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Short Paper
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Assessment of Building Damage in Raqqa during the Syrian Civil War Using Time-Series of Radar Satellite Imagery

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Abstract

Change detection is one of the key tasks of earth observation. In the humanitarian domain, information about the impacts of natural disasters or military conflicts are of particular interest. This study uses time-series of Sentinel-1 radar imagery to identify changes resulting from armed combats in the city of Raqqa, Syria. The concept of permanent scatterers (PS) was applied to the data for the identification of stable information, which is then used for temporal analysis of pixel amplitudes. In an urban context, this gives insights into both the locations of damage and the exact date of the destruction. Instances of damage manually identified by UNOSAT are used for validation. The study shows that Sentinel-1 data can be a suitable indicator for heavy damage, but limitations arise from the comparably low spatial resolution and in cases of moderate changes which do not affect the structure of buildings. The study demonstrates the potential of radar imagery regarding its spatial and temporal resolution and gives examples of detailed analyses at selected areas of special interest.

Keywords:

damage assessment, Synthetic Aperture Radar (SAR), change detection, civil war, time-series analysis

1 Introduction

Remote sensing has proven to be a valuable source of information for the mapping of natural hazards and disasters (Joyce et al., 2009). Applications include the aftermath of single events, such as floods (Klemas, 2015), landslides (Scaioni et al., 2014) or earthquakes (Tronin, 2006), and the long-term monitoring of continuous phenomena, such as tectonic or geomorphologic movement (Alvan & Azad, 2011), air pollution (Martin, 2008) or ecosystem degradation (Xie et al., 2008)

The possibility of accessing large image archives is especially helpful for the assessment of changes over long time periods. In this context, the temporal resolution of a sensor can become more important than its spatial resolution, because it allows both the clear identification of the date of occurrence of an event and the detailed monitoring of subtle changes (Lazecky et al., 2017; Gernhardt & Bamler, 2012)

Earth observation (EO) using multi-spectral imagery is often constrained by cloud cover and shadows (Wulder et al., 2008; Giles, 2001; Pearce, 1985). This becomes a problem for time-critical applications which rely on immediate access to images, as during emergency responses (Boccardo & Giulio Tonolo, 2015; Joyce et al., 2010). Furthermore, operational services strongly rely on data that do not risk being affected by cloud cover (Moser et al., 2017).

As a part of earth observation which is more independent of cloud cover, data from spaceborne synthetic aperture radar (SAR) have been established in the field of remote sensing applications since the 1990s. Because of the long wavelengths of the signals, they are highly capable of penetrating clouds and can also operate at night (Ulaby et al., 1982). In addition, active microwaves image different characteristics of the earth's surface, such as texture, shape, orientation, material or roughness of surfaces, from optical sensors. For these reasons, SAR remote sensing is highly suitable for applications in disaster mapping, emergency response or, more generally, in the humanitarian domain, as demonstrated in numerous studies (Braun & Hochschild, 2017; Braun et al., 2016; Plank et al., 2016; Amitrano et al., 2013; Sato et al., 2008; Boni et al., 2007; Brekke & Solberg, 2005; Wiesmann et al., 2004; Brakenridge et al., 2003; Wegmuller et al., 2002; Yonezawa & Takeuchi, 2001; Lu et al., 1997).

Thanks to the availability of archived data, change detection based on multiple images taken at short intervals can be performed. While for a long time this was restricted to high-resolution optical imagery, the permanent scatterer (PS) technique allows the investigation of targets over a given period using high-resolution SAR data based on the analysis of the amplitude and phase of the signal (Prati et al., 2010; Perissin & Ferretti, 2007; Ferretti et al., 2001). This study demonstrates whether and how Sentinel-1 data can be used for damage assessment in urban areas affected by civil war.

2 Study area and data

Raqqa

Raqqa (or Ar-Raqqa) is a city in northern Syria with a population of around 220,000 (2004 census). It is located on the northeastern bank of the Euphrates and has a spatial extent of around 10 km in the east–west direction by 4 km in the north–south direction (Figure 1). Its surroundings are dominated by wheat and cotton cultivation; the climate is semi-arid.

Due to its strategic location in the north of the country, it was the first Syrian provincial capital to fall out of government control, starting with an occupation by rebels in March 2013 (Aljazeera, 2013). Since that time, the city and its population have been subject to various occupations and heavy battles, leading to the death of numerous civilians, and enormous damage to buildings and infrastructure. It was finally declared liberated in October

2017, but by that date, nearly 90 % of the city had been levelled due to heavy bombardments (Malsin, 2017).

As seen in Figure 1, the city is bound by two main roads in the north and west and the Euphrates in the south. Urban roads and blocks, which are influenced by Iranian architecture, are arranged in a grid-like pattern whose centre is the former Great Mosque (Hillenbrand, 1985)

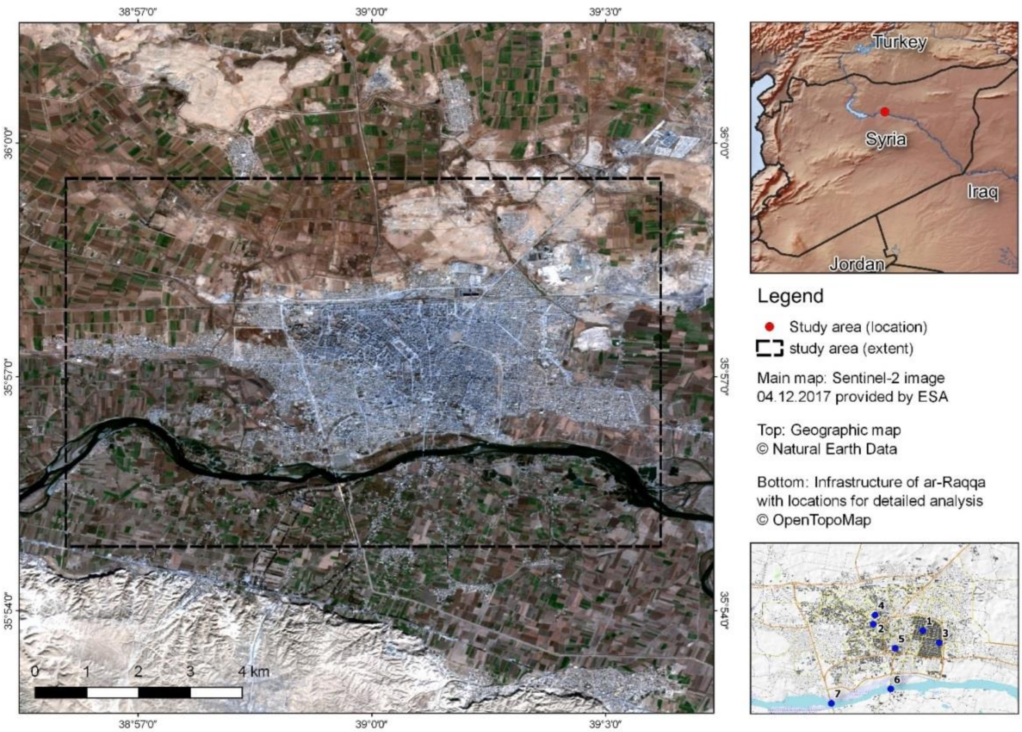

Figure 1: Location and structure of the study area. The numbers on the smaller map (bottom right) indicate the locations for the detailed analysis in section 4.3.

Sentinel-1

Thanks to the continuous acquisition of C-band radar imagery and its provision via the Copernicus programme (Panetti et al., 2014), a total of 55 Sentinel-1 images taken between 10/2014 and 12/2017 were available for this study. Different intervals between the images were chosen in order to cover the largest time span possible while simultaneously keeping processing efforts low. As Figure 2 shows, intervals of 12 days were chosen for the first five months (December 2014 to April 2015) and for the whole of 2017; for the period in between, intervals of 48 days were used. This ensures that changes with high significance can be identified. Important dates, such as changes in occupation and those of military offensives, are also marked on the graph. Unfortunately, the Sentinel-1 mission only started in October 2014, so the time before the Syrian civil war and Raqqa's occupation by IS in

March 2013 could not be analysed. But it is estimated that most of the heavy damage has been caused since 2014 (Hassan, 2017).

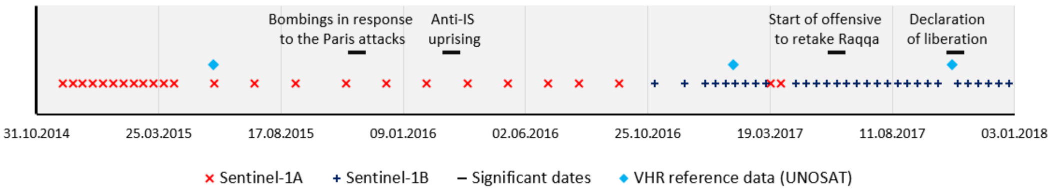

Figure 2: Temporal distribution of Sentinel-1 data used in this study

Reference data

For validation, a dataset available publicly from the UNOSAT programme of the United Nations Institute for Training and Research (UNITAR, 2017) was used. It consists of a total of 13,160 points of manually digitized damaged structures. These are based on the visual interpretation of five very high resolution (VHR) satellite images, of which three date from the period analysed. As Table 1 shows, most of the damage was detected between 03.02.2017 and 21.10.2017. This results both from the slightly higher resolution of 30 cm and from the fact that most of the damage was caused by the intensified battles for Raqqa after May 2017 (Hassan, 2017).

Table 1: Optical imagery of UNOSAT

Sensor (spatial resolution)	date of image acquisition	number of newly identified points
WorldView-1 (50 cm)	22.10.2013	340
WorldView-2 (50 cm)	12.02.2014	124
Pléiades (50 cm)	29.05.2015*	1,104
WorldView-2 (50 cm)	03.02.2017*	250
WorldView-3 (30 cm)	21.10.2017*	11,342

*=used for this study

Table 2 shows the UNOSAT damage assessment for the last period in greater detail. It breaks all changes down into their degree of confidence. This helps to ascertain the suitability of these data as a reference in this study, in particular because they were all digitized manually and never validated in the field. Around 50% of the damage was identified with a ‘very high’ level of confidence. A total of 2,576 structures were labelled as ‘destroyed’; these account for 20% of all identified damage. Most uncertainties occur for structures that have suffered moderate damage, because the buildings are still present, but shadows or other patterns indicate that something has changed. Impact craters in roads or open fields are also identified in the dataset, but they are not considered in this study. 'No change' in this context means that the structure was already identified as damaged in an earlier image, but no further change has occurred since. The table shows that only a small fraction of the data was labelled as 'uncertain'. Yet, the severity of the damage and the total number of destroyed structures should not be taken as the ultimate truth but rather help to validate the results of this study in terms of plausibility and matching spatial patterns.

Table 2: Damage identified by UNOSAT between 03.02.2017 and 21.10.2017, modified from UNITAR (2017)

		Damage confidence			
		uncertain	**medium**	**very high**	sum
Type of damage	**no change**	14	102	1	**117**
	impact crater	0	27	235	**262**
	moderate damage	353	5,117	23	**5,493**
	severe damage	0	293	3,669	**3,962**
	destroyed	0	750	2,576	**3,326**
	sum	**367**	**6,289**	**6,504**	**13,160**

3 Methods

Pre-processing

Sentinel-1 data were acquired in Interferometric Wide Swath (IW) mode and provided as SLC products, which include complex pixel information as well as rasters in slant geometry. Subsets of the study area (see Figure 1) were extracted and all images were co-registered to a single stack (mean RMSE for all pairs: 0.1320 mean; standard deviation: 0.0784). All data was processed in the Sarproz software (Perissin, 2018).

Analysis

The main advantage of a stack consisting of multiple SAR images is that it allows the identification of pixels which show a stable sequence of amplitude values (the measured backscatter) throughout the whole period investigated. The position of these stable targets, also called permanent or persistent scatterers (PS), can be determined with sub-pixel accuracy; their elevation can also be determined (Ferretti et al., 2001). The scattering mechanisms, identified as a function of normal baseline and Doppler centroid, can then be used to investigate changes in the targets along a timeline (Ferretti et al., 2005). In an urban context, radar amplitudes of built-up structures are enhanced due to corner reflection (Lee, 2001), and by building materials (Henderson & Xia, 1997) and orientation towards the sensor (Ferro et al., 2011). These factors help to determine the presence or absence of buildings.

Employing Gaussian algorithms to the temporal profile of an amplitude time-series allows the identification of the ‘life time’ of pixels and their underlying objects, especially their changepoints (Chambers et al., 1996). We use this to identify changes in built-up structures, most probably caused by armed conflicts.

In order to reduce the number of pixels of interest, a polygon covering the city’s extent was used as a mask, leaving the permanent scatterers over the built-up area (n = 46,472). Figure 3 shows the mean image of all S1 images (left) and the identified permanent scatterers (right). The colours indicate the stability of each PS, which was calculated based on the mean and standard deviation of all amplitude values of a pixel (Lei et al., 2013). As expected, most of them are stable during the whole period (values > 0.5), which means that no distinctive change is expected at this location. However, there are also many points which are not stable during this period, as indicated by the yellow and blue colours. These will be investigated below.

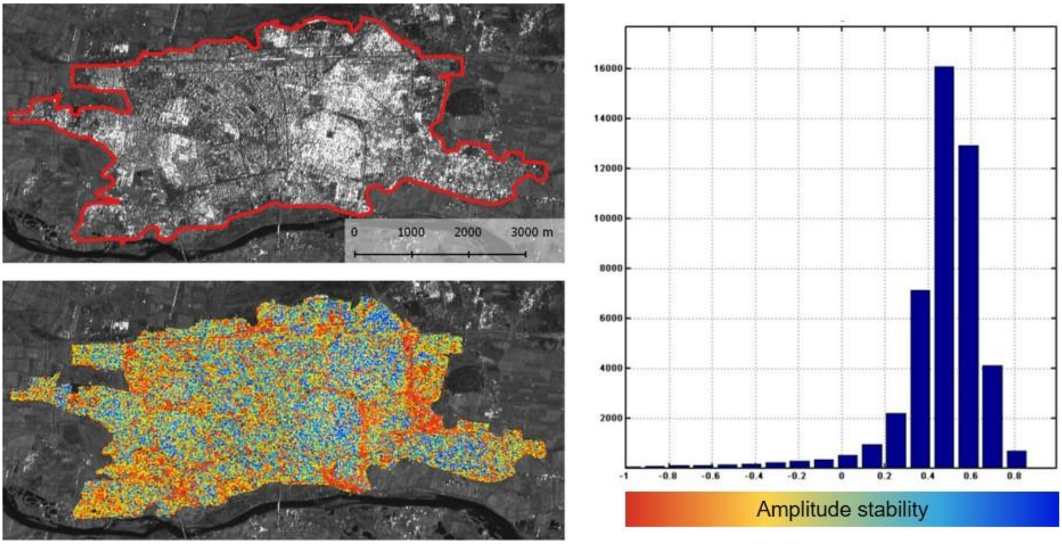

Figure 3: Mean amplitude image (top left), selected permanent scatterers (bottom left) and histogram of amplitude stability (right).

4 Results

Temporal changes

In the first step, PSs with a limited life-time were identified – that is, those which show a significant decrease of backscatter between two observations, which persists until the end of the period investigated (Perissin et al., 2006). A total of 3,334 PSs with a limited life-time were identified. They were plotted against the number of instances of damage derived by UNOSAT, as demonstrated in Figure 4. While there is a strong underestimation of changes of uncertain, middle and high confidence and of moderate and severe damage (see Table 2), the number of instances of severe damage (dark blue) strongly correlates with the number of PSs identified, which show a significant decrease over the period investigated. Later analyses show that not all of them are necessarily at the same location, but these findings indicate that Sentinel-1 data constitute a highly suitable temporal indicator for severe damage in urban areas. However, the discrepancy between roughly 2,900 destructions detected by Sentinel-1 and the total estimates of 11,300 made by UNOSAT shows the limits of radar data at this resolution: more subtle damage to buildings, such as cracked walls or partly collapsed roofs, are hardly detectable by PS techniques because their overall amplitude doesn't change significantly. Additionally, changes in colour, for example caused by fire or dust, are not detected by microwaves of this wavelength. A detailed discussion on the difficulties is given in section 5.

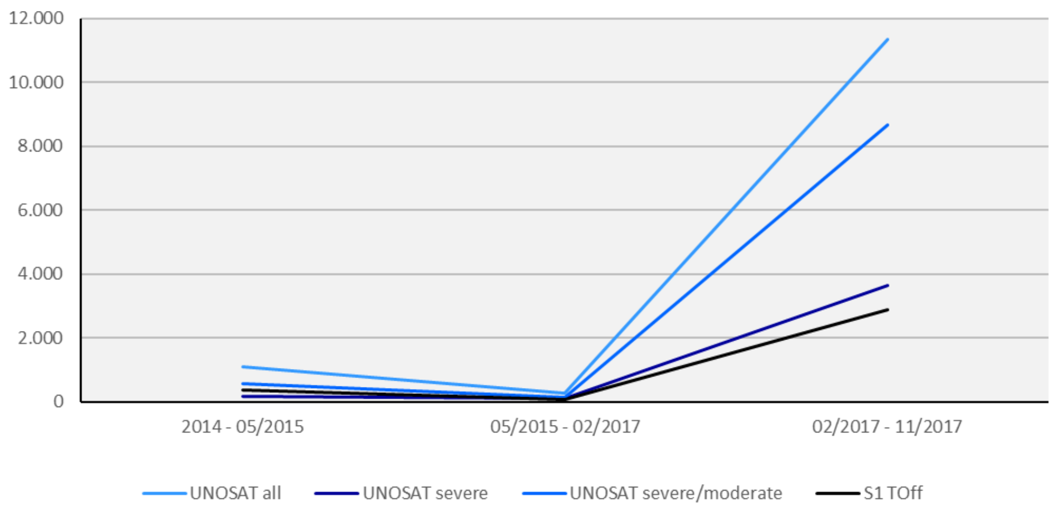

Figure 4: Number of changes identified by UNOSAT validation data (blue) and Sentinel-1 (black).

Spatial changes

Figure 5 shows the overall changes detected in the Sentinel-1 images (A) compared with the destroyed structures identified by UNOSAT (B). The results in map A are displayed as the sum of all changes in backscatter amplitude based on an image-by-image comparison over the period investigated. The results in map B were derived using a kernel density analysis (radius 150 metres) of points which were labelled as destruction of medium or very high confidence (see Table 2). The comparison shows that there is considerable agreement between the automatically derived changes and the manually identified damage, especially in the eastern part of the city. Mismatches can be observed in the north of the urban area, where the radar analysis did not detect large-scale damage. Additionally, in the UNOSAT data, damage is seen to gradually decrease towards the outskirts of the city. The reasons for the differences are discussed in section 5.

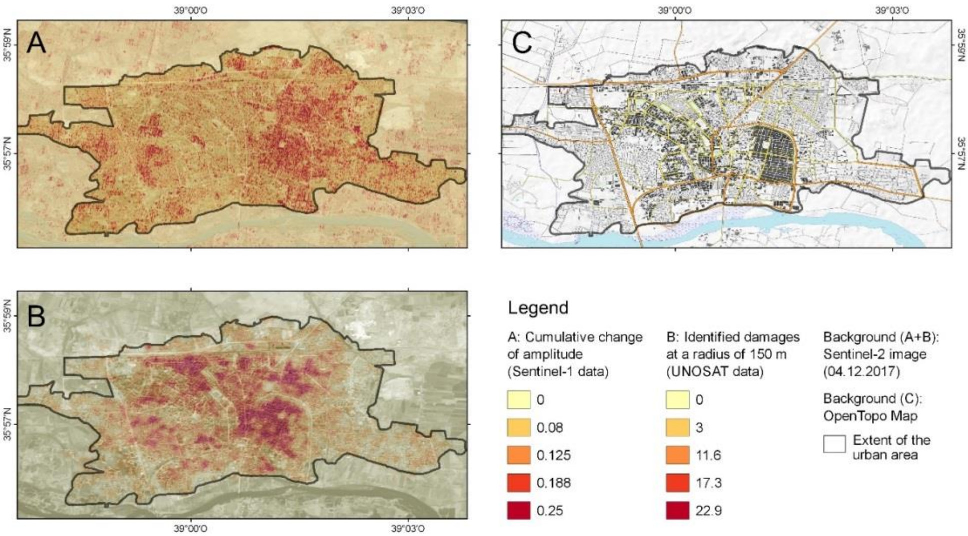

Figure 5: Overall changes identified by Sentinel-1 (A) and UNOSAT (B) in Raqqa during the period investigated.

Changes at points of interest

To demonstrate the potential of PS analyses for urban damage detection, seven sites were selected (see numbers in Figure 1, bottom right): two of the largest mosques in Raqqa (The Great Mosque [1] , and Al Firdous Mosque [2]), which were occupied during the civil war (Weinstein, 2017); the ancient ruins of Qasr al-Banat [3], where heavy combat took place (Perry & Lawrence, 2017); the stadium [4], the basements of which were used as headquarters and jails (Walsh, 2017); the former IS command centre [5] (Walsh et al., 2017); two bridges [6-7] across the Euphrates in the south of the city. Life-times of PSs were analysed as well as their amplitude over the period studied to retrieve information on the location and date of potential damage.

Significant buildings

Analyses of both amplitude stability and life-time of pixels showed that no significant changes were detectable to the Al Firdous Mosque and the ruins of Qasr al-Banat, probably because the latter is already in a state of ruin, with generally low backscatter. The Great Mosque in the eastern part of the city, however, showed some indications of damage, as demonstrated in Figure 6. The large points indicate all PSs with a calculated end-date before 2018. Their amplitude stability is indicated in blue. After manual inspection, many of them were rejected because their amplitude values did not show a clear temporal pattern. The point marked in red is a good example of probable damage because of the clear decrease in amplitude (also called 'off-date'). The time-series graph (Figure 6, bottom right) shows that, based on the statistics of all 55 images, a significant change happened in July 2017 when the amplitude clearly decreased at the corner of the southern wall. This indicates that some of the massive minarets or walls collapsed. These findings coincide temporally with the second battle for Raqqa, from May to October 2017, during which the Great Mosque was reported to have been recaptured by US forces in September 2017 (Weinstein, 2017). This location was also labelled in the UNOSAT data as having been damaged, but before May 2015. We offer as a tentative explanation that the first damage was visually detectable in 2015, but the collapse of this structure occurred later.

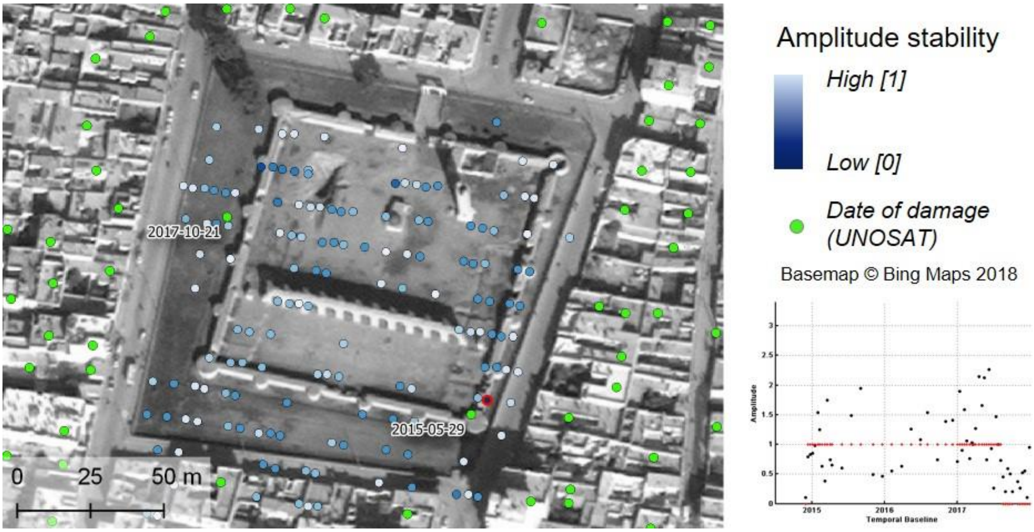

Figure 6: Amplitude stability of PS at the Great Mosque of Raqqa. The amplitude series of the location is marked in red, bottom right. The damage identified in the UNOSAT data is indicated in green, with selected dates. Note that the basemap image was taken before the civil war.

Military infrastructure

Figure 7: Off-dates of PS around the Raqqa stadium (left), and drone footage of CNN (right). Note that the basemap image was taken before the civil war and shows the stadium from a different orientation.

Figure 7 shows selected PSs around the Raqqa stadium. While the IS command centre did not show any damage during the period investigated, the stadium has a clear concentration of damage detected by Sentinel-1 imagery, along the roof of the grandstand. The colours indicate the date from when the backscattering within a pixel no longer occurred as a function of time. While the surroundings of the stadium were clearly affected at later times, the grandstand was apparently destroyed between November 2015 and May 2016. During that time, the city was under heavy fire as consequences of the Paris attacks and of an uprising against the occupation within the city (Abou Fadel, 2016). These findings are supported by drone footage released by CNN in late 2017 (Fox & Munayyer, 2017). Notably, UNOSAT data did not include damage to the stadium.

Bridges

Of the two bridges in the south of Raqqa, the 'Old bridge' in the east shows considerable damage. Figure 8 shows that there are generally few PSs with Off-dates during the period studied, and many of them can be excluded because they are over the river itself and do not characterize the reflectance of the bridge. However, there are four PSs in the middle part of the bridge (shown in green, two of them highlighted by a red frame) which indicate clear damage in May and August 2017. Their amplitudes show a significant decrease compared to the many stable PSs on the bridge (exemplified by the yellow-framed circle). Due to the location of the bridge outside the city, it was not part of the UNOSAT analysis, but destruction of the bridge was later confirmed by aerial footage (Walsh et al., 2017).

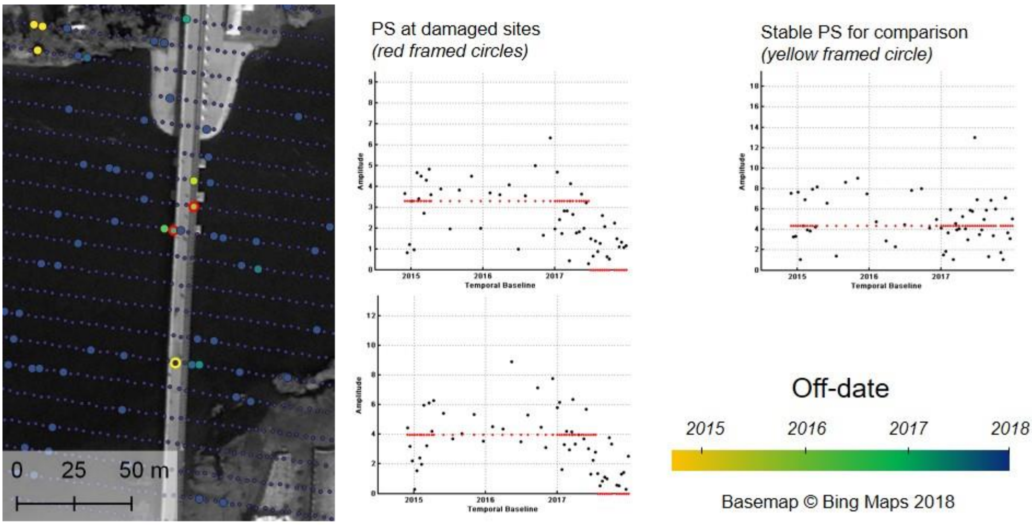

Figure 8: Off-dates of PSs at the Old Bridge in the southeast and amplitude time-series for selected points. Note that the basemap image was taken before the civil war.

5 Discussion and outlook

This study has demonstrated how freely available Sentinel-1 data can be used to detect changes along time-series. Many established approaches in change detection are based on optical imagery or commercial SAR satellite sensors like TerraSAR-X or Cosmo SkyMed, which provide images at the metre scale and below. However, in our case, the high temporal resolution was found to compensate partly for the moderate spatial resolution of Sentinel-1 data. The data provided suitable indicators for damage within urban areas due to the high backscatter of built-up structures. However, there are some points to discuss.

As Figure 4 demonstrates, SAR data of this resolution cannot compete with the visual inspection of VHR imagery, especially when there is only light damage, such as cracks in roofs or limited missing parts of buildings which are otherwise intact.

However, these differences do not result just from the lower spatial resolution. It has to be kept in mind that optical sensors and radar satellites capture completely different features: while WorldView and Pléiades, used by UNOSAT, depend on the spectral diversity of surfaces, the microwaves of Sentinel-1 interact with the shape, size, orientation and material of objects. If none of these properties change in the case of a damaged building, there is no possibility of capturing any damage (Karimzadeh et al., 2017; Matsuoka & Yamazaki, 2004). Of course, there are SAR-based approaches which utilize interferometric phase to obtain information about surface deformation (Hooper, 2008), or even changes at the building level (Gernhardt & Bamler, 2012), but they all rely on either data of higher resolution or a-priori knowledge of the expected change (Fornaro et al., 2011).

Another point to bear in mind is the absence or reduced availability of persistent scatterers in urban areas that have lower building density or use light construction materials. As indicated in Figure 5, quarters with lower reflectivity are likely to be structurally excluded from the PS analysis. This can be partly solved by applying small baseline (SBAS) interferometry approaches, which are less dependent on strong scatterers (Ardizzone et al., 2012).

Regarding the time-series analysis, it should be noted that damage to a building does not necessarily mean an abrupt decrease of the amplitude to a level of zero. If an object only changes its height or orientation, there might just be lowered backscatter response (Ferro et al., 2011; Gernhardt et al., 2010).

The advantages of SAR-based approaches are obvious. The time required to extract areas of change is probably a fraction of that spent on manual interpretation or comparison of pre- and post-images. The high costs of commercial imagery might also be a determining factor for NGOs, which aim for cost-effective approaches. Lastly, manual analysis also carries the risk of misinterpretation or lack of objectivity (Yamazaki et al., 2005).

Since there are large numbers of studies demonstrating (semi-)automatic damage assessment based on VHR imagery of satellites (Tiede et al., 2011; Schöpfer et al., 2007) or UAVs (Fernandez Galarreta et al., 2015), one possible approach could be an integration of both optical and radar data for damage assessment. In the humanitarian domain, fusion methods have been used successfully to assess earthquake damage (Brunner et al., 2010) and landslides

(Plank et al., 2016), and for urban mapping (Aravena Pelizari et al., 2018; Corbane et al., 2008).

Sentinel-1 imagery provides excellent image archives and freely available data, which increases the chance that pre-event data is available. However, its applicability in disaster mapping is constrained by the fact that there is not much time in cases of emergency. As shown in this study, at least two post-event images are required to automatically detect significant changes based on well-founded statistics. Concerning revisit rates, these would be once a month or less frequently, depending on the availability of both Sentinel-1 A and B data. However, human catastrophes require much shorter response times. Upcoming Sentinel-1 C and D missions could reduce this time to a more acceptable length.

On the other hand, we see a high demand for operational SAR sensors which regularly capture images of medium extent at spatial resolutions of around 5 metres. Images at that resolution are currently not taken at regular intervals, but they would certainly improve many applications in the humanitarian domain, because they allow an acceptable compromise between spatial coverage and temporal detail. If technological advancements continue as currently observed, this seems realistic in the medium-term. Until then, scientific institutions and organizations must continue to collaborate in developing further use-cases applications and services to assist the work of humanitarian operations.

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