GEODETIC ANALYSIS AND MODELLING OF THE SANTORINI VOLCANO, GREECE, FOR THE PERIOD 2012-2015

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ABSTRACT

Santorini Volcanic Complex (SVC) is the most active part of the South Aegean (Hellenic) Volcanic Arc, which marks the subduction of the African underneath the Eurasian plate, and is considered a prime site for conducting geophysical research. The SVC showed signs of unrest in January 2011 and has been inflating almost radially around a source northern of the Kameni islands.
We present deformation maps for the SVC as obtained from the multi-temporal analysis of Synthetic Aperture Radar (SAR) imagery for the post-inflation period, using datasets from COSMO-SkyMed (CSK) and TerraSAR-X (TSX) satellites.
Displacement rates indicate mainly subsidence at Nea Kameni Island and horizontal motion at the northern part of the caldera. These movements may be due to smooth deflation of the volcano. The signal for the rest of the SVC indicates a phase of relative stability.
Finally, we model our results assuming a Mogi model for magma chambers. The data inversion was based on InSAR data and also accounting GPS measurements.

1. STUDY AREA

The boundary between the Eurasian plate and the African plate is widely referred to as the Hellenic Arc (Fig. 1). It is an arcuate tectonic feature of the Eastern Mediterranean Sea related to the subduction of the African plate underneath the Eurasian plate. It consists of an oceanic trench (Hellenic Trench), one volcanic arc (Aegean Volcanic Arc) and an inner non-volcanic arc.

Santorini Volcanic Complex (SVC) consists of five islands, which together comprise a volcanic caldera that has experienced dominant explosive eruptions every 10,000 to 30,000 years, [1]. The last eruptions on the Kameni islands took place from 1939 to 1941, with a negligible phase of extrusion in 1950.

Figure 1. Main tectonic settings in Greece and Santorini volcanic complex.

A series of ground based observational networks have been installed in SVC, including continuous GPS (c-GPS) and seismographs. Data from several instrument campaigns have become available. Consequently, the exploitation of the dense geodetic measurements offered by Spaceborne Synthetic Aperture Radar Interferometry (InSAR) and especially PSI in combination with in-situ measurements presents an exceptional opportunity for a trans-disciplinary monitoring of the Santorini volcano.

2. RECENT VOLCANIC ACTIVITY

Between 1950 and 2010, the volcano remained quiet, with no important recorded reports of seismic activity. The SVC showed signs of unrest for the first time in over half a century back in January 2011, when a series of small earthquakes began beneath the islands [2, 3, 4]. Ground deformation was also detected by use of GPS receivers and an island-wide network of triangulation stations. Envisat data confirmed that the islands have risen about 15 cm since January 2011 until March 2012, in the Line Of Sight (LOS) [2]. The SVC has been inflating – gradually moving upward and outward – almost radially around a source northern of the Kameni islands. Publications showed as probable that molten rock has accumulated in a magma chamber at a depth of about 4 km [2].

The satellite data showed that the amount of molten rock that has arrived beneath Santorini over the 12+ month period (2011-2012) is almost equal of 10–20 years' rise of the volcano. However, the seismicity rate dropped off in early 2012. Our study shows that deformation has not fully recovered thus the goal of the present work is to enhance our knowledge for the physical processes that take control of Santorini volcano after the inflation event.

For the pre-inflation period, some studies have shown that the volcano unrest period was preceded by a period of rather insignificant deformation [3]. Displacement up to -5 mm/yr was observed for the period 2006-2010 at the southwestern part of Nea Kameni Island and at the south-eastern part of Therassia (Fig. 2).

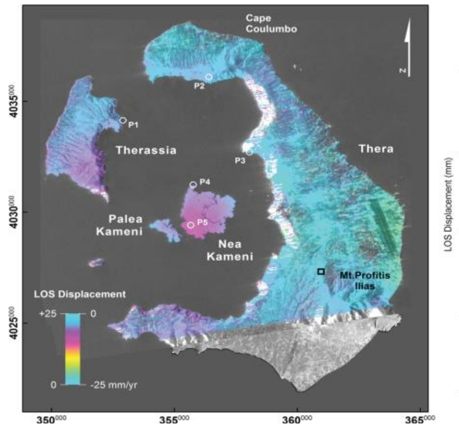

Figure 2. Average LOS displacement rates from PALSAR ascending frame over the period 2006 December–2010 December. Reference point is shown with a black square [3].

During the inflation episode, a special radial inflation pattern was observed declining towards the external side of the caldera, highlighting that the displacement was due to volcanic activity [3]. An important LOS uplift on Nea Kameni reached almost 9 cm in March 2012 and a maximum displacement of 14 cm was noticed at Cape Skaros NNW of Fira (Fig. 3).

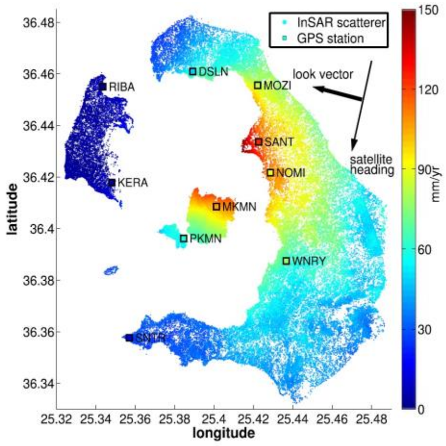

Figure 3. LOS velocities for the merged PSI and SBAS cloud. MOZI station square corresponds to the reference area [2].

3. GPS DATA

Fig. 4 shows the extent of the study area along with the locations of continuous GPS stations. There are eleven GPS stations in the study area. We present just the time series of GPS measurements at the North, East and Vertical components of motion. Several noise sources might affect the GPS measurements.

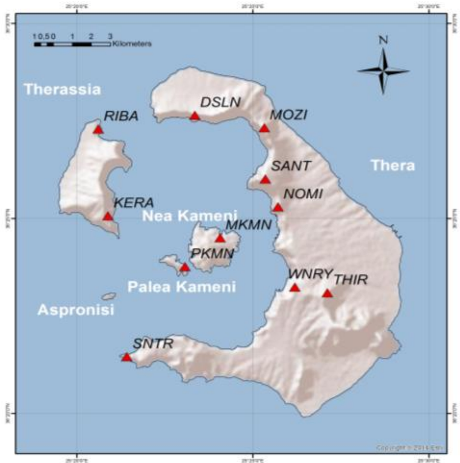

Figure 4. Santorini GPS network of permanent stations

The initiation of the strong uplift is observed in January 2011. In February 2012 the phenomenon exhibits decay in velocity. Selected time series of GPS measurements are depicted in Figure 5. Black lines indicate the start and end of the inflation event.

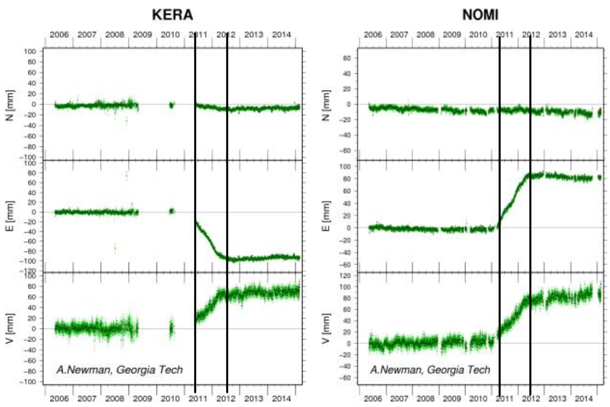

Figure 5. Raw time series of GPS measurements for two selected permanent stations. Black lines indicate the start and end of the inflation event, Georgia Institute of Technology

All GPS data indicate that after February 2012, SVC is heading to South and East and that means that its normal tectonic motion has recovered and returned to the velocities it had before the inflation episode.

Generally, GPS stations measure the general tectonic movement of the plate as well as the local volcanic motion.

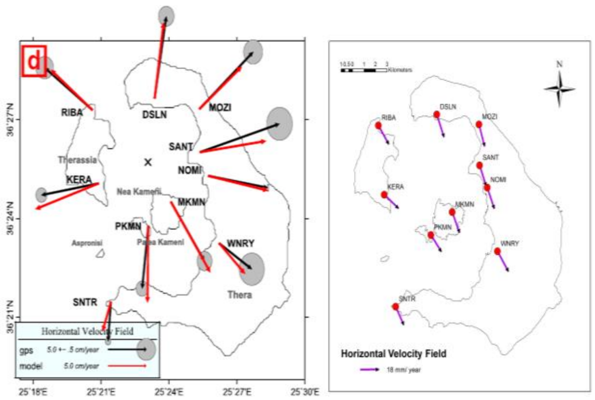

Figure 6. Left: Velocities derived from the regression applied on the GPS time series measurements and the corresponding Mogi model [2]. Right: GPS velocities after the inflation episode.

In Fig. 6 (left), GPS vectors depicted the intrusion of magma in the shallow chamber and the volcanic motion is the dominant one, making the tectonic slow motion disappears. These SAR results during the inflation were very well fitted with a Mogi model, which source is located north of the Nea Kameni Island.

Since February 2012, when the rapid episode ceased, the observed displacement has declined significantly, possibly signaling a new phase of relative stability. In Fig. 6 (right), where the dominant motion is the tectonic, all GPS stations are heading to South and East.

4. DATA AND METHODOLOGY

In order to investigate the displacement of Santorini after the inflation event, we utilize TerraSAR-X and COSMO-SkyMed data. The TerraSAR-X dataset concerns the time span between May 2012 and June 2013 and is in a descending orbit (incidence angle ~28 deg.). The COSMO-SkyMed dataset spans from March 2015 to September 2015 in an ascending orbit (incidence angle ~ 40deg.). Fig. 7 illustrates the footprint for both datasets.

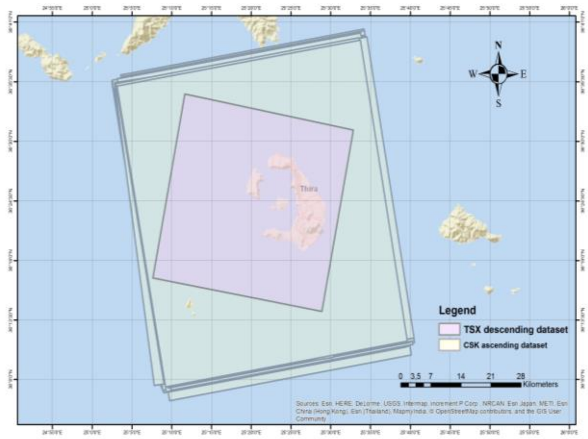

Figure 7. COSMO-SkyMed and TerraSAR-X dataset footprint

Time series analysis is a well-established process employed in InSAR for the joint processing of a stack of SAR images in order to monitor changes induced by natural phenomena or human intervention covering an area of interest. For this study we have applied time series analysis techniques in the island of Santorini to produce an annual deformation rate map. Two of the most popular approaches are the method of Persistent Scatterers (PS) [5] and Small Baseline Subset (SBAS) techniques [6]. Both PS and SBAS techniques can be used to investigate phenomena which cause surface deformation due a geophysical process. The advantages of these techniques are the accuracy of the results at a millimetre level and the large spatial coverage capacity, achieving the equivalent of a very dense GPS network of permanent stations (Fig. 8).

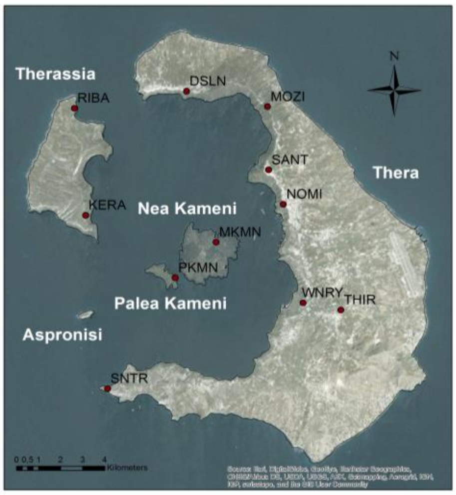

Figure 8. Santorini volcanic complex map. Red dots shows the GPS network of permanent stations

Persistent Scatterer (PS) is an effective technique for deformation measuring and monitoring using interferometric SAR imagery: it is based on large stacks of SAR images and suitable data modelling procedures that make the estimation of different parameters such as the deformation time series, the average displacement rates and the residual topographic error [5].

SBAS technique is a differential synthetic aperture radar (SAR) interferometry algorithm for monitoring the temporal change of ground deformations. This technique is based on an appropriate combination of differential interferograms produced by data pairs identified by a small orbital baseline in order to limit the spatial decorrelation phenomena [6].

Stanford Method for Persistent Scatterers (StaMPS) software [7] is used, which adopts a spatial correlation approach to identify coherent pixels that retain their scattering characteristics through time. The algorithm has been applied to several volcanic areas in the past [8, 9] and implements a robust and innovative three-dimensional phase unwrapping algorithm. StaMPS has additionally the capability to merge the results of the two techniques, to extract the deformation signal at more points and with higher overall signal-to-noise ratio than can either approach alone [10].

5. PROCESSING AND RESULTS

In Fig. 9 we present the velocities for the frame of TerraSAR-X (May 2012- June 2013) with a descending orbit and in Fig. 10 the velocities of the COSMO-SkyMed ascending frame (March 2015- September 2015). The results we are presenting are merged results of the methodologies of PS and SBAS [10]. Topographic errors were corrected with the use of Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of 90 m resolution.

A really important part of the processing is the selection of the reference point. As reference area we selected an area around GPS station “MOZI” of the Greek Network with a radius of 100 meters. All the displacement rates are referred to MOZI. Indicatively, when we observe a negative velocity at a point of interest in the descending satellite results, then we assume that this point is moving downwards or westwards with respect to MOZI. This means that either the point is heading to the west/down with respect to MOZI or it is heading to the East/Up but with much lower rate than the MOZI’s rate. It should be mentioned, however, that due to the sensing geometry, the LOS velocity is far more sensitive to vertical motion compared to the horizontal East-West movements.

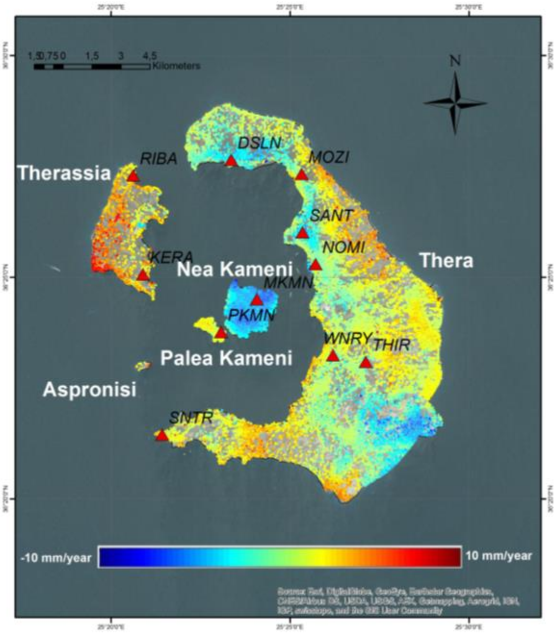

Figure 9. PSI LOS displacement rates from TerraSAR-X data

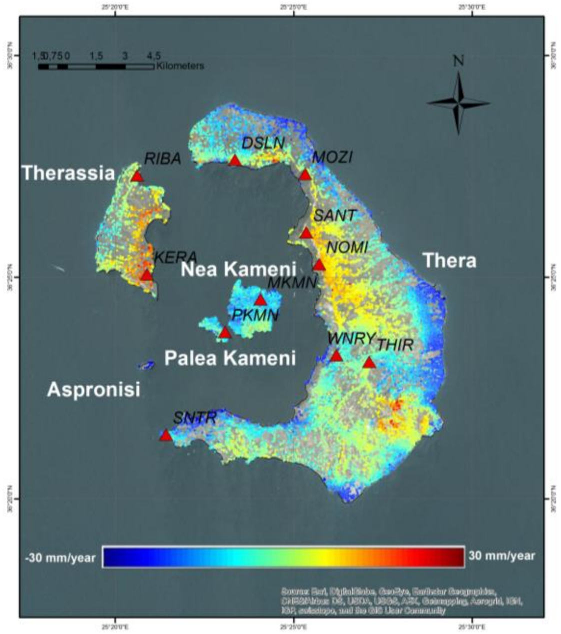

Figure 10. Average LOS displacement rates from COSMO-SkyMed data

When TSX descending data shows positive rates means that the movement is upward or/and eastward with respect to the reference point of MOZI and when there are negative rates, it is about downward or westward tendency of the ground. However CSK dataset is much noisier than TSX and that's why we use them only for qualitative analysis to see the motion pattern and TSX results are used for quantitative analysis for the modelling part.

With regard to COSMO Sky-Med ascending dataset, the deformation rates exhibit exactly the opposite from TSX: positive rates show up and/or west motion. At COSMO Sky-Med results, the velocities rates are higher due to the fact that the incidence angle of the satellite has wider incidence angle than TerraSAR-X (40 deg. comparatively to 28deg. of TSX) and east-west direction contributes more to the LOS measurement.

It is observed that after April 2012 inflation event is over, as we do not notice any upward tendency like 2011-2012 period (Fig 8, 9, 10). The signal in the entire SVC is rather complex and some areas (Mt Profitis Ilias) are strongly correlated with the topography as we used SRTM DEM which has not very good resolution. The most prevailing signal is observed in Nea Kameni and leads to the conclusion that caldera seems to be deflated.

5.1. Nea Kameni

On the pre-inflation period (1992-2010), only a noticeable deformation was observed during the 18 year of monitoring. This is the concentric deflation pattern centered at the southern part of Nea Kameni, demonstrating dominant subsidence of 5.2mm/yr (Fig. 2) [3].

During the inflation event, Nea Kameni Island reached a peak of 40 mm/yr uplift in its north-eastern part. While up until January 2012, the uplift rate is almost constant, since February 2012 uplift stopped. This pattern is also detected in the deformation behaviour observed with the GPS measurements [2].

It is detected that for the period mid-2012 to mid-2013 the area has been deforming with over -6 mm/yr with TerraSAR-X data. During the 2015 study period in 2015, CSK displayed also a noticeable subsidence (Fig. 11).

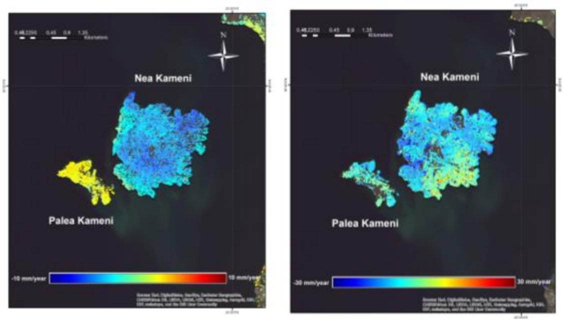

Figure 11. Nea Kameni displacement rates from TerraSAR-X (left) and COSMO-SkyMed (right) data.

Nea Kameni Island shows a negative rate to both datasets, ascending and descending hence it can be inferred that this corresponds to vertical subsidence with respect to MOZI reference point.

5.2. Imerovigli

Imerovigli area indicates rather low-displacement rates that do not exceed on average 1mm/yr prior to the inflation event. During the unrest period, this area had the maximum uplift (+15mm/yr) an unprecedented magnitude for Santorini since quantitative monitoring of the area began.

After the event, CSK ascending frame shows an uplift (up and/or west) and TSX descending a subsidence (down and/or west). Thus, the area around Imerovigli is heading to the West with respect to MOZI (Fig. 12) and approaches Nea Kameni Island.

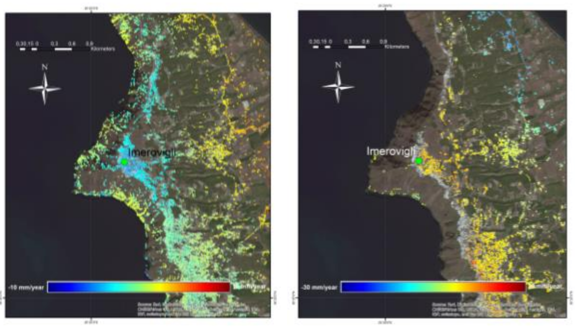

Figure 12. Imerovigli displacement rates from TerraSAR-X (left) and COSMO-SkyMed (right) data.

5.3. Therassia

At the pre-inflation period, Therassia Island seem to be almost steady and only the south-eastern part of the island subsides with a rate of about 4 mm/yr with respect to the reference area of this processing (Mt. Profitis Ilias).

Therassia Island was relatively stable at the inflation event ranging from 0mm/yr to −10mm/yr in western Therassia with respect to MOZI reference area.

In May 2012-June 2013 period there is uplift (Fig. 13) in the western part of the island. In the 2015 period with the ascending dataset, it is observed subsidence at the same part of the island.

As a result, Therassia in the post-inflation period has been moving to the East, coming closer to Nea Kameni Island.

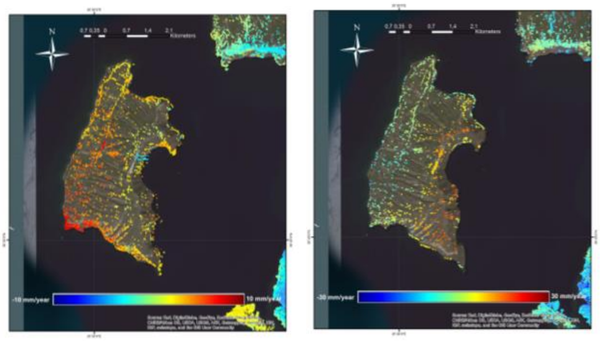

Figure 13. Therassia island displacement rates from TerraSAR-X (left) and COSMO-SkyMed (right) data

6. MODELING APPROACH

Data modeling was carried out only for TSX measurements, because of the low signal-to-noise ratio affecting CSK results. We run a non-linear inversion to get the best-fit parameters of a simple point pressure source [11], by minimizing a chi-square cost function through a Levenberg-Marquardt algorithm [12], implemented with multiple restarts to work around the presence of local minima.

Actually, after investigating several solutions, we decided to constrain the source location and depth such to keep coherence with the modeling results of the inflation period [2]. Under these conditions, the inversion becomes linear, making the source volume variation the only parameter free to vary in order to get the best-fit prediction (Tab.1). A further parameter is however introduced, without losing the linearity conditions: a constant value affecting all the observed data. While this stratagem is usually introduced to account for a possible offset affecting InSAR data, due to an improper reference point, in this case we exploit this opportunity to account for a possible large scale signal due to the island tectonic drift, whose presence is also visible in GPS data.

Table 1: The best fit parameters of the Mogi model

Data set	**Longitude**	**Latitude**	**Depth (km)**	**ΔV (10^6 m^3/yr)**
TSX	25.3844	36.4286	3.48	-0.76

We therefore simultaneously found the best fit volume variation of the Mogi source together with the tectonic signal, projected into the line-of-sight (Fig. 14).

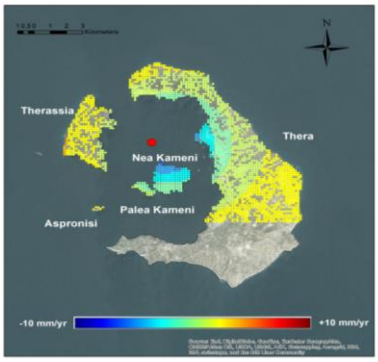

Figure 14. Mogi model of TerraSAR-X dataset

7. CONCLUSIONS AND FUTURE WORK

Time series analysis is a promising and powerful tool that has been developed over the last decades to produce Line of Sight (LOS) ground deformation maps with wide coverage and high accuracy.

SVC experiences two types of movements: The tectonic motion, which moves SVC South and East and the local volcanic one with much smaller rate which move every spot of the island with different velocities with reference area the MOZI GPS station.

In this study, PS and SBAS approaches were used to measure deformation on the island of Santorini. The signal for the rest of the SVC indicates a phase of relative stability after the inflation event in 2012. Velocities indicate mainly subsidence rates at Nea Kameni Island maybe due to smooth deflation of the volcano. Additionally, GPS data indicate that SVC is heading to South and East and that implies that its normal tectonic motion has recovered and returned to the velocities it had before the inflation episode.

Finally, Mogi model for inflation phase provides a good fit also for the post-inflation motion.

On-going works includes the time series analysis of Sentinel-1 data for the period 2014 until today.

8. ACKNOWLEDGMENTS

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