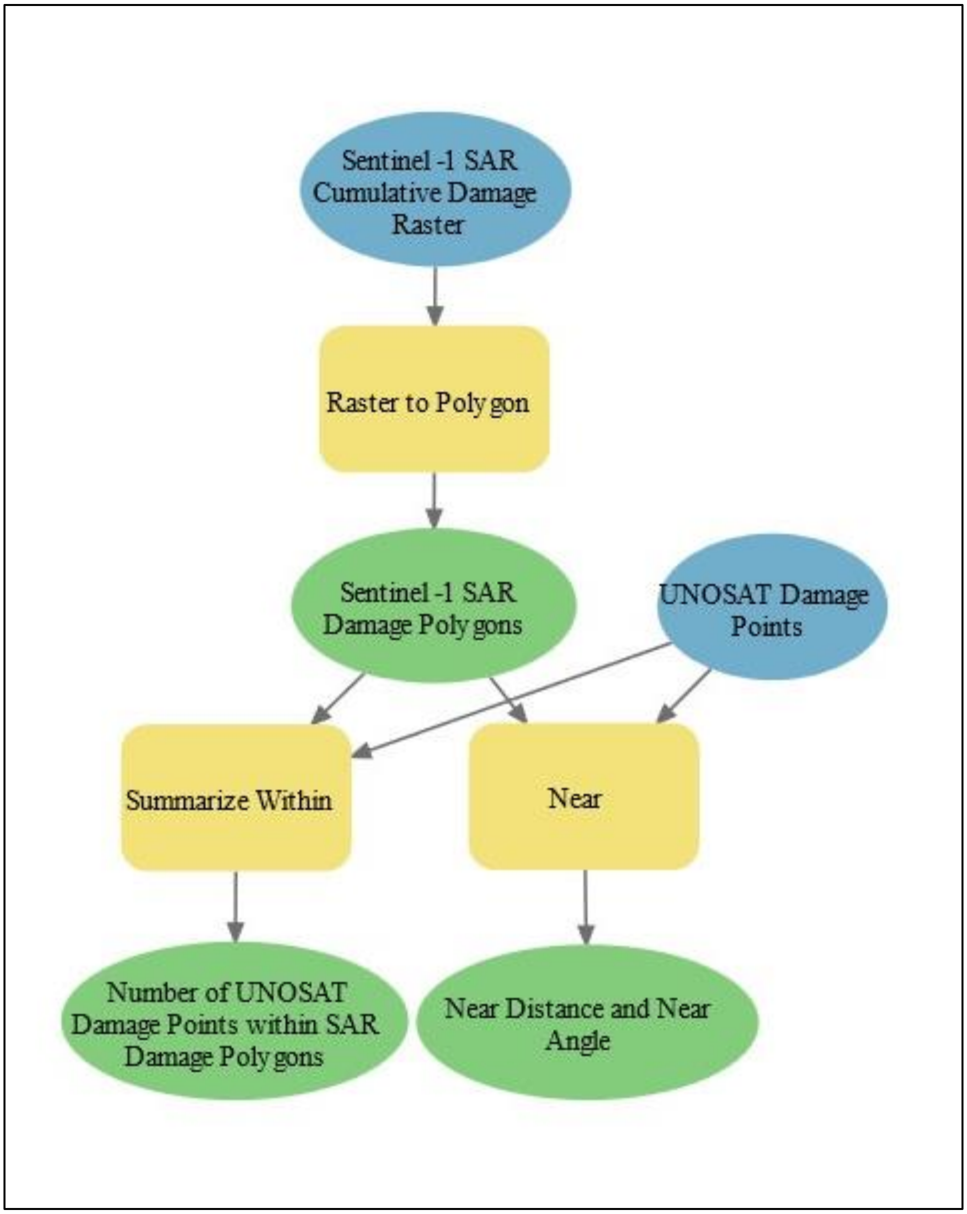

Figure 14. Workflow for Sentinel-1 and UNOSAT damage evaluation

3.2.1 Imagery Preparation

One of the most significant challenges of working with SAR data is distortions resulting from the satellite's side-looking sensor. A process called radiometric terrain correction (RTC) addresses these concerns and stabilizes backscatter values to reduce geometric distortions that may lead to geolocation errors (ASF n.d.d). SAR datasets must be RTC processed to align well with other geospatial data before working in GIS applications for time-series analysis. This study used the On-Demand RTC Processing tool in the ASF Data Search Vertex portal with the Copernicus Digital Elevation Model to adjust for distortions. All images were RTC processed in amplitude scale to accommodate follow-on optimization. The On-Demand RTC Processing tool replaces the lengthy process of manual image-preprocessing and drastically reduces the overall workflow completion time. This benefit is crucial for human rights practitioners in need of timely information.

3.2.2 Calculate Log Difference

A simple and practical way to detect change between two SAR images is the log difference calculation detailed in Chapter 2 (Aimaiti 2022; Matsuoka and Yamazaki 2004; ASF 2020). This study used the calculation of Log10 (Date2/Date1) to identify significant changes in backscatter between two images (1). Negative values indicate a decrease in radar backscatter between two images and positive values indicate an increase in backscatter. Areas with little to no change in backscatter will indicate no change in value. This study followed the simple and robust SAR log equation used in a similar study by Aimaiti et al. (2022) based on the hypothesis that building backscattering characteristics will change after natural or anthropogenic disasters resulting in building damage (Equation 1).

After downloading the ArcGIS Python Toolbox, the Calculate Log Difference Tool was used to calculate the log of the ratio of pixel values from two images of the same area taken at different times. A total of 9 images were used to create 9 backscatter intensity change rasters indicating damage due to Russian attacks on the AOI in Mariupol.

3.2.3 Manual Threshold

The SAR intensity-based change detection method applied in the previous step produced a backscatter intensity change raster. The study used an amplitude scale for SAR images which is optimal for calculating log difference ratios (ASF n.d.d). Values in the amplitude scale are the square root of the power scale values, which brightens darker pixels and darkens brighter values, reducing the range of the image (ASF n.d.d). Positive values in the difference raster indicate increased backscatter over time, whereas negative values indicate decreased backscatter over time (ASF 2020). Since these values are not easily interpreted by non-imagery experts, pixels were classified to visualize damaged and undamaged areas. A binary classification draws attention to significant change areas rather than displaying the full spectrum of backscatter change values (ASF n.d.d). This study adapted the simple histogram thresholding method outlined in Chapter 2 to achieve a binary classification scheme (ASF 2020; Braun 2018; Kim 2023). Using the method provided by the ASF Log Difference Tool tutorial, values less than and greater than one standard deviation are used to indicate damage, since both positive and negative backscatter values can represent change (ASF 2020; van Heyningen 2018). The histogram statistics of the log difference raster were used to set class break points of one and two standard deviations for both positive and negative values. For simplicity, this study does not attribute positive or negative values to certain types of damage. Any change in backscatter, positive or negative values, was classified as potential damage. The Raster Calculator geoprocessing tool was used to create a binary classification using pixel values from the difference raster to produce a map of undamaged (no change in backscatter) and damaged areas (change in backscatter). Finally, the raster was clipped to the Mariupol AOI to create a damage map.

3.2.4 Zonal Statistics as Table

The Zonal Statistics as Table geoprocessing tool was used to calculate mean percentage of damage. This tool calculated mean values of undamaged area in the AOI represented as a fraction. Multiplying these values by one hundred produced mean percentage of undamaged area. Mean percentage of damaged pixels were calculated using Equation 2:

$$Mean\,\%_{Damaged} = 100 - Mean\,\%_{Undamaged} \tag{2}$$

The calculation was repeated for each timestep every 12 days from the February – May 2022 timeframe of Russian attacks. Table 5 summarizes results.

3.2.5 Sentinel-1 SAR Damage and UNOSAT Damage Evaluation

To evaluate SAR damage accuracy, the SAR damage assessment was compared to UN damage points representing geolocated damaged buildings derived from VHR optical imagery. To compare SAR damage assessment to UNOSAT damage assessment, SAR damage pixels were converted to SAR polygons using the Raster to Polygon tool. Summarize Within tool was used to summate UN points representing damaged buildings that fell within SAR damage polygons.

3.2.6 Near Tool Analysis

The Near Tool was used to calculate distance and angle information between SAR damage polygons and UN damage points. Near Distance calculated the number of UN points within various radius distances (0 m, 5 m, 10 m, 20 m, and 30 m) of SAR damage polygons. Radius distances were selected based on reasonable damage radius estimates resulting from four types of weapons identified by the Independent International Commission of Inquiry on Ukraine’s report: unguided bombs from aircraft, long-range anti-ship missiles, cluster munitions, and multiple launch rocket systems (UN 2023a). Near Angle measured the direction of the line connecting UN damage points to the nearest SAR damage polygon. The range spans from -180° to 180°, with 0° to the east, 90° to the north, 180° (or -180°) to the west, and -90° to the south (ArcGIS Pro n.d.b).

Chapter 4 Results

This chapter describes results of SAR imagery analysis and compares damage estimates with UNOSAT damage assessment derived from VHR optical imagery. The following sections present results in the form of maps and spatial statistics.

4.1 Sentinel-1 Damage Assessment

Sentinel-1 SAR damage analysis using methods described in Chapter 3 exhibited increasing damage prevalence with time. The following sections exhibit damage results from Russian attacks culminating in the seizure of Mariupol in May 2022. The results of this study revealed that the Sentinel-1 SAR imagery underestimated cumulative damage compared to damage estimated from UNOSAT VHR optical imagery over the same AOI.

4.1.1 Spatiotemporal Results

A key assumption used in this project is that any significant change in backscatter intensity, positive or negative, is indicative of war-induced damage, an assumption shared by van Heyningen in a study on Sentinel-1 damage detection (2018). Figure 15 shows an example of backscatter intensity change detection between two images using the log of the ratio of the pixel values over the same AOI (ASF 2020).

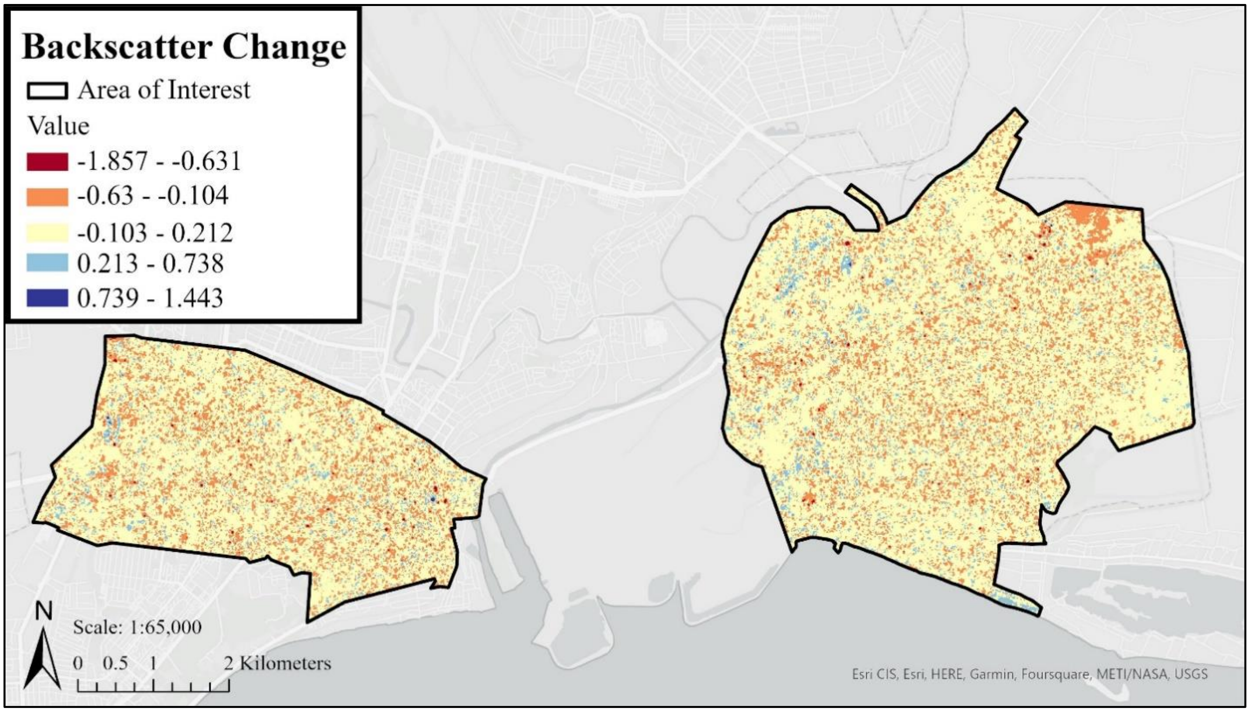

Figure 15. Intensity change between February 16, 2022 and May 23, 2022

Areas in yellow represent values associated with no backscatter change. Red and blue represent the greatest changes in intensity (negative and positive values), indicating damages. These rasters are considered intermediary products since they do not provide easily discernable or meaningful information to non-imagery experts.

Using methods described in Chapter 3, re-classified rasters resulted in maps identifying damaged and undamaged areas. Results show detected changed areas as “damaged” in red, and unchanged areas as “undamaged” in yellow. Old damage detected from each previous 12-day period is shown in transparent red. SAR damage change results for individual districts of the AOI are provided beginning with Figure 17 to easily note changes. Figure 16 shows the first damage assessment using a pre-invasion Sentinel-1 SAR image and a post-invasion image 12-days later.

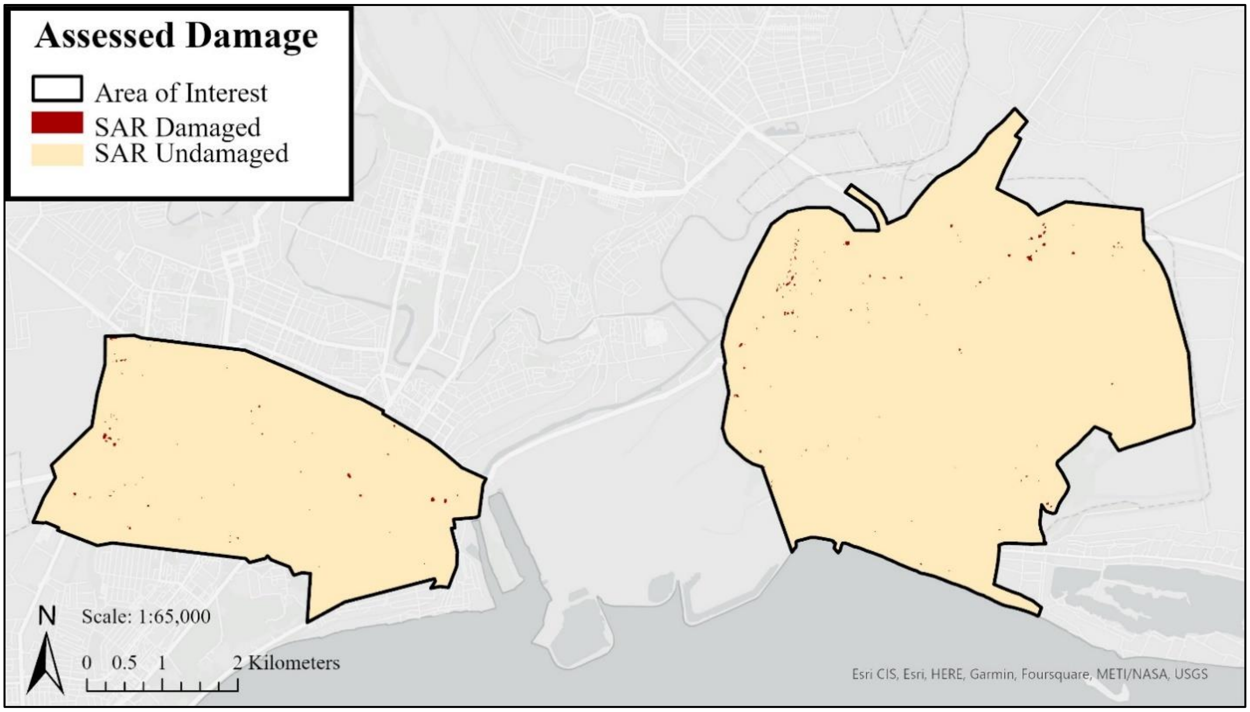

Figure 16. Damage assessment using SAR for February 16 – 28, 2022

Very little detected SAR damage in the AOI is indicative of low levels of conflict during the early stages of the war. Change detection over this period includes war-induced damages inflicted over four days (since Russia's invasion on February 24, 2022). Low levels of damage detection suggest Mariupol had not yet experienced heavy attacks.

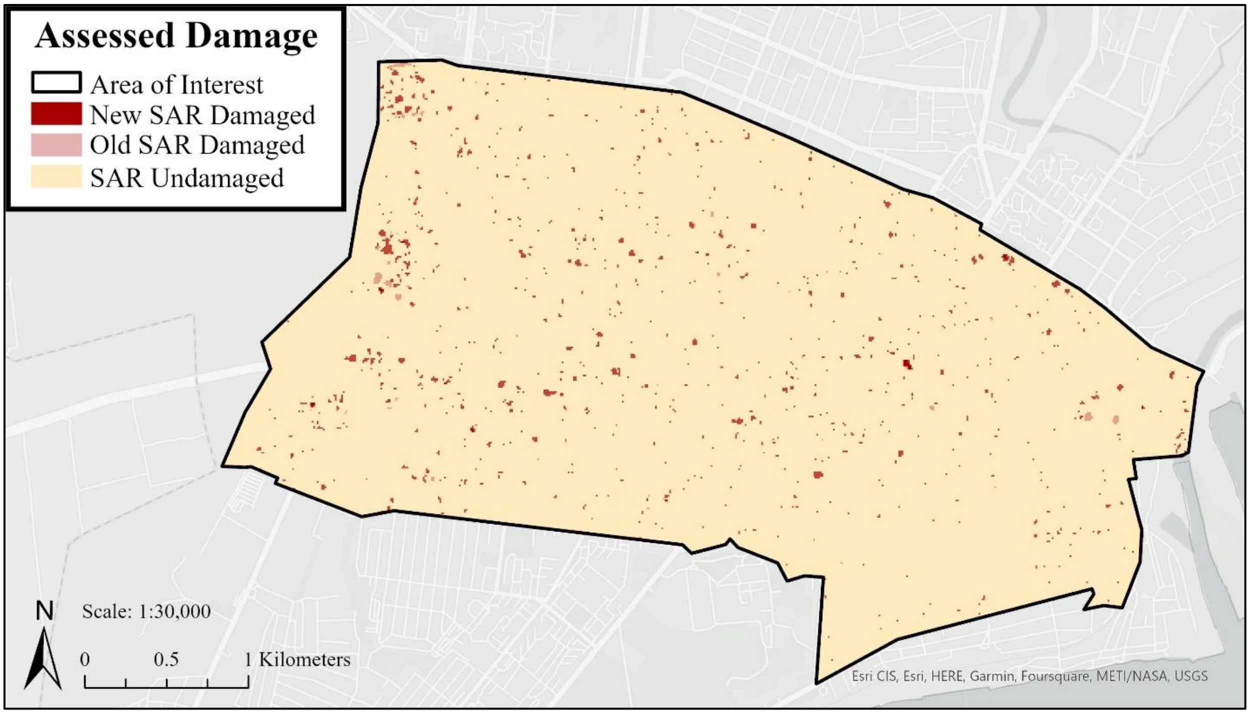

Figure 17. Zhovtnevyi District damage assessment using SAR for February 16 – 28, 2022 (old damage), and February 28 – March 12, 2022 (new damage)

Figure 17 shows SAR damage changes in the Zhovtnevyi District. Red pixels indicate SAR damage detected from images between February 28, 2022 – March 12, 2022. Transparent red pixels indicate old SAR damage detected from images between February 16 – February 28, 2022. Results show an increase in damage extent and magnitude which corresponds with reports of devastating attacks in Mariupol during this time period, including the deadly attack on a Mariupol maternity hospital on March 9, 2022 (Cullison 2022; OHCHR 2023a).

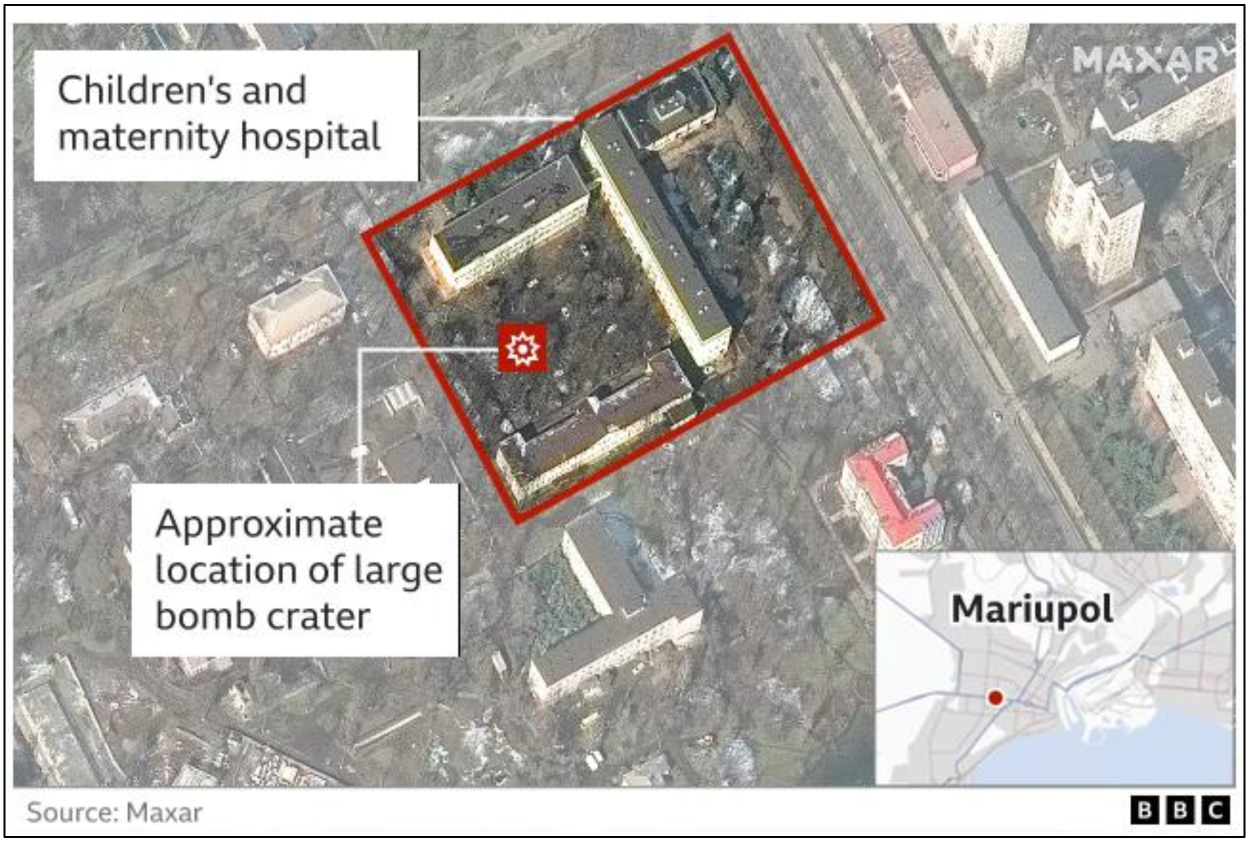

Figure 18. Mariupol maternity hospital attack imagery

Commercial optical satellite imagery from Maxar shows the site of the Mariupol maternity hospital attack, approximately located in areas of increased SAR damage in corresponding analysis (Figure 18). This timeline and damage comparison demonstrate how SAR damage analysis can corroborate alleged war crimes such as unlawful attacks and also challenge misinformation attempts to uphold aggressors accountable (Hinnant and Chernov 2022b). When available, complementary VHR optical imagery can be used together with medium-resolution SAR imagery to detect, monitor, and attribute attacks causing damage to civilian infrastructure.

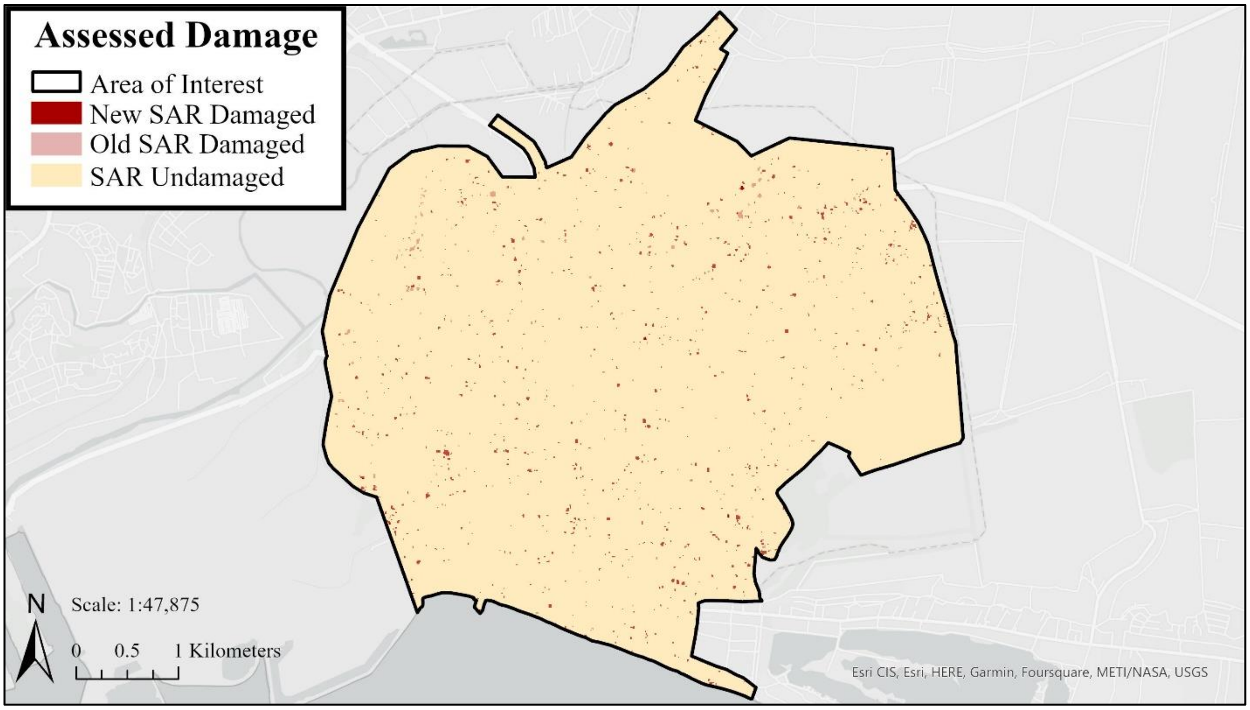

Figure 19. Livoberezhnyi District damage assessment using SAR for February 16 – 28, 2022 (old damage) and February 28 – March 12, 2022 (new damage)

Figure 19 shows SAR damage changes in the Livoberezhnyi District. Red pixels indicate SAR damage detected from images between February 28, 2022 and March 12, 2022. Transparent red pixels indicate old SAR damage detected from images between February 16 – February 28, 2022. Similar to estimates in the Zhovtnevyi District, results show an increase in damage extent and magnitude.

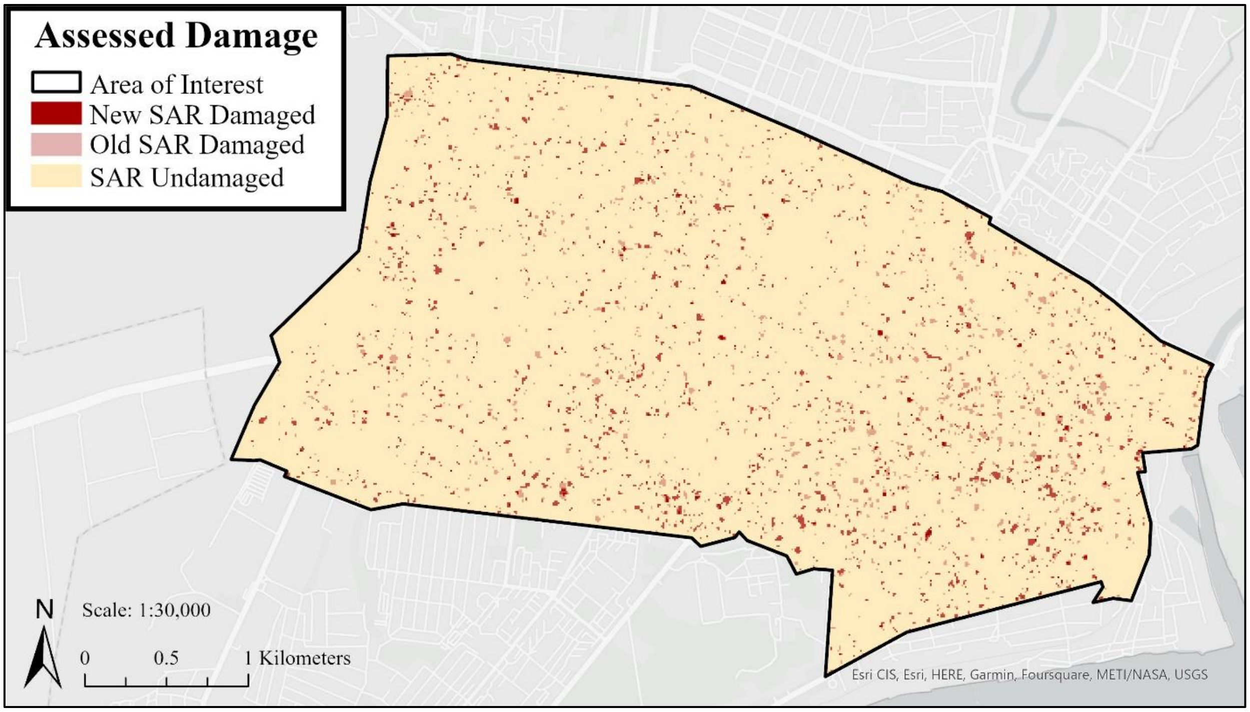

Figure 20. Zhovtnevyi District damage assessment using SAR for February 28 – March 12, 2022 (old damage) and March 12 – 24, 2022 (new damage)

Increasing levels of new SAR damage were detected in the Zhovtnevyi District for the period of March 12 – March 24, 2022. Damaged pixels are prevalent throughout and concentrated in the east. New SAR damage results agree with reports of missile and air strikes in Mariupol, including the deadly bombing of the Mariupol drama theatre located in the Zhovtnevyi District on March 16 (Hinnant and Chernov 2022a; OHCHR 2023a). Increased SAR damages during this period correspond to the attack violating international humanitarian law (Benedek et al. 2022). Figure 21 and Figure 22 display pre- and post- drama theatre attack VHR optical images corresponding to SAR damage detected from March 12 – 24, 2022.

Figure 21. Mariupol drama theatre imagery before attack

Figure 21 shows how buildings and ground features are easily discernable with VHR optical imagery compared to medium-resolution SAR imagery. Commercial VHR optical imagery from CNES/Airbus shows the undamaged Mariupol drama theatre on March 14, two days before the attack.

Figure 22. Mariupol drama theatre imagery after attack

Sixty cm resolution optical imagery from CNES/Airbus on March 16, 2022 shows Mariupol drama theatre damage, including a destroyed roof and two debris fields to the north and the south of the building. Figure 22 shows how smoke in the lower and upper left corners of the image can conceal ground features. This demonstrates how dependence on optical images alone can be unpredictable and unreliable for monitoring war-induced damages. Since SAR is not affected by smoke, clouds, weather, or time of day, it provides consistent imaging capability regardless of imaging conditions, ideal for human rights practitioners (Brown and Hogan 2020).

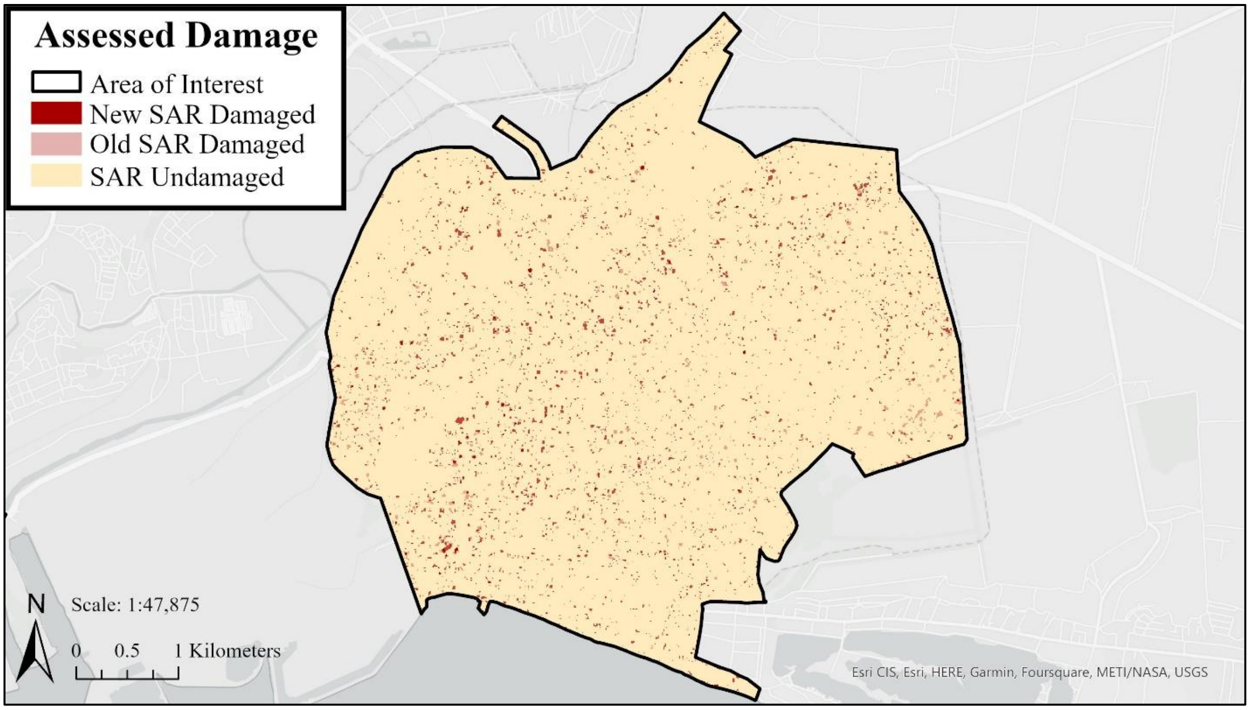

Figure 23. Livoberezhnyi District damage assessment using SAR for February 28 – March 12, 2022 (old damage) and March 12 – 24, 2022 (new damage)

Increasing levels of new SAR damage were detected in the Livoberezhnyi District. Less damage was detected in the north and south. Damage extent was scattered and distributed throughout the area.

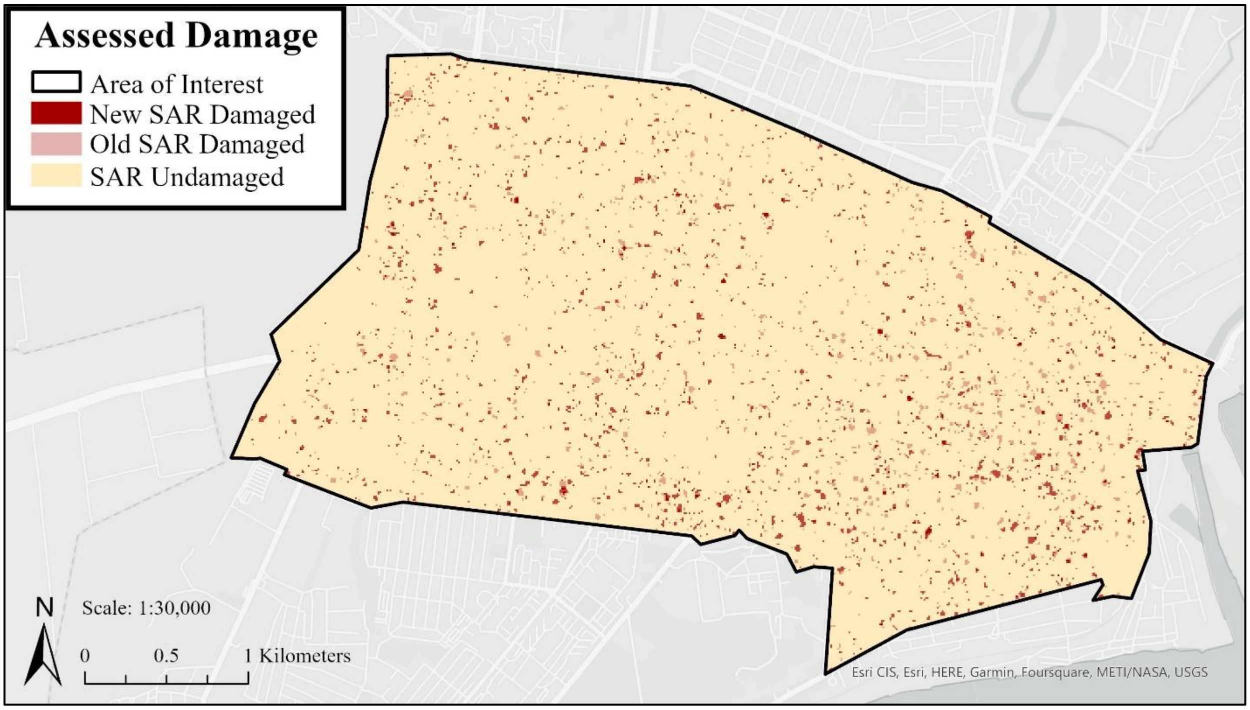

Figure 24. Zhovtnevyi District damage assessment using SAR for March 12 – 24, 2022 (old damage) and March 24 – April 5, 2022 (new damage)

The third consecutive increase in SAR damage occurred from March 24 – April 5, 2022, represented in red. The size of new SAR damage pixels appeared larger than old SAR damage pixels from analysis for March 12 – 24, 2022 represented in transparent red. Higher levels of SAR damage appeared in the south and east. Increased damages suggest intensifying attacks which could include severe shelling, airstrikes, and bombing responsible for civilian casualties (UN OHCHR 2023a).

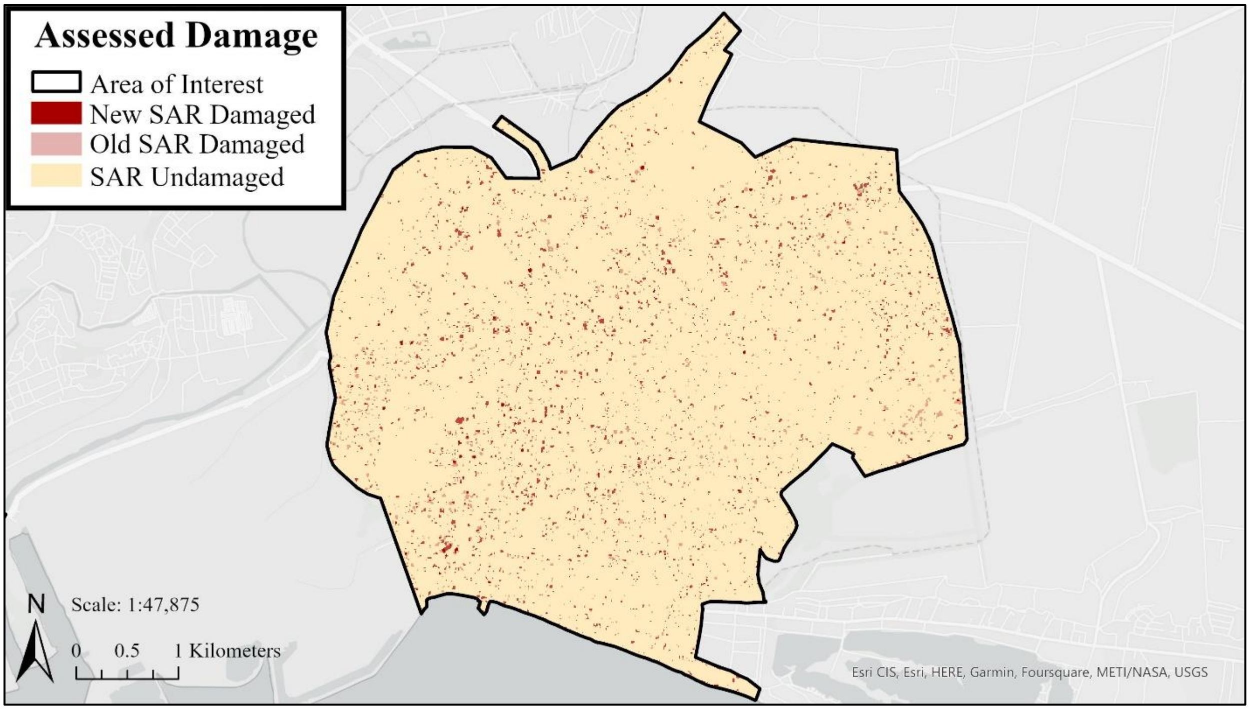

Figure 25. Livoberezhnyi District damage assessment using SAR for March 12 – 24, 2022 (old damage) and March 24 – April 5, 2022 (new damage)

Figure 25 shows a mix of new and old SAR damage. Red shows new damage detected from March 24 – April 5, 2022, and transparent red shows old damage detected from March 12 – 24, 2022. Results in the Livoberezhnyi District indicate extensive damages. Damage was concentrated mostly in the central area and in the southwest.

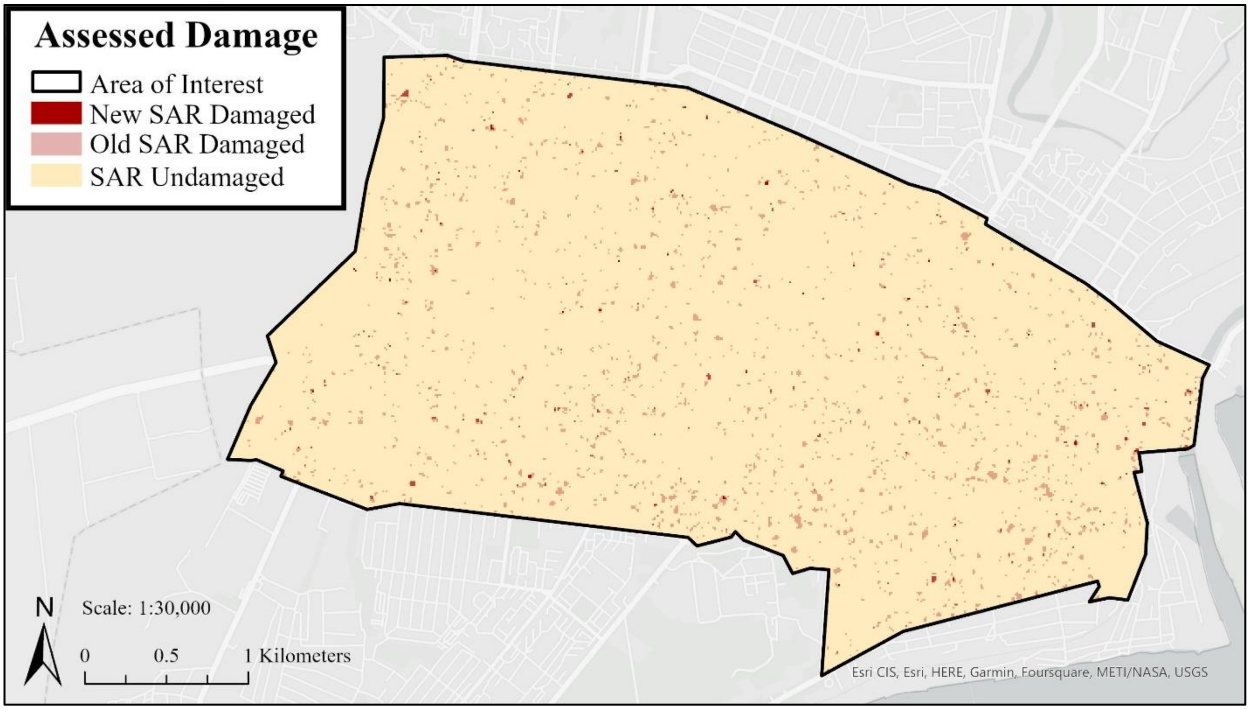

Figure 26. Zhovtnevyi District damage assessment using SAR for March 24 – April 5, 2022 (old damage) and April 5 – 17, 2022 (new damage)

Detected SAR damage significantly decreased from April 5, 2022 – April 17, 2022, for the first time since February 28, 2022. Figure 26 shows a majority of old SAR damage corresponding to significant levels of damage from March 24 – April 5, 2022. Results indicate a possible decrease in Russian attacks or reduction in overall conflict.

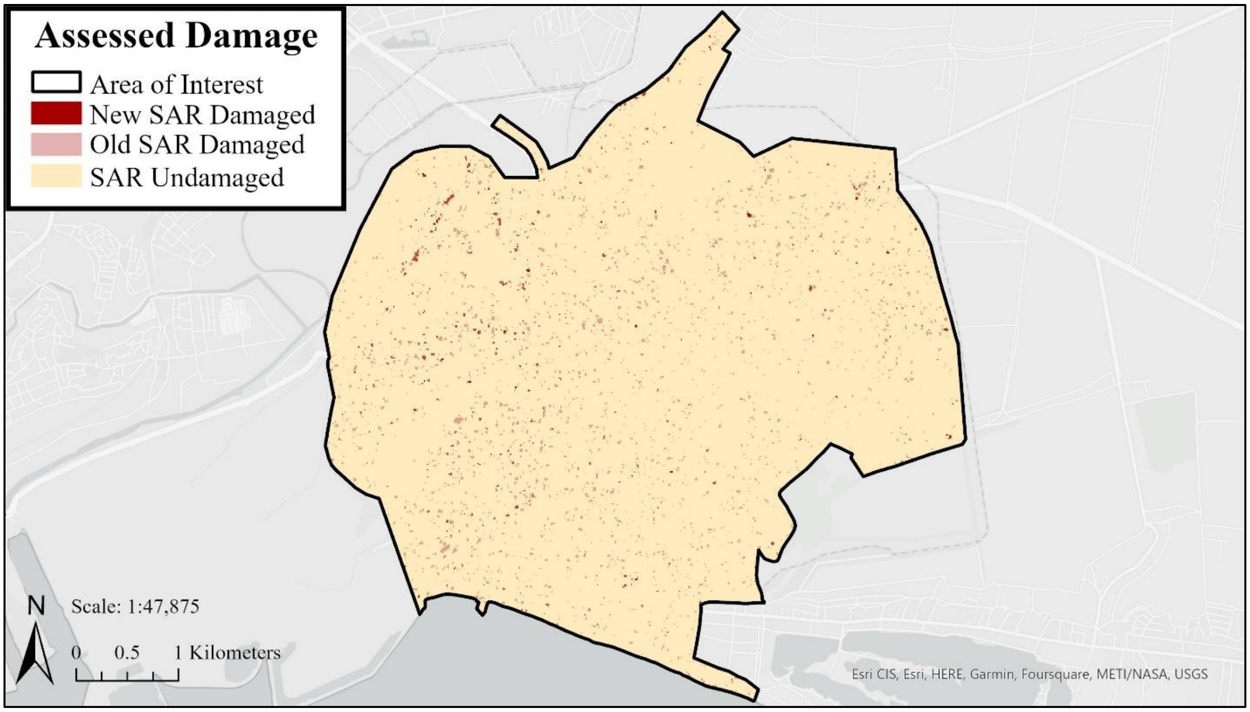

Figure 27. Livoberezhnyi District damage assessment using SAR for March 24 – April 5, 2022 (old damage) and April 5 – 17, 2022 (new damage)

Figure 27 shows a majority of old SAR damage corresponding to significant levels of damage from March 24 – April 5, 2022. Low levels of new SAR damage were detected in the Livoberezhnyi District for this period.

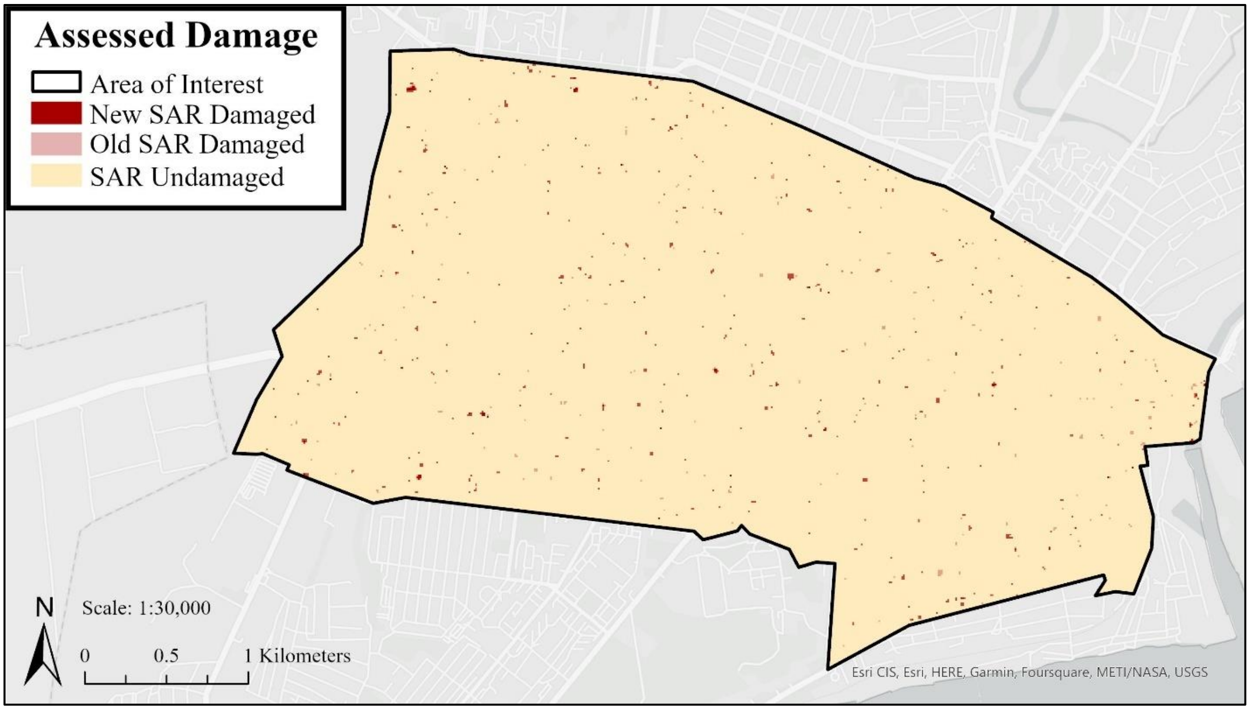

Figure 28. Zhovtnevyi District damage assessment using SAR for April 5 – 17, 2022 (old damage) and April 17 – 29, 2022 (new damage)

Damage remained low from April 17, 2022 – April 29, 2022. This decrease in detected damages corresponds with Russia’s announcement of Mariupol’s capture on April 21, 2022 (Bowen 2023). Low levels of dispersed red pixels representing new damage could depict damages from intermittent fighting or result from a pause in fighting.

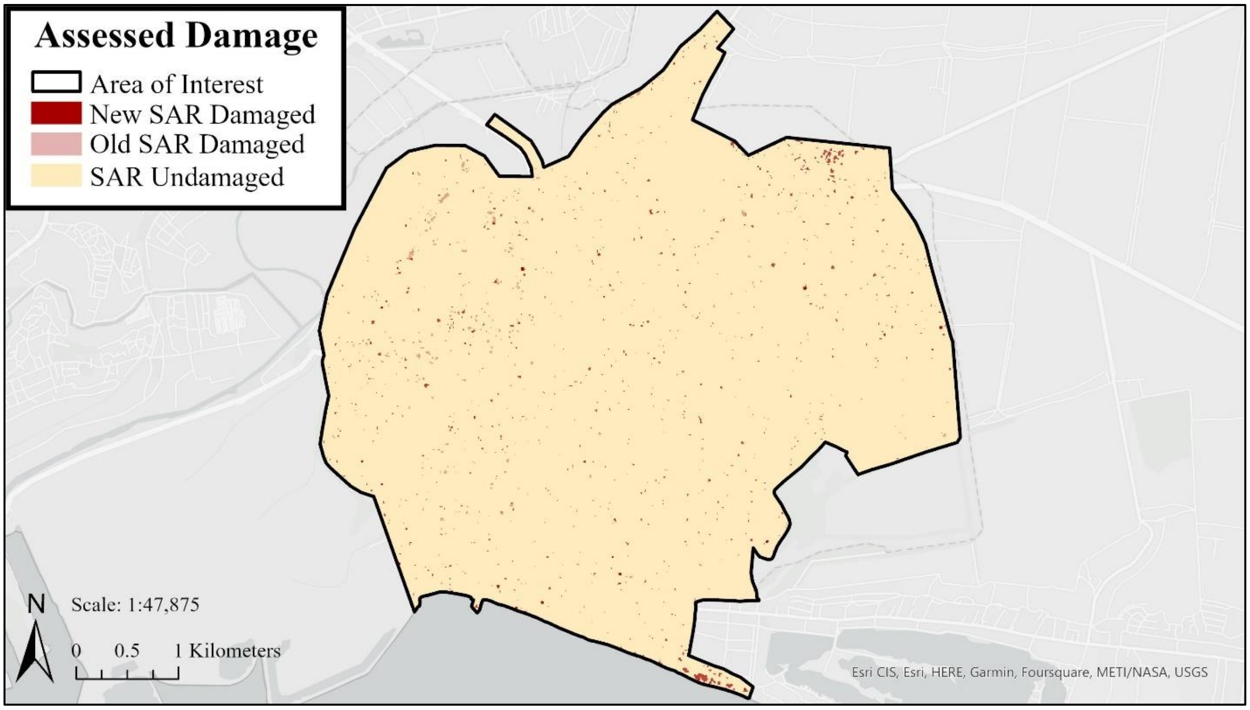

Figure 29. Livoberezhnyi District damage assessment using SAR for April 5 – 17, 2022 (old damage) and April 17 – 29, 2022 (new damage)

Damages remained low for the second consecutive period in the Livoberezhnyi District from April 17 – 29, 2022. No significant new damages suggest low levels of fighting. This reduced fighting corresponds to Russian claims of Mariupol’s seizure (Bowen 2023).

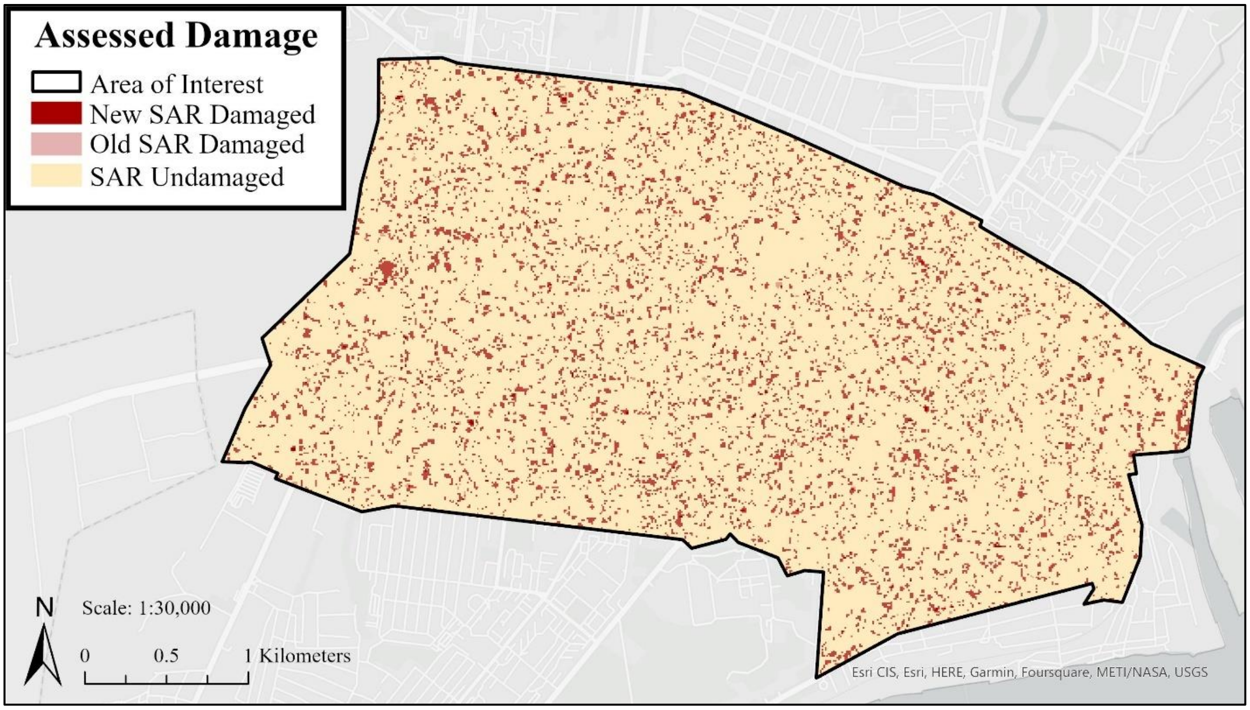

Figure 30. Zhovtnevyi District damage assessment using SAR for April 17 – 29, 2022 (old damage) and April 29 – May 11, 2022 (new damage)

Despite Russia's announcement of Mariupol's capture on April 21, 2022, Ukrainian forces displayed continuous resistance against Russian forces (Bowen 2023). SAR damage detection indicates extensive and severe damages from April 29 – May 11, 2023. This widespread sudden significant increase in new damage suggests continued fighting took place despite Russia's claims of capture.

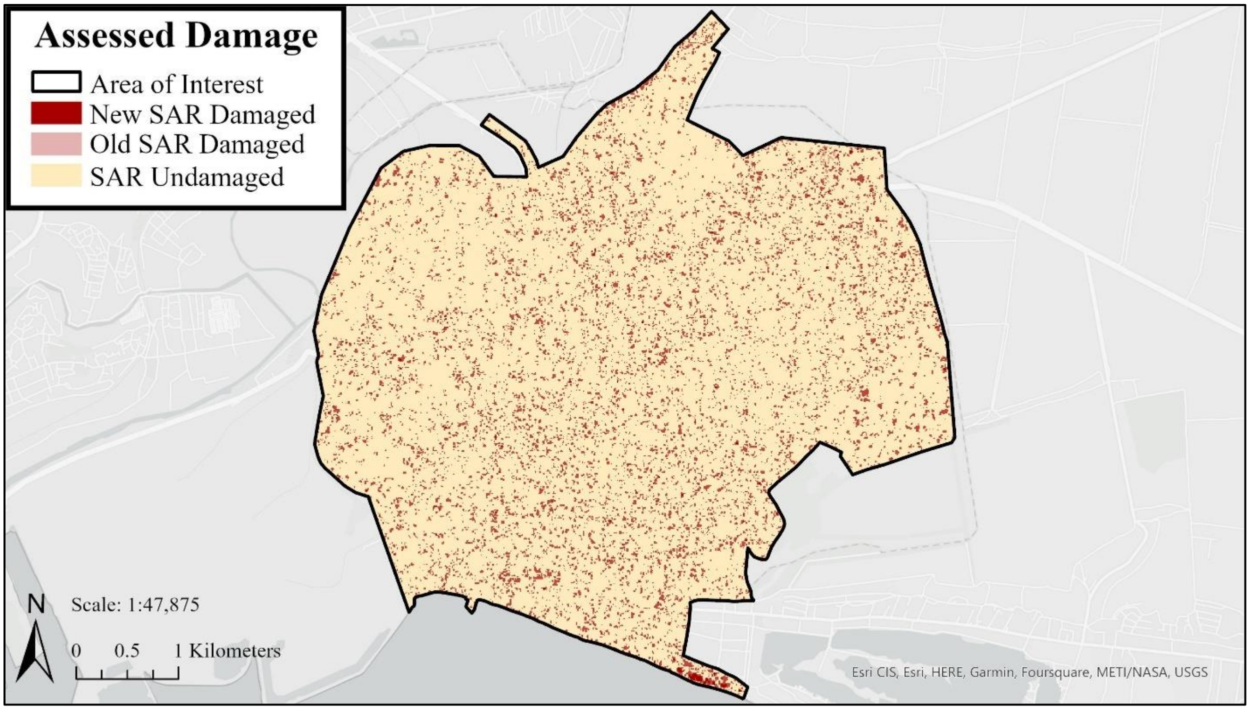

Figure 31. Livoberezhnyi District damage assessment using SAR for April 17 – 29, 2022 (old damage) and April 29 – May 11, 2022 (new damage)

Damage was similar in severity and extent in the Livoberezhnyi District from April 29 – May 11, 2022. New damages were dispersed throughout the district indicating widespread attacks. While SAR damage pixels alone cannot attribute attacks to either Russian or Ukrainian forces, the prevalence during this period suggests increased hostilities during the late stages of Mariupol's attacks.

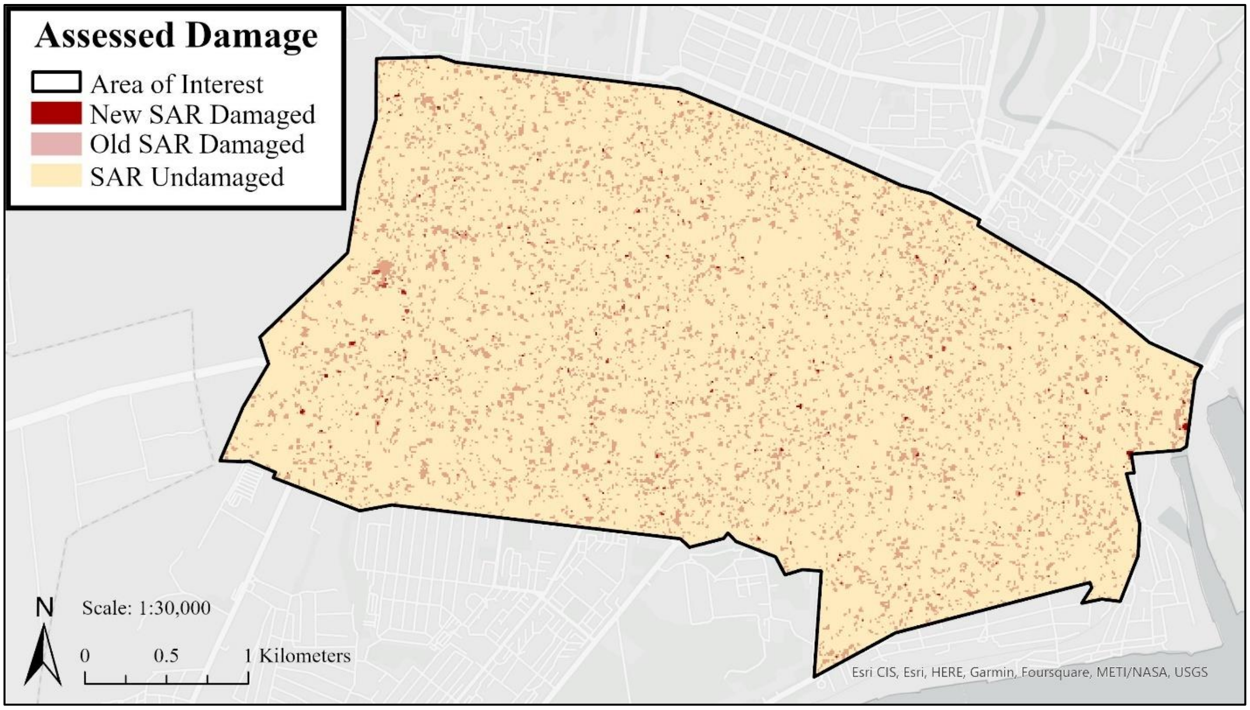

Figure 32. Zhovtnevyi District damage assessment using SAR for April 29 – May 11, 2022 (old damage) and May 11 – 23, 2022 (new damage)

From May 11 – 23, 2022, damages decreased dramatically to low levels similar to those during early April 2022 (Figure 27 and Figure 28). This striking decrease corresponds with reports of Ukrainian forces' surrender of Mariupol in mid-May 2023 after ceasing combat at the Azovstal iron and steel plant (Bowen 2023).

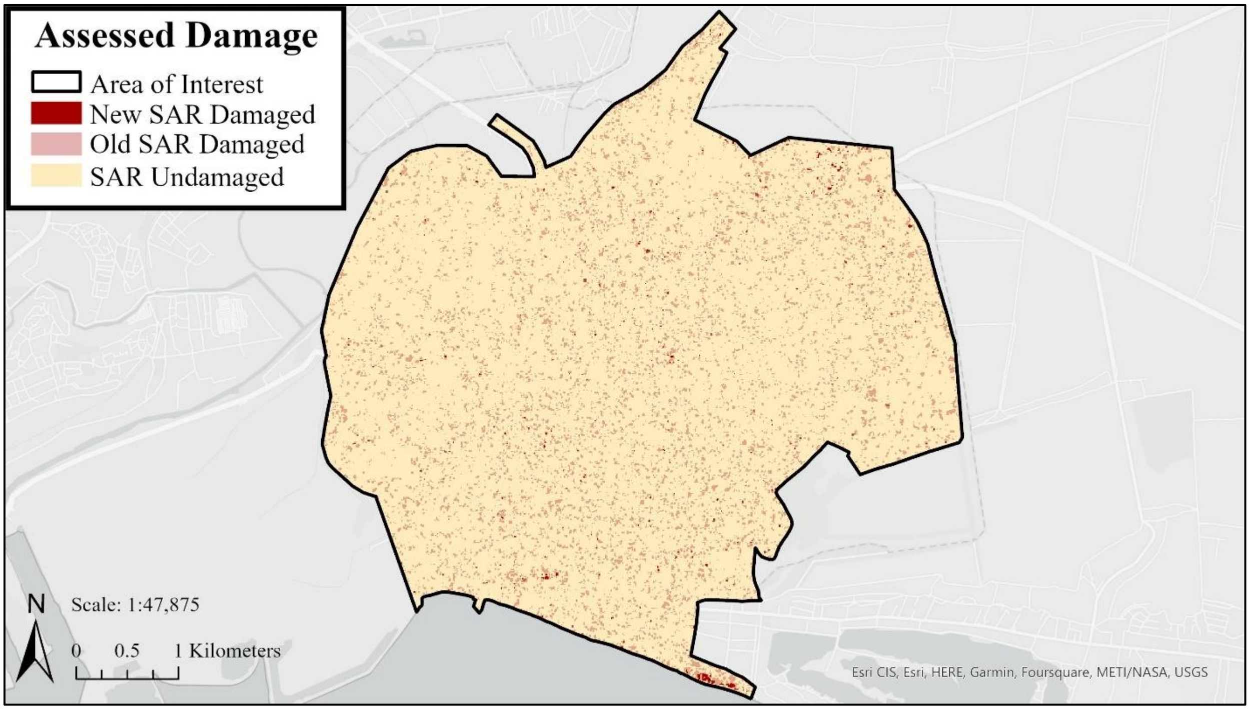

Figure 33. Livoberezhnyi District damage assessment using SAR for April 29 – May 11, 2022 (old damage) and May 11 – 23, 2022 (new damage)

Damages decreased to low levels in the Livoberezhnyi District from May 11 – 23, 2022. This dramatic decrease in SAR damage agrees with Ukranian forces' surrender in mid-May 2022. Transparent red pixels correspond with old damage from April 29 – May 11, 2022.

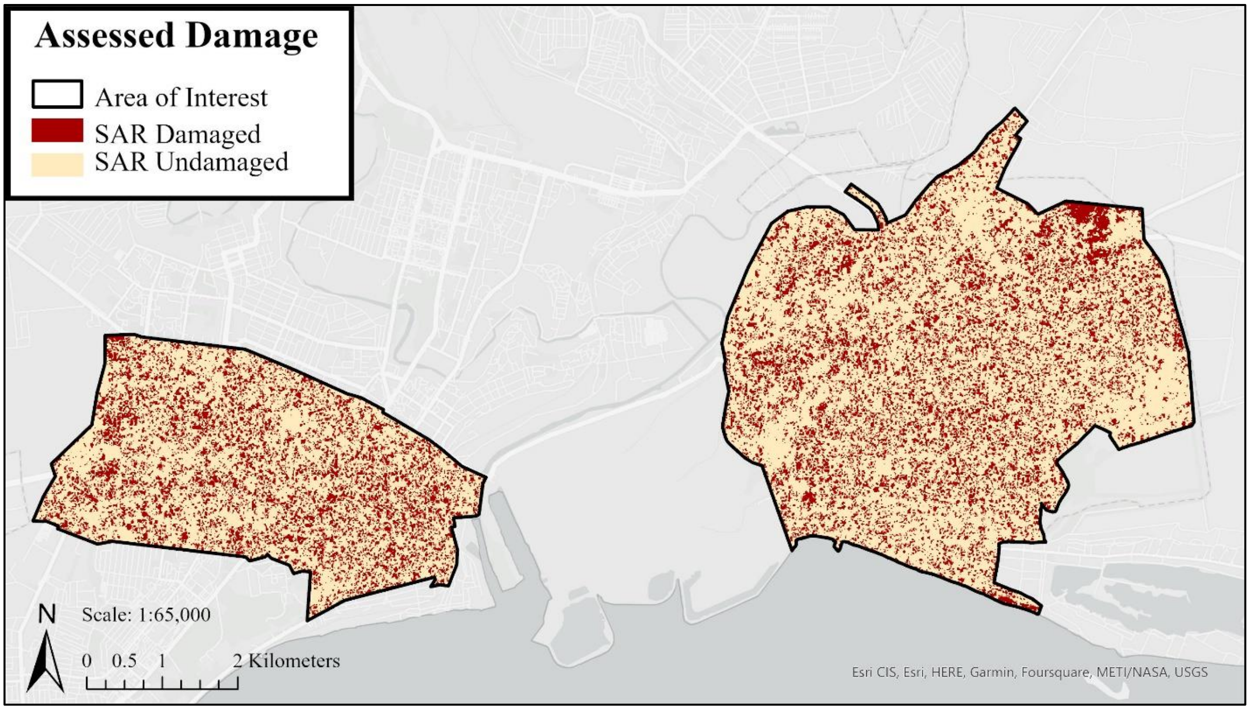

Figure 34. Damage assessment using SAR for February 16 – May 23, 2022

Figure 34 shows the cumulative damage reclassified from its backscatter intensity change raster (Figure 15). Results show extensive damages throughout both districts comprising the Mariupol AOI. A spatiotemporal trend is a clear consecutive increase in damage from February 28, 2022 – March 12, 2022, March 12, 2022 – March 24, 2022, March 24, 2022 – April 5, 2022, and April 29, 2022 – May 11, 2022. Damage changes remained low from April 5, 2022 – April 17, 2022, and April 17, 2022 – April 29, 2022. The most severe damage in extent and magnitude occurred from April 29, 2022 – May 11, 2022. Finally, damages appeared low from May 11, 2022 – May 23, 2022, during the final stages of Russia's capture of the city of Mariupol. Spatiotemporal changes in damage extent and magnitude correspond to statistical changes highlighted in Table 5.

4.1.2 Damage Statistics

Damage statistics align with spatiotemporal trends of SAR imagery damage assessment. Mean damage percentage values indicated increasing degrees of damage with Russia's progressing war. These results demonstrate the potential to corroborate open-source reports of attacks and subsequent violations of human rights and international humanitarian law described in Chapter 1.

The cumulative damage assessment from February 16, 2022 (pre-invasion) and May 23, 2022 (post-Russian seizure of Mariupol) estimates 27% of mean damage. Gradual increases in mean percentage of damage occurred between February 28, 2022 – March 12, 2022 (1.25%), March 12, 2022 – March 24, 2022 (2.5%), and March 24, 2022 – April 5, 2022 (3.5%). The period from April 5, 2022 – April 17, 2022, and April 17, 2022 – April 29, 2022 showed low mean percentages of damage. The greatest mean percentage damage of 11.2% occurred from April 29, 2022 – May 11, 2022. This sudden increase in damage detection indicates a significant surge in violence and active attacks corresponding to Russia's capture of Mariupol. The sudden decrease in detected damage over the next 12-day period from May 11, 2022 – May 23, 2022, indicates little to no conflict-induced damage, signifying the end of conflict due to Russia's seizure of Mariupol. Table 5 summarizes mean statistics.

Table 5. Mean percentage statistics of undamaged and damaged buildings

Dates (pre-, post-)	Mean % Undamaged	Mean % Damaged
February 16, 2022 February 28, 2022	99.75%	0.25%
February 28, 2022 March 12, 2022	98.75%	1.25%
March 12, 2022 March 24, 2022	97.5%	2.5%
March 24, 2022 April 5, 2022	96.5%	3.5%
April 5, 2022 April 17, 2022	99.6%	0.4%
April 17, 2022 April 29, 2022	99.35%	0.65%
April 29, 2022 May 11, 2022	88.8%	11.2%
May 11, 2022 May 23, 2022	99.6%	0.4%
February 16, 2022 May 23, 2022	73%	27%

4.2 UNOSAT Comparison

Sentinel-1 SAR damage results were compared to the UNOSAT damage assessment to assess accuracy. The overall damage statistics derived from Sentinel-1 SAR imagery underestimated damage compared to the rapid damage assessment of UNOSAT. UNOSAT's manual building inspection using 30 cm WorldView-3 imagery and 50 cm WorldView-2 imagery resulted in 32% estimated total damage. This is 5% greater than the 27% mean percentage of damage estimated from Sentinel-1 SAR analysis. Direct comparison of individual damaged buildings represented by UNOSAT geolocated point data was not possible with Sentinel-1 imagery due to the satellite sensor's 10 m resolution constraints.

4.2.1 Summarize Within

Sentinel-1 SAR damage results were compared with UNOSAT's damage assessment to assess overall accuracy and feasibility of using SAR imagery to detect infrastructure damage. The Summarize Within tool resulted in 37% of all UN damage points within SAR damage polygons. Despite the low accuracy estimate, the magnitude and extent of damages are comparable between SAR estimates and UNOSAT's assessment. While SAR damage underestimated total damage, the spatial distribution of damages was consistent with the distribution of UNOSAT damage buildings. Figure 39 shows an example of UN damage points within SAR damage polygons. Limitations of this estimate are discussed in Chapter 5.

4.2.2 Near Distance

Near Tool analysis indicates that the percentage of total UN damage points within SAR damage polygons increases with an increasing distance radius. While 37% of all UN damage points occur within SAR damage polygons (0 m radius), 94% of all UN damage points occur within SAR damage polygons within a 30 meter radius. Results are summarized in Table 6.

Table 6. Near distance of UN damage points to SAR damage polygons

Near Distance (Meters) of UN Points to SAR Damage Polygon	Percentage of Total UN Damage Points Within SAR Damage Polygon
0	37%
5	54%
10	67%
20	85%
30	94%

Results suggest SAR imagery can offer damage detection from true locations within a reasonable distance. Since the UN OHCHR reports most of civilian casualties were caused by heavy artillery shelling, rockets, and missile and air strikes, this project assumes a reasonable damage radius from such weapons up to 30 meters (UN OHCHR 2023a). Figure 35 displays results from Near Distance analysis.

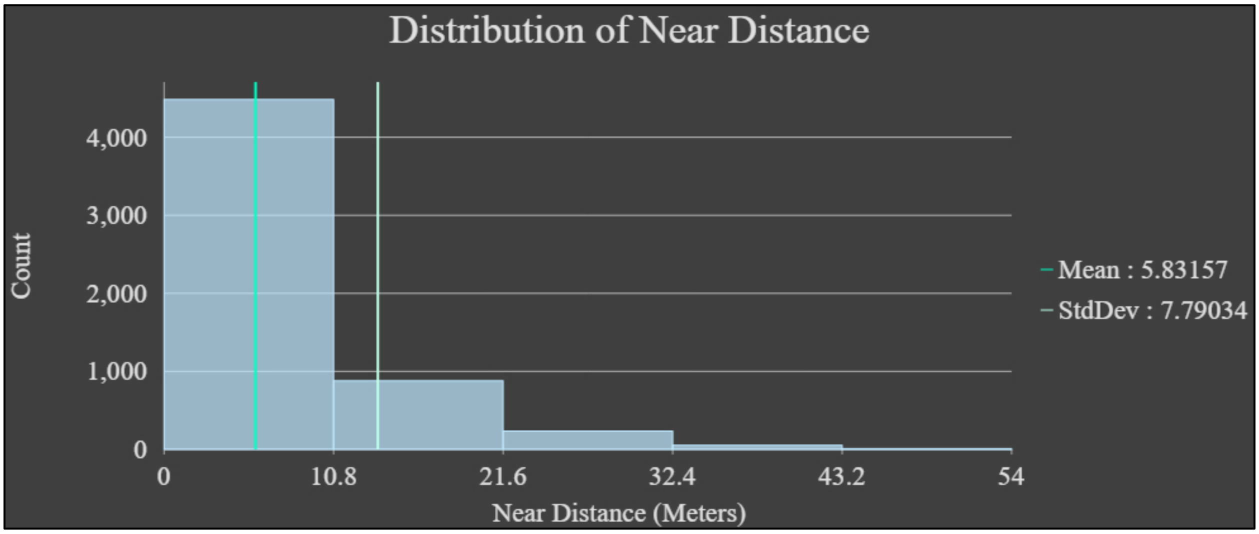

Figure 35. Distribution of near distance

79% of UN damage points were located within 10.8 meters of the nearest SAR polygon. Results suggest UN damage points are reasonably distanced from corresponding damage pixels from SAR analysis. These results complement Table 6.

4.2.3 Near Angle

Near angle results of UN damage points to SAR damage polygons appear randomly distributed throughout the AOI, suggesting no correlation between near angles of UN damage points to SAR polygons and location (Figure 36).

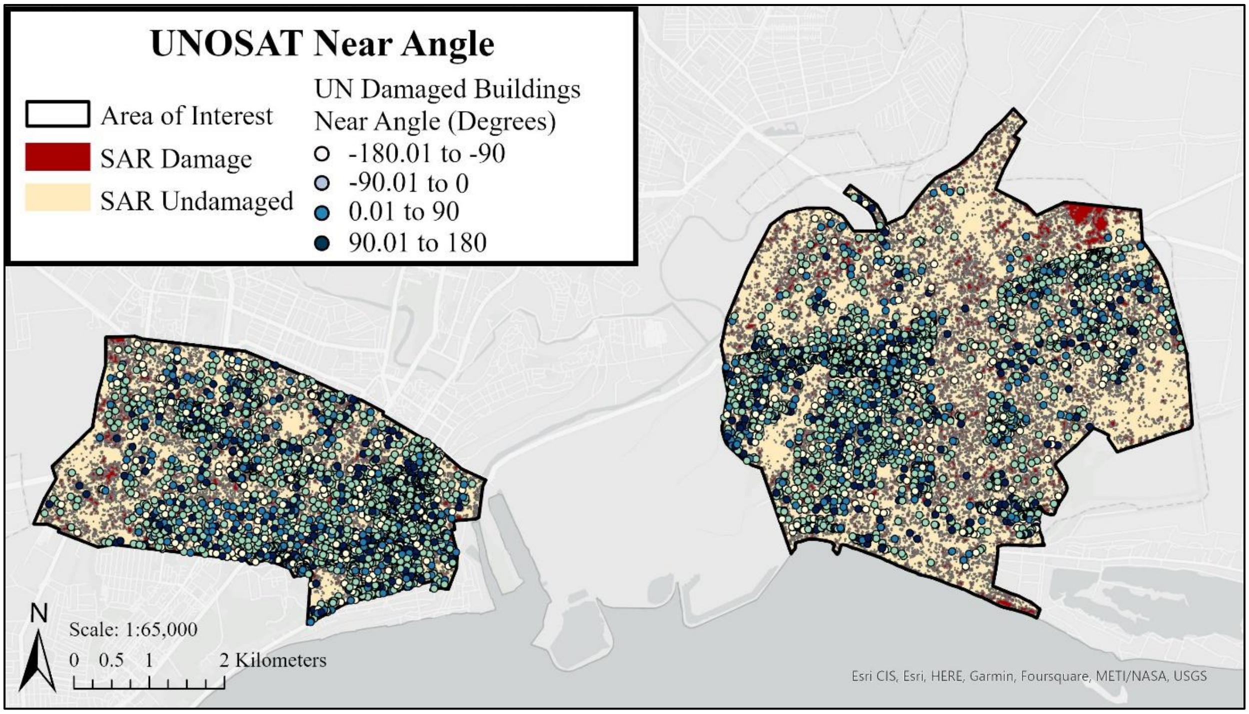

Figure 36. Near angle of UN damage points to SAR polygons

Most UN damage points have a near angle to a SAR damage polygon between -90 to 0 degrees, in the southeast direction (Figure 37).

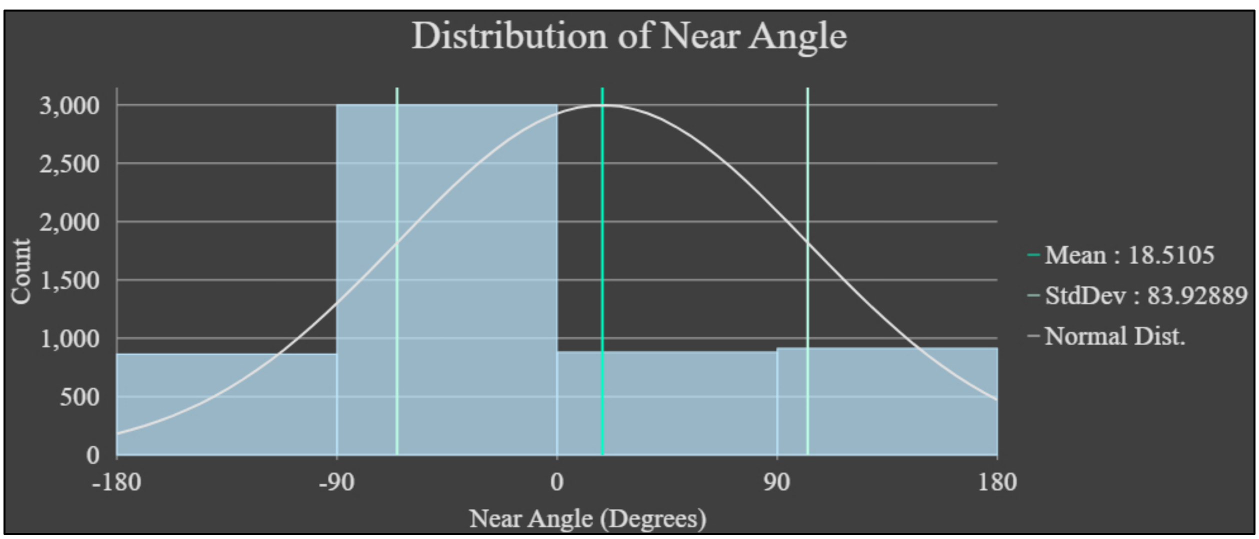

Figure 37. Distribution of near angle

One possible explanation for this distribution is the incidence angle of the acquired imagery, which is the angle between the radar sensor and a line perpendicular to the surface (Marghany 2020). Another factor could be building orientation which could affect the backscatter intensity.

Chapter 5 Discussion

The goal of this study was to assess the effectiveness of using medium-resolution publicly available SAR imagery in place of expensive high-resolution optical imagery for human rights violations monitoring purposes. Chapter 5 addresses the limitations and challenges of this project and provides suggestions for future research.

5.1 Limitations and Challenges

Limitations of this project affect assessment accuracy and present implications for human rights researchers. The following section describes limitations that create challenges for conducting analysis using Sentinel-1 and UNOSAT data.

5.1.1 Sentinel-1

Coarse spatial resolution is a significant limitation of the Sentinel-1 SAR imagery used in this study. Since 10 m resolution cannot identify individual building damages, determination of degree of damage (possible, moderate, severe, destroyed) is not possible with medium-resolution SAR imagery. This may be a limiting factor for human rights researchers aiming to identify specific degree of damage. Coarse resolution may affect accuracy of assessment since multiple pixels can represent damage spanning multiple buildings. Figure 38 shows an example of SAR damage pixels covering partial or multiple buildings for a sample area in Mariupol adjacent to the Mariupol drama theatre. Damage pixels result from analysis using images on February 16, 2022 and May 23, 2022.

Figure 38. SAR damage pixels overlaying ground features in Zhovtnevyi District

SAR pixels in Figure 38 illustrate the challenge of attributing SAR damage to individual buildings. Moreover, SAR damage pixels do not exclusively represent building damage. Pixels may represent any disturbance to ground surfaces, including roads, fields, and other infrastructure. Human rights researchers using medium-resolution SAR imagery must be aware of this limitation and subsequent challenges.

The Raster to Polygon method presents accuracy challenges affecting False Positive and False Negative conclusions. A False Positive is defined as a SAR damage polygon that does not contain a UNOSAT damage point, and a False Negative is defined as undamaged SAR area that contains a UNOSAT damage point (Qian et al. 2020). When investigating individual events such as the devastating attack on the Mariupol drama theatre (Hinnant and Chernov 2022a), researchers must be aware that damage to a single point of interest may be represented by multiple damage polygons rather than a single point. Since a SAR damage polygon may cover multiple buildings or represent multiple types of damages, researchers may be challenged with determining how to attribute damages to single locations of interest. Figure 39 demonstrates this challenge with the Mariupol drama theatre. Damage pixels result from analysis using images on March 12,2022 and March 24, 2022.

Figure 39. SAR damage polygons and UNOSAT damage points over Mariupol drama theatre

The infamous attack on the drama theatre is an example of an indiscriminate and disproportionate attack which violates international humanitarian law (UN 2023a). Several separate SAR damage pixels cover the drama theatre in Figure 39. However, the UNOSAT damage point representing the drama theatre occurs near, but not within, a SAR damage polygon. A possible explanation is that debris or rubble resulting from the theatre attack dispersed radar signals and affected backscatter intensity, resulting in multiple detected damage pixels over the same building and vicinity (van Heyningen 2018). Although the SAR damage polygons do not contain UNOSAT damage points, suggesting multiple False Positives, UNOSAT data included only one damage point representing associated drama theatre damage. Researchers must be aware of the Raster to Polygon tool limitation when evaluating results and comparing with other data derived from VHR optical imagery.

Temporal resolution is another limitation of this study. While 12 days may be sufficient for monitoring general activity, it may not be sufficient for international criminal courts requiring assurance with high quality evidence. Frequent revisit rates within a 24-hour period, or within 1-2 days may be necessary depending on the application.

Despite these limitations and challenges, coarse resolution may offer sufficient information for researchers aiming to track trends or identify potential violation areas and prompt investigation using higher fidelity satellite imagery. Coarse results are sufficient for human rights researchers seeking timely results during active conflict. Thus, medium-resolution SAR imagery may still be desirable for some human rights practitioners due to accessibility, sufficient accuracy, low cost, and simplicity. Satellite imagery alone is not sufficient to prove war crimes or crimes against humanity in international tribunals (Hazan 2017; Kroker 2015). However, results of this project encourage continued research to advance SAR imagery that will compliment non-imagery evidence presented in international criminal courts.

5.1.2 UNOSAT

Limitations of UNOSAT data used in this study include lack of verification, potential geolocation errors, and different imagery dates. While this project uses UNOSAT's data to validate the SAR damage assessment, UNOSAT damage assessment has not been verified in the field due to unsafe conflict zones making it impossible for in-person confirmation of infrastructure damage. A key assumption of this project is that UNOSAT's data is accurate based on increased spatial resolution of optical images used.

Geolocation errors may potentially affect analysis in this research. UNOSAT provided geolocated point data derived from VHR optical images but did not specify geolocation methodology. Depending on the base map used, UNOSAT data might not always exactly match buildings or SAR damage polygons in this analysis. Even minor errors could result in unmatched UNOSAT damage points within SAR damage polygons. Figure 40 illustrates position of UNOSAT damage points in relation to SAR damage pixels.

Figure 40. UN damage point representing Mariupol Drama Theatre

Using multiple distances for the near tool analysis described in Chapter 3 addresses possible geolocation errors. For example, an expanded radius of 30 meters results in 94% of UNOSAT damage points within SAR damage pixels (polygons). Since manual inspection and judgement of matching UNOSAT data points with SAR damage is impractical over large areas, the near tool offers practical analysis with geolocation errors in mind.

While the majority of UNOSAT damage points classify building damage, data also includes non-building damage, such as roads and fields. Less than 1% of UNOSAT building point data includes non-building damage (17 out of 5,5660 points). This study did not filter out other infrastructure since SAR damage pixels also include non-building damage. Future analysis could consider including this distinction in analysis.

Another limitation is a non-exact comparison of different imagery dates from Sentinel-1 and UNOSAT's WorldView-3 and WorldView-2 imagery. UNOSAT's assessment used pre-conflict imagery from June 21, 2021, whereas the first pre-conflict SAR image used for this project was from February 16, 2022. The last image used for UNOSAT's analysis was from May 12, 2022, whereas the last SAR post-conflict image used was from May 23, 2022. Although UNOSAT and SAR analysis used different images acquired on different dates, these images are considered adequate for this study.

5.2 Future Research

Future research can improve accuracy of SAR damage assessments and refine remote sensing analysis methods for human rights practitioners. Two recommended research areas are backscatter intensity threshold selection and imagery analysis tools.

5.2.1 Backscatter Intensity Threshold Selection

One area of future research to improve accuracy of SAR damage assessment is an evaluation of True Positive, False Positive, True Negative, and False Negative rates. Comparing SAR damage with UNOSAT damage results in these values. In another study looking at Russia's war-induced damage conducted by Aimaiti et al. (2020), researchers calculated the precision, recall, and F1 score values under different threshold values for a backscatter intensity change image. Precision is the true positive divided by all that was classified as positive; recall is the true positive divided by all actual positives, and F1 score is the harmonic average of precision and recall (Aimaiti et al. 2020). A method incorporating this approach could refine the approach used in this project and potentially refine damage detection accuracy.

5.2.2 Alternative Analysis Tools

This study used the ASF Vertex portal and ArcGIS Pro as the primary imagery data source and analysis tool. Another imagery data source option is ESA's Copernicus Open Access Hub, which offers freely accessible Sentinel-1 SAR imagery with the creation of an account. ESA also offers freely available SNAP software. Aimaiti et. al. (2020) successfully conducted change detection using SNAP software as an alternative to ArcGIS Pro. Data and software access are key limiting factors for human rights practitioners and the specific restraints of researchers should be considered when selecting data sources and software applications.

Future projects could also reframe data incorporated from multiple disciplines to enhance MARS research. Reframing data from a human security perspective could offer additional insights by fusing imagery with geospatial data, social media information, and witness testimony. Multi-source analysis is critical for advancing the MARS field and developing new methods for human rights researchers.

5.3 Conclusion

This project achieved its objective by assessing the feasibility of using medium-resolution SAR imagery in place of expensive VHR optical imagery to detect war-induced infrastructure damage. Mean damage percentage was assessed every 12 days from the beginning of Russia's invasion to the seizure of Mariupol and results indicated a general increase in damage as the conflict continued. Results indicate that time of day, weather, and cloud cover did not affect imagery used in this workflow and highlights the practical benefit for human rights practitioners. A cumulative SAR damage assessment underestimated total damage compared to a UNOSAT VHR optical imagery damage assessment. SAR analysis estimated 27% cumulative damage while UNOSAT estimated 32% damage. Analysis of total UN damage points occurring in SAR damage polygons showed low accuracy, but improved significantly with an expanded damage radius of 30 m. Furthermore, damage results were consistent with open-source reports of attacks and violations, including those from media, independent researchers, and the UN. These coherent results from multiple sources reveal how the human rights community can use SAR imagery to uncover violations and promote accountability.

Despite the lower fidelity SAR estimates, damages were spatiotemporally consistent with UNOSAT data. Further inspection also shows challenges with comparing different spatial resolutions as data points do not always align with SAR damage pixels representative of the same damage. Future studies can investigate methods to improve backscatter intensity threshold and damage classification. While medium-resolution SAR imagery underestimates total damage, it may still offer critical insights to human rights practitioners who must set aside precision in favor of timely assessment for wartime conditions.

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