SENTINEL-1 SUPPORT IN THE GAMMA SOFTWARE

Urs Wegmüller, Charles Werner, Tazio Strozzi, Andreas Wiesmann, Othmar Frey, and Maurizio Santoro

Gamma Remote Sensing, Worbstrasse 225, 3073 Gümligen BE, Switzerland
tel: ++41 31 951 7005, fax: ++41 31 951 7008, e-mail: wegmuller@gamma-rs.ch

ABSTRACT

First results using the new Sentinel-1 SAR look very promising but the special interferometric wide-swath data acquired in the TOPS mode makes InSAR processing challenging. The steep azimuth spectra ramp in each burst results in very stringent co-registration requirements. Combining the data of the individual bursts and sub-swaths into consistent mosaics requires careful "book-keeping" in the handling of the data and meta data and the large file sizes and high data throughputs require also a good performance. Considering these challenges good support from software is getting increasingly important. In this contribution we describe the Sentinel-1 support in the GAMMA Software, a high-level software package used by researchers, service providers and operational users in their SAR, InSAR and PSI work.

1. Introduction

On 3. April 2014 ESA launched the first of the two Sentinel-1 (S1) satellites with the interferometric wide-swath (IWS) mode selected as the main acquisition mode. In IWS mode, the data are acquired using the so-called TOPS mode [1]. TOPS stands for Terrain Observation with Progressive Scans in azimuth, but the word is also the reverse of SPOT and actually the beam scanning done is the opposite of the scanning done in spotlight mode. One of the strengths of the IWS mode is that wide areas can be covered, about 250km in the case of S1. S1 is operated at C-band with an orbit repeat cycle of 12 days. The orbital tube is very narrow (of the order of 100m) and the TOPS mode bursts are almost perfectly synchronized to support SAR Interferometry (InSAR).

The GAMMA Software is a high-level software package that supports researchers, service providers and operational users in their SAR, InSAR and PSI (Persistent Scatterer Interferometry) related work. In this contribution, we describe the support the GAMMA Software provides for interferometry, offset tracking and PSI using S1 IWS data and the related procedures used.

2. S1 IWS data handling and basic functionality

S1 IWS data are available as RAW, SLC (Single Look Complex) and GRD (Ground Range Dataset) products. S1 IWS RAW data are distributed for specific usage only. Currently the use of S1 IWS SLC and GRD data is supported in the GAMMA Software. The GRD products can be imported, calibrated and geocoded in the GAMMA Software. The GRD products may be used to analyze the backscattering coefficient and for offset tracking, e.g. to map glacier motion.

The S1 IWS SLC product is a set of three "burst SLC", each one including a number of SLCs obtained by processing the bursts over one of the IWS sub-swaths. An example of a burst SLC of sub-swath IW1 is shown in Figure 1. The area covered by the individual bursts overlaps in both azimuth (between sub-sequent bursts) and range (between neighboring sub-swaths), as sketched in Figure 2. In the GAMMA Software the S1 IWS SLC product is imported and stored as "burst SLC" consisting of the image data of the 3 sub-swaths and related parameter files containing the relevant metadata. In the importing step, the radiometric calibration is applied. Functionality to process the "burst SLC" includes the possibility to generate a mosaic SLC and a mosaic MLI (Multi-Look Intensity image, Figure 3). In both cases, this is a single data file with a single parameter file. The data are cut in the overlap region such that only pixels (looks) from the same burst and sub-swath are combined into a MLI pixel. Geometrically and radiometrically the S1 IWS SLC have a very high standard, so that the generated mosaics are typically seamless in both range and azimuth. The Doppler Centroid of the data varies rapidly along-track, which is very relevant for the SLC co-registration and interferometry. MLI mosaics can be geocoded using the normal procedure used in the GAMMA Software. Typically the S1 state vectors distributed with the data are of very high quality which results in co-registration accuracies of a few meter or better, even without applying a refinement to the geocoding. In addition the GAMMA Software includes programs to extract SLC data of a single burst into an individual data file with a corresponding parameter file and to remove the azimuth spectrum variation related phase ramp from burst SLCs or SLCs of individual bursts.

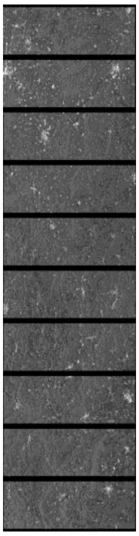

Figure 1 IW1 SLC bursts

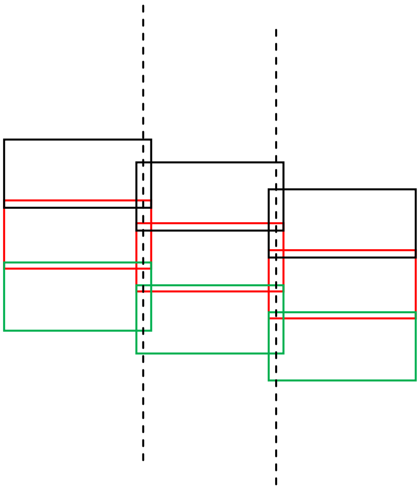

Figure 2 S1 burst structure with small overlaps between bursts and sub-swaths.

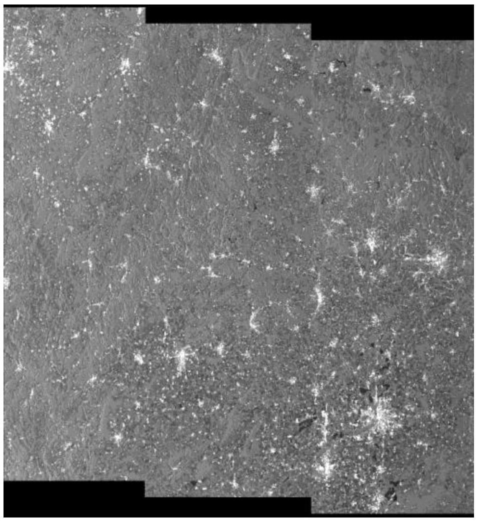

Figure 3 MLI mosaic for a "full Sentinel-1 TOPS scene" consisting of 3 sub-swaths with 10 bursts each.

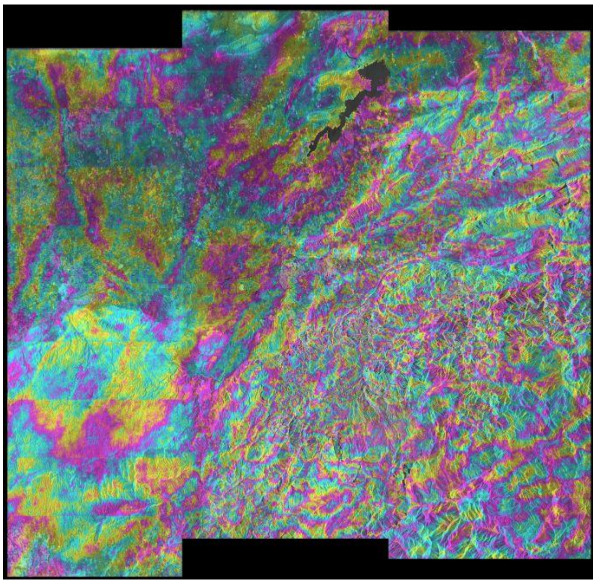

Figure 4 S1 TOPS differential interferogram as obtained after the matching co-registration refinement One color cycle corresponds to one phase cycle. Phase jumps are clearly visible between some consecutive bursts.

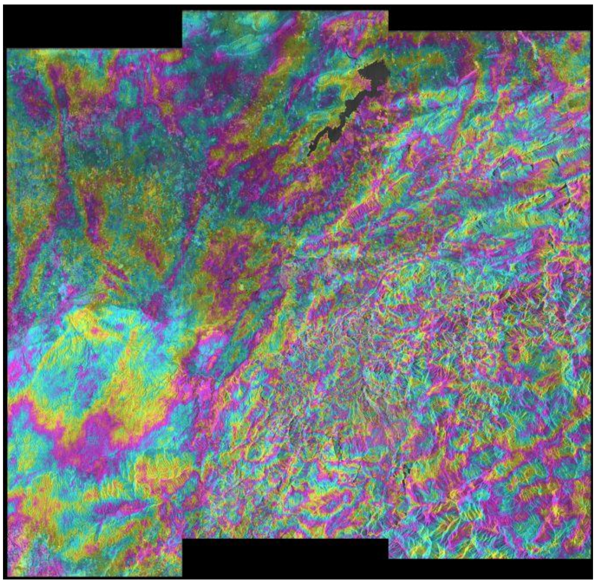

Figure 5 S1 TOPS differential interferogram as obtained after the spectral diversity co-registration refinement. One color cycle corresponds to one phase cycle. No more phase jumps are visible at the burst interfaces. The phase matches also well between adjacent sub-swaths.

3. S1 IWS Interferometry

For TOPS interferometry an extremely accurate co-registration in the azimuth direction is required [2] and therefore the refinement of the co-registration is done very carefully, using several methods and potentially iterating some of the steps to maximize the quality achieved. In the azimuth direction an accuracy of a few thousandths of a pixel is absolutely required, otherwise phase jumps between subsequent bursts are observed. To assure this very high co-registration accuracy we use a method that considers the effects of the scene topography. To determine the refinement of the transformation we use several methods. Furthermore, the results need to be tested, e.g. by calculating the differential interferogram to check visually for phase jumps at the interfaces between subsequent bursts. Normally, more than one method is applied to iteratively improve the co-registration refinement. Typically, this includes first a matching procedure and then a spectral diversity method [3] that considers the interferometric phase of the burst overlap region. The refinement determined is only a constant offset in slant range and in azimuth (the same correction is applicable for all bursts and all sub-swaths).

A differential interferogram calculated after the refinement with the matching procedure (accuracy of the order of 1/100 azimuth pixel) is shown in Figure 4 and the final differential interferogram after refinement with the spectral diversity method is shown in Figure 5. In the following, phase filtering, phase unwrapping, e.g. using a minimum cost-flow approach, phase to displacement conversion and coherence estimation are the same as for conventional stripmap interferometry. The corresponding geocoded RGB composite of the coherence (red), the backscatter (green) and the backscatter change (blue) is shown in Figure 6.

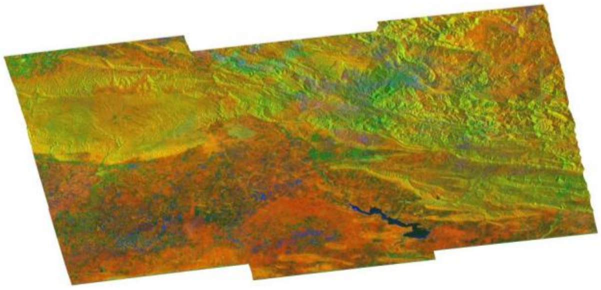

Figure 6 S1 IWS geo-referenced RGB composite of the coherence (red), the backscatter (green) and the backscatter change (blue).

4. Interferometric time series analysis

In the GAMMA IPTA Software a broad range of tools supporting different interferometric time series analysis approaches are supported, using either single or multi-looked interferometric phase and using either single reference or multi reference stacks to derive the deformation time series. For initial tests with S1 IWS data we used a stack over Mexico City, consisting of a relatively small number of 12 repeat observations. Because of the small stack and the very significant ground motion in the Mexico City area we used multi-reference stacks for both the SBAS and PSI processing done.

As input to the time series analysis we co-registered all the S1 IWS SLC to one selected reference scene (20151015). This was done using the procedure described in section 3, including the refinement with the spectral diversity method. This worked well as confirmed by differential interferogram mosaics without visible phase jumps at burst interfaces and between sub-swaths and with generally very high coherence over urban areas. For the SBAS and PSI processing we deramped the co-registered SLC mosaics for the azimuth phase ramps and cut out a common 16000 x 5000 pixel section over Mexico city. In the following the SBAS and PSI procedures used and the results achieved are discussed.

4.1 SBAS time series analysis with S1 IWS data

We followed an SBAS procedure similar to the one described in [8,9]. In particular we considered multi-looked differential interferometric phases using 10 range and 2 azimuth looks. For the entire stack all the baselines are below 250m and so all spatial baselines are short. To maximize the temporal coherence but also to facilitate the phase unwrapping by minimizing the deformation phase we considered the shortest time intervals possible. As we wanted to include redundant observations we decided to include all pairs between scenes that are up to 3 positions away from each other in the time series (i.e. 1-2, 1-3, 1-4, 2-3, 2-4, 2-5, 3-4, …), which resulted in a total of 30 pairs.

For each pair we calculated the differential interferogram using the SRTM height as topographic reference and unwrapped the phase. The unwrapped phases were then converted to a time-series using singular value decomposition (SVD, as supported in the program mb). Besides the phase time series quality information such as the phase standard deviation from the time series is provided. For areas where an unwrapping error occurred phase standard deviation from the time series get significantly higher and so the result in these areas can be excluded from the solution. The main results are the average deformation rate and the deformation time series (Figures 7,8). Converting the line-of-sight values to a vertical displacement rate (assuming the movement is in the vertical direction) we observed maximum subsidence rates of more than 40cm/year. No anomalies were observed at the interface between subsequent bursts. Besides, height corrections were estimated in the SVD step.

4.2 PSI time series analysis with S1 IWS data

The co-registered deramped SLC mosaic stack over Mexico City can be used as input to a PSI processing in the same way as used for conventional stripmap mode data. In the identification of persistent scatterer candidates, we applied a spectral diversity criteria as well as criteria on the backscatter variability and level [4]. The spectral diversity method available in the GAMMA IPTA software for the identification of point-like scatterers can be used as well as range oversampling of the SLCs if the SLCs are deramped.

Thanks to the good range resolution of the S1 IWS data a high number of suited persistent scatterers was identified. In urban areas the point density was often significantly larger than 1000 points/km^2 To make the PSI processing more efficient, especially if processing large areas, we initially reduce the candidate list size using the methodology described in [5]. This is done adaptively, such that the point density is strongly reduced in areas with a very high point density while not reduced at all in areas with a low point density (Figure 10). The fact that only the vector data stacks are used in most IPTA programs means that the relevant parameter for the speed of a processing step is not the size of the area or of the full SLC but only the number of points in the point candidate list. This makes the IPTA approach very efficient for S1 IWS PSI. Because of the limited number of scenes (12) available we used the same multi-reference stack as used in the SBAS processing. Using this multi-reference stack we estimated point height corrections, linear deformation rates and atmospheric phases. These initial linear deformation rate estimates are not of very high quality because they are based on the short interval pairs. Besides of these parameters this step also provides the unwrapped phase components. These component are then added to get the total point differential phases for the multi-reference stack. SVD is then used to convert the multi-reference stack phases to a single reference time series. Further processing may be done on this result considering the single reference stack. In this example this was not done because of the small stack size.

The average deformation rate derived in the PSI processing (Figure 9) corresponds closely to the result of the SBAS processing (Figure 7). Considering stable areas shows that mm/year precision is clearly not reached with this C-band stack of 12 scenes between October 2014 and March 2015. In this PSI result no anomalies were observed at the interface between subsequent bursts.

In the above described PSI method only data of one burst is considered in the burst overlap (and sub-swath overlap) regions. This seems reasonable as it results in spatially consistent point densities. Nevertheless, to specifically investigate how points behave in the two different bursts (or sub-swaths) of an overlap area the programs to extract SLCs of single bursts can be used.

5. S1 IWS offset tracking

To apply offset tracking for S1 TOPS mode SLC data the basic strategy is to first co-register the two burst SLC as described in Section 3. In order to apply oversampling in the offset tracking procedures it is recommended to first deramp the SLC data for the azimuth phase ramp. Further processing (quality control, geocoding, conversion to displacements in meters, visualization) is then done as for normal stripmap mode data. An example of a glacier velocity map over a part of Greenland is shown in Figure 11. As compared to ENVISAT ASAR the sensitivity is improved in range direction thanks to the higher S1 range. On the other hand the resolution is lower in azimuth direction as a consequence of the lower azimuth resolution of the IWS data.

For S1 TOPS mode GRD data offset tracking can be applied using the procedure as for strip-map mode data. The main interest in offset tracking is to map displacements. But azimuth offsets may also be of interest to identify ionospheric effects [1] or for radargrammetry.

6. Conclusions

The procedures used in the GAMMA Software for interferometry, offset tracking and interferometric time series analysis (SBAS and PSI) using S1 IWS data were described. The main differences to "normal" strip map mode data are the organization of the IWS SLC data in 3 sub-swaths and by burst, and the extremely accurate co-registration accuracy required for interferometry to avoid phase jumps between consecutive bursts (caused by the strong along-track Doppler Centroid variation). As a consequence much more care is taken with the co-registration procedure also including new elements as the use of a spectral diversity method applied to the burst overlap areas. The results achieved confirm that the S1 IWS data are well suited for interferometry, offset tracking and interferometric time series analysis. Besides the presented SBAS and PSI approach other time series approaches, e.g. working with a single reference stack or methods combining single and multi-look interferometric phases [10] are also applicable, especially with larger stacks becoming available.

7. References

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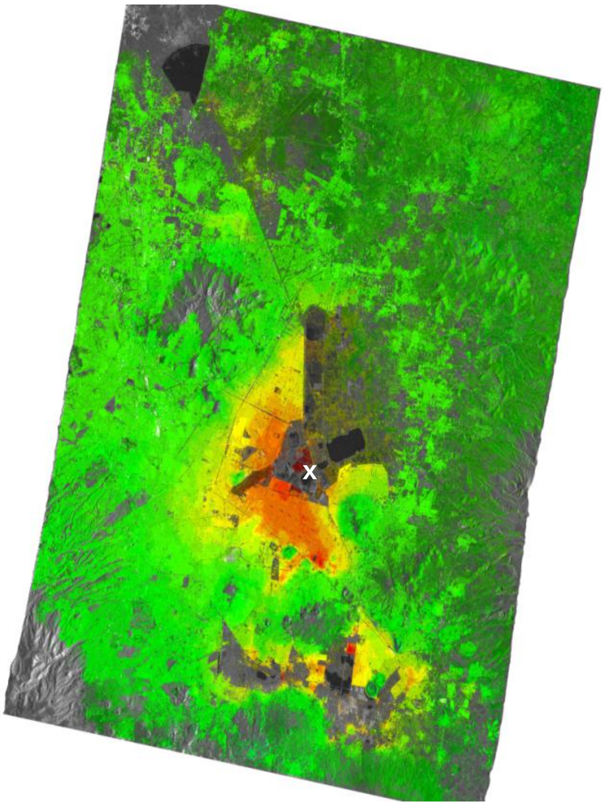
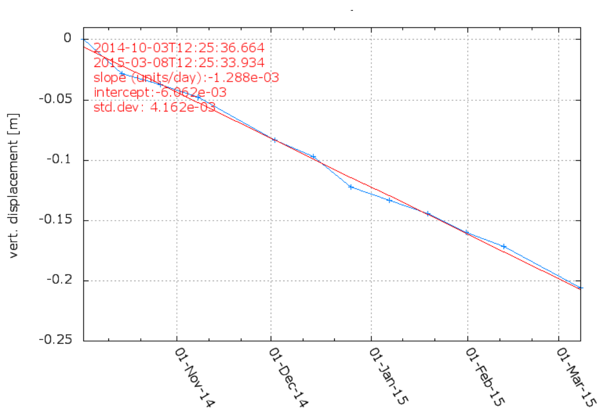


Figure 7 Average vertical displacement rate derived from a stack of 12 S1 IWS SLC over Mexico City using an SBAS procesdure (color scale is indicated to the right)



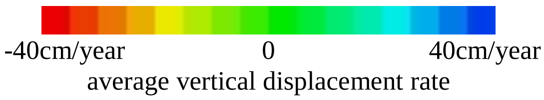


Figure 8 Displacement history of an area near the international airport (see white **x** *in Figure 7) derived using the described SBAS procedure.*

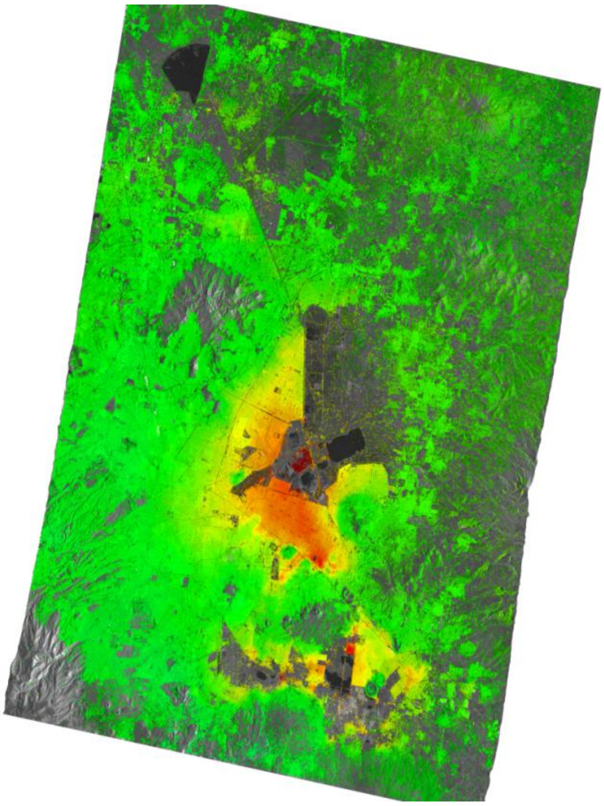


Figure 9 Average vertical displacement rate derived from a stack of 12 S1 IWS SLC over Mexico City using a PSI procedure (color scale is indicated above to the right).

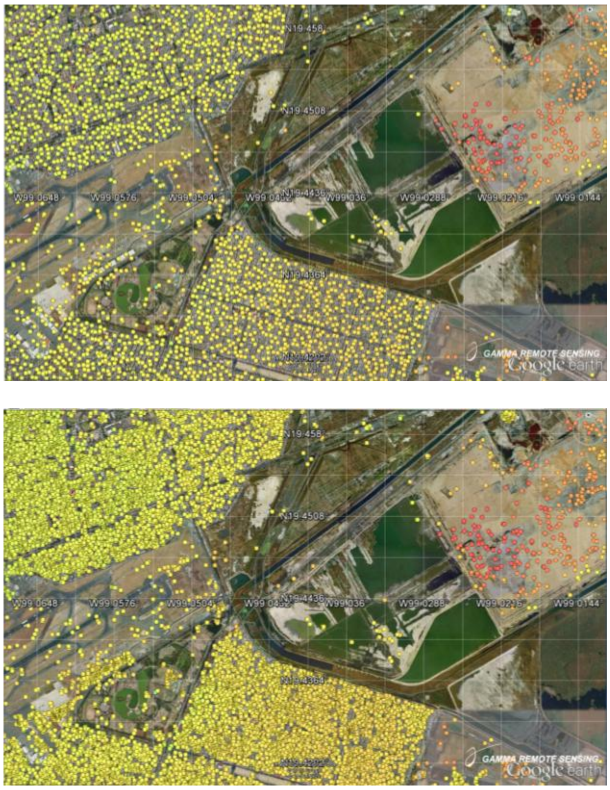


Figure 10 Local visualization of the S1v IWS PSI result over Mexico City (LOS displacement rates) in Google Earth with reduced (top) and full (bottom) point density.

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8. Acknowledgments

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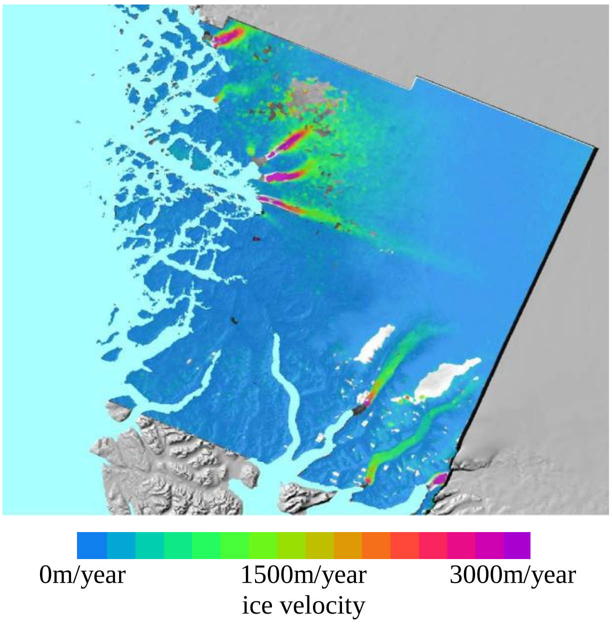

Figure 11 Velocity map of the Upernvaik area overlayed the shaded relief of the Greenland Mapping Project (GIMP) DEM [11]. Image width is about 250 km.