Mapping Tsunami Impact in Nanggroe Aceh Darussalam, Indonesia, Using RADARSAT-1

Syam, R.[†], Jayadi[†], Dean, A.M.[‡], Tri Sasongko Adi, B.[†], Taylor, G.[‡], Bruce, G.S.[‡], and Boivin, T.B[‡*].

[‡]Hatfield Consultants Ltd., Suite 201-1571 Bellevue Avenue, West Vancouver, BC, Canada

[†]PT Hatfindo Prima, Jl. Bango No. 2-4,Tanah Sareal, Bogor 16161, Indonesia

[*]Corresponding author email: tboivin@hatfieldgroup.com

Abstract

In response to the December 26th 2004 tsunami in the Indian Ocean, activation of the Charter resulted in acquisition of numerous Standard Mode RADARSAT-1 images over affected areas of Indonesia, Sri Lanka, India, Myanmar, and Thailand between December 26th and 31st December, 2004. In addition, a number of archive RADARSAT-1 images were made available. Under the Disasters Charter (www.disasterscharter.org), RADARSAT-1 imagery has been acquired numerous times in support of disaster mitigation and monitoring activities related to storms and flooding, and has clearly proven its usefulness to detect flooded land surfaces.

Through the Canadian Space Agency (CSA), 10 additional RADARSAT -1 Fine and Standard Mode RADARSAT-1 images were acquired over coastal areas of Sumatra, Indonesia. RADARSAT-1 Standard Mode data (25 m resolution) were used to investigate tsunami impacts for the northern coast of Sumatra and Nias and Simeulue islands, whereas RADARSAT-1 Fine Mode data provided fine detail imagery (9 m resolution) for detection of tsunami impacts around Aceh City. The ability of radar to penetrate clouds is a significant operational advantage over visible and near-infrared (V-NIR) imagery in tropical regions, although a number high to medium resolution V-NIR were acquired during and immediately following the tsunami. A comparison of composite RADARSAT-1 images before and after the tsunami with available V-NIR imagery provided a clear demonstration that RADARSAT-1 was effective at mapping tsunami impacts along the coast, including damage to agricultural land and aquaculture infrastructure. Recovery efforts for the impacted region would benefit from ongoing image acquisitions in order to monitor vegetation and agricultural land recovery and changes in land use.

Comment [AD1]: Pak – do we know the number? If not, "numerous" is OK

Comment [AD2]: Pak – How many new CEOS format RADARSAT images did we receive in total, including the new ones?

I. Introduction

Synthetic aperture radar (SAR) satellites provide a reliable source of data that are well suited for time sensitive applications including support for disaster management and mitigation activities, particularly those related to flooding. Radar imagery is not affected by cloud cover, which is a significant advantage over V-NIR imagery, especially for flood mapping applications. C-Band radar such as RADARSAT-1 (5.3 GHz; HH polarization) are particularly well suited for flood mapping applications, because return signals from flooded areas are readily differentiated from non-flooded areas. RADARSAT–1 backscatter is dependent on water surface conditions (roughness) and presence of other structures (e.g. flooded vegetation, man made structures). Calm water generally results in low backscatter, whereas flooded vegetation and infrastructure can result in "double-bounce", which causes high returns of microwave energy back to the sensor. RADARSAT-1 imagery has been widely applied for flood mapping in Asia (e.g. MRC, 2001; Lee and Lee, 2003), Africa (e.g. UNOSAT: http://unosat.web.cern.ch), and North America (e.g. Bonn and Dixon, 2005; Townsend, 2001). Since radar imagery consists of a single image band, the image of interest (e.g. a flooded area) is commonly compared with an image acquired before the event (baseline image); analysis is based on changes detected between the baseline and subsequent images.

On December 26, 2004, two tectonic plates heaved under the sea along a 1,000 kilometer-long fault line 150 kilometers off the coast of the Indonesian island of Sumatra, causing the most powerful earthquake that the world has experienced in 40 years. The magnitude 9 earthquake caused parts of the sea floor to rise by up to 10 meters, displacing hundreds of cubic kilometers of seawater and generating a massive tsunami across the Indian Ocean. Indonesia was the closest country to the epicenter, and consequently was the most severely impacted by the tsunami. As of January 14, 2005, Indonesian casualties included 110,229 confirmed dead, 12,132 missing and 703,518 persons displaced (BAPPENAS and CGI, 2005). The majority of casualties and damage occurred in the north Sumatran province of Aceh.

The Indian Ocean tsunami caused significant inundation along the coast of Northern Sumatra and RADARSAT-1 Standard and Fine Mode imagery was used to map impacted areas. Cloud free atmospheric conditions at the time of the tsunami allowed substantial acquisition of V-NIR imagery, which enabled comparison with RADARSAT-1 imagery. An evaluation of the usefulness of radar imagery to provide information on tsunami impacts was important because, in many disaster situations, cloud cover limits the ability of other sensors to acquire timely data.

As part of the response by the international community, the Disasters Charter was activated and satellite imagery was acquired in order to provide information on the extent of the tsunami impacts across Southeast Asia. Satellite imagery included SPOT-5, Landsat ETM, IRS-P6, RADARSAT-1 and archived imagery from a range of sensors. In addition, high-resolution V-NIR imagery from Ikonos (Space Imaging) and Quickbird (Digital Globe) were made available for governmental and non-governmental organisations co-ordinating the disaster relief effort. The objective of this study was to investigate the capability of RADARSAT-1 imagery to provide information on the physical impacts of the tsunami around Banda Aceh and Lho Nga in the northwest coast of Nanggroe Aceh Darussalam province, Indonesia in northern Sumatra. In particular, the impacts on the coastline, soils, and agriculture and aquaculture were investigated.

II. Study Area and Data

RADARSAT-1 carries a synthetic aperture radar (SAR) instrument, which transmits energy at C-band microwave frequency (5.3 GHz) with a single HH polarisation (CSA, 2005). A number of beam modes are available, providing imagery at several resolutions and incidence angles for swaths up to 500 km; this provides flexibility in acquiring images with a range of resolutions, incidence angles, and coverage areas.

The study area focused on the northern coast of Sumatra (Figure 1). Two RADARSAT-1 Fine Mode and four RADARSAT-1 Standard Mode images were acquired for this study, as listed in Table 1. In addition, V-NIR imagery from Ikonos and Landsat 7 (ETM+ SLC-off) and a digital soil map were used to support the analysis, as shown in Table 2.

Despite the difficulties in accessibility to northern Sumatra, three field visits were possible. The dates are February 6-9, 2005, June 6-10, 2005, and June 21-24, 2005. These field surveys focus on preliminary damage assessment of agriculture, fisheries and environment. The focus areas of field survey are Banda Aceh city and Lho Nga village.

Table 1. New acquisitions and archived RADARSAT-1 images from northern Sumatra.

Geographical location	Acquisition date	Beam Mode	Resolution	Orbit
Banda Aceh	24 January 2005	F4F	9 m	Ascending
Banda Aceh	29 September 1999	F4F	9 m	Ascending
Northern Aceh	31 December 2004 30 December 2004	S7 S5	25m 25m	Ascending Descending
Northern Aceh	09 April 1998 (2 scenes)	S3	25m	Ascending

Note: for more information on RADARSAT-1 Beam Modes, see CSA (2005).

Table 2. Complementary V-NIR images and soil map data.

Data Type	Geographical location	Acquisition date	Resolution

Ikonos	Banda Aceh	29 December 2004	1m
Ikonos	Banda Aceh	10 January 2003	1m
Landsat- 7 ETM+ (SLC Off)	Aceh Province	29 December 2004	30m
Soil Map	Aceh Province	1990	1:250,000

III. Image Processing

RADARSAT-1 data were received in CEOS format and imported into PCI Geomatica version 7.0 for analysis. All RADARSAT-1 data were processed as follows: speckle filtering was applied to remove 'noise' inherently present in SAR imagery; radar calibration, which involves conversion to backscatter, and; ortho-rectification to remove image distortions introduced by the image acquisition geometry and the terrain and to conform imagery to a standard map projection.

In order to reduce inherent radar speckle effects, an adaptive filter is usually applied to radar imagery. In this study, a Frost filter was applied (Frost et al., 1983) using a 3 x 3 moving window (kernel). All images were calibrated to backscatter (scale in decibels) and georeferenced to UTM zone 46 North, WGS84 datum. Georeferencing is necessary to analyze spatially related data, such as satellite imagery, GIS layers, and local information.

A multi-temporal image composite was created to facilitate change detection analysis between images acquired before and after the tsunami. Display of the multi-temporal images in an RGB colour composite provides a graphical display in which surface changes such as the tsunami impacted areas can be identified and interpreted qualitatively.

Change detection of the multi-temporal composite involved quantitative 'thresholding', which is a technique to classify an image into two discrete classes based on image values, for example flooded and non-flooded areas. In this case, a threshold value was used to allocate an image pixel to tsunami-affected and unaffected classes; the value was determined by examining sample image pixels, V-NIR imagery and the limited ground verification data collected. This methodology generally produces accurate and consistent results more quickly than manual digitizing. However, there are limitations to thresholding, including impacts of unfiltered speckle, misclassification of shadow as inundation, and misclassification because of imperfect calibration of backscatter values between individual images.

The application of a "Frost" filter reduced misclassifications resulting from radar speckle. In order to reduce impact of topographic shadow from coastal mountains, an assumption was made that the tsunami did not affect coastal areas greater than 5 km from the coast (a reasonable assumption based on available sources of data).

IV. Results and Discussion

Interpretation of the radar imagery was based on a visual assessment of the imagery and a quantitative assessment of changes in backscatter.

Coastline change

There was generally lower backscatter from seawater-inundated areas compared to unaffected areas based on a comparison with imagery acquired before the disaster. The multi-temporal image comparison reveals that the severe coastline destruction along the northern and western coast of Nanggroe Aceh Darussalam could be detected using RADARSAT-1 Standard Mode imagery. In Figure 2, imagery acquired before the tsunami, following the tsunami, and a multi-temporal image composite is shown for three sub-areas of the Aceh coastline. The multi-temporal composite shows the post-tsunami image using the blue and green display channels and the pre-tsunami-image is displayed using the red channel. In the individual RADARSAT images, the ocean and flooded land are represented by dark tones because water surfaces have low backscatter and land areas are represented in various tones of grey. The multi-temporal composite shows destroyed coastline and flooded areas as a deep red colour. Figure 2a illustrates a cape completely destroyed by the tsunami, whereas Figure 2b and 2c illustrate coastal destruction and also significant areas flooded by seawater as a lighter red colour.

In selected areas in Figure 2, the tsunami destroyed areas up to 5 km inland, including transport infrastructure (bridges, roads, etc.) and settlements, especially those close to the shore. By manually digitizing individual vectors of a composite RADARSAT-1 standard beam, the tsunami affected area was estimated at 46,153 ha (only in the western and northern coastal areas of Aceh province).

Tsunami Affected Soils

The immediate impact of the tsunami was great loss of life and the destruction of settlements. In the longer term, damage to aquaculture infrastructure and agricultural land become increasingly important.

Figure 3 shows a section of the tsunami-affected area overlayed on a soil map for the western and northern coast of Aceh province. Generally, the soils of western and northern coast of Aceh province affected by the tsunami belong to the marine soil group, with slopes less than 3% (Table 3). The marine soil group is characterised as tidal with an elevation of 0 – 10m, an electrical conductivity ≥ 2 dS (Centre for Soil and Agroclimate Research, 1990) and is broken down into five sub-groups. The northern coast of Aceh includes Banda Aceh city (capital of Nanggroe Aceh Darussalam), which lies on soil sub-groups Bf 4.2, Bf 4.3, Bf 4.4, Bf 4.5, and Bfq 1.1. This lowland area consists of settlements, paddy fields and fishponds. On the western coast are Lho Nga and other villages, which are located on a narrow lowland strip, wedged between hills and Karst area; the Lho Nga formation consists of soil sub-groups Bf 4.2 and Bfq 1.1.

Comment [GSB3]: What are Karst?

Field surveys prior to the tsunami disaster found that common land use activities within certain areas of the marine soil group included agriculture and aquaculture. These fertile areas consisted of finely granulated and well drained soils. The tsunami destroyed much of the infrastructure and deposited coarse material on agricultural lands and destroyed or blocked drainage systems. The tsunami also resulted in increased soil salinity.

Backscatter from RADARSAT-1 is affected by surface roughness, soil moisture (affects dielectric constant), and non-homogeneous media (Revees, Robert G. et. al. 1975). RADARSAT-1 data can assist with the recovery effort, by providing data on what areas were impacted, and assist with the evaluation on damage to agricultural soils and drainage systems and potentially detect tsunami related changes to soil salinity.

Table 3 Tsunami affected areas for each Land unit type around Banda Aceh and Lho Nga coast.

No.	Type of Land unit	Physiographic group	Description (before Tsunami disaster)	Area (Ha)
1.	Afq.1.2.1	Alluvial	Flooding flat, meander, slope < 3%	616
2.	Afq.1.2.2	Alluvial	Flooding flat, meander, slope < 3%	140
3.	Au.1.1.1	Alluvial	Alluvial flat change to marine area, slope < 3%	511
4.	Au.2.2.1	Alluvial	Alluvial and colovial, undulate, slope 3-8%	631
5.	Bf.4.2	Marine	Marshy tidal flat behind shore	3,195
6.	Bf.4.3	Marine	Tidal flat along seashore; mangrove vegetation	1,310
7.	Bf.4.4	Marine	Estuarine flat along major rivers; nipa and/or mangrove vegetation	1,097
8.	Bf.4.5	Marine	Flat above mean sea level; partly ripened.	1,498
9.	Bfq.1.1	Marine	Complex of young beach ridges and swales	2,032
10.	Hab.1.2.2	Hill	Hill, slope 16-25%	24
11.	Kc.3.3	Karst	Karst hill, slope 16-55%	1,518
12.	Kc.4.3	Karst	Karst with limestone stratum horizontally	35
13.	Kc.5.3	Karst	Karst hill, slope > 25%	74
	Total Area			12,681

Comment [GSB4]: re you sure its not Karst??

Source: Centre for Soil and Agroclimate Research, 1990.

Impacts on Land Cover

The acquisition of RADARSAT-1 Fine Mode imagery allowed for an evaluation of the usefulness of high spatial resolution radar imagery for mapping tsunami impacts. Fine Mode imagery covers a relatively smaller area than lower resolution images, therefore the analysis focused on Banda Aceh city and Lho

Nga. For these areas, analysis was supported by multi-spectral Ikonos imagery (acquired before and after tsunami), which was used to supplement limited ground data.

Manual image interpretation was considered the most appropriate method for analysing RADARSAT-1 data to detect changes in vegetation following the tsunami disaster. The land cover classes are necessarily limited, due to lack of field data. Land cover classes were: 1) paddy field; 2) settlement; 3) bare land; 4) bush, and; 5) fishpond.

Figure 4 shows the tsunami-affected area around Banda Aceh using RADARSAT-1 Fine Mode imagery. The multi-temporal composite displays the post-tsunami image using blue and green display channels and the red channel for the pre-tsunami image. In Figure 4, the high spatial resolution image clearly shows destruction of individual fishponds structures and the destruction of coastal sand bars, as illustrated with a deep red colour. Surfaces covered by water in pre- and post-tsunami images are dark in tone, including active fishponds. Some land was flooded, as represented by red colouring; however, the destruction of the city of Banda Aceh resulted in complex backscatter changes, with some areas showing a higher backscatter (blue-green colour). This is likely due to debris from destroyed structures and flooded vegetation, which are rough surfaces or corner-reflectors, but some backscatter differences might be caused by seasonal differences between archived and more recent image acquisition.

Table 4 provides a summary of the area of specific land cover types affected by the tsunami. At present, there ire limited ground data available for validation of these values, but the analysis indicates that large areas of important productive agricultural and aquaculture land was destroyed, in addition to settlement areas.

Table 4 **Tsunami affected area for each landuse class around Banda Aceh city.**

No.	Tsunami affected area	Area (Ha)
1.	Paddy field	400
2.	Settlement/field/mix garden	1412
3.	Bareland	16
4.	Scrub/Bush	223
5.	Fishpond	640
6.	Water body	94

A composite of RADARSAT-1 Standard and Fine Mode imagery was also used to assess the retreat of the seawater from flooded agricultural land following the tsunami. For example, at Lho Nga on December 31, 2004, the area of sea water inundation was 272 ha, whereas one month later (January 24, 2005) the area of seawater inundation had declined by 127 ha to 145 ha. These changes are illustrated in Figure 2d and are clearly represented with a blue-green colour. The remaining flooded area (dark tone) was previously a natural freshwater lake, now salanized.

The imagery acquired one month after the tsunami demonstrates the need for regular image acquisitions post-disaster, in order to monitor the full extent of seawater inundation and potential long-term impacts of agriculture.

V. Conclusions

In response to the Indian Ocean tsunami, imagery from a range of satellite sensors was acquired in order to provide information on affected areas to the international relief community. For affected areas of the Aceh coastline, the imagery ranged from high resolution V-NIR for selected areas (e.g. Ikonos and Quickbird), to medium resolution V-NIR for large parts of the coast. In addition, a large number of RADARSAT-1 images were acquired over a range of resolutions along the Aceh coastline. The availability of cloud free V-NIR imagery meant that disaster response organisations such as UNOSAT (http://unosat.web.cern.ch) were able to provide immediate and accessible 'image maps' for relief agencies. However, our study has shown that information on the tsunami-affected area can be also extracted from RADARSAT-1 imagery. The advantage of radar imagery is that it is not affected by cloud cover, but is able to provide information on inundation of land cover.

Future work is focusing on land cover changes visible in RADARSAT-1 imagery in the months following the tsunami. Specifically, radar may provide information on the retreat of the seawater and in the sailinization of coastal agriculture areas (e.g. Aly et al., 2004, Mohamed et al., 2003). Ongoing mapping and monitoring of the land recovery should be based on a range of satellite images, and RADARSAT-1 may continue to provide useful information, especially during the monsoon season.

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