Santorini seismo-volcanic event: GNSS time series and preliminary models

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Table of contents

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1. Location of the three available stations, SANT, 048A and SANU

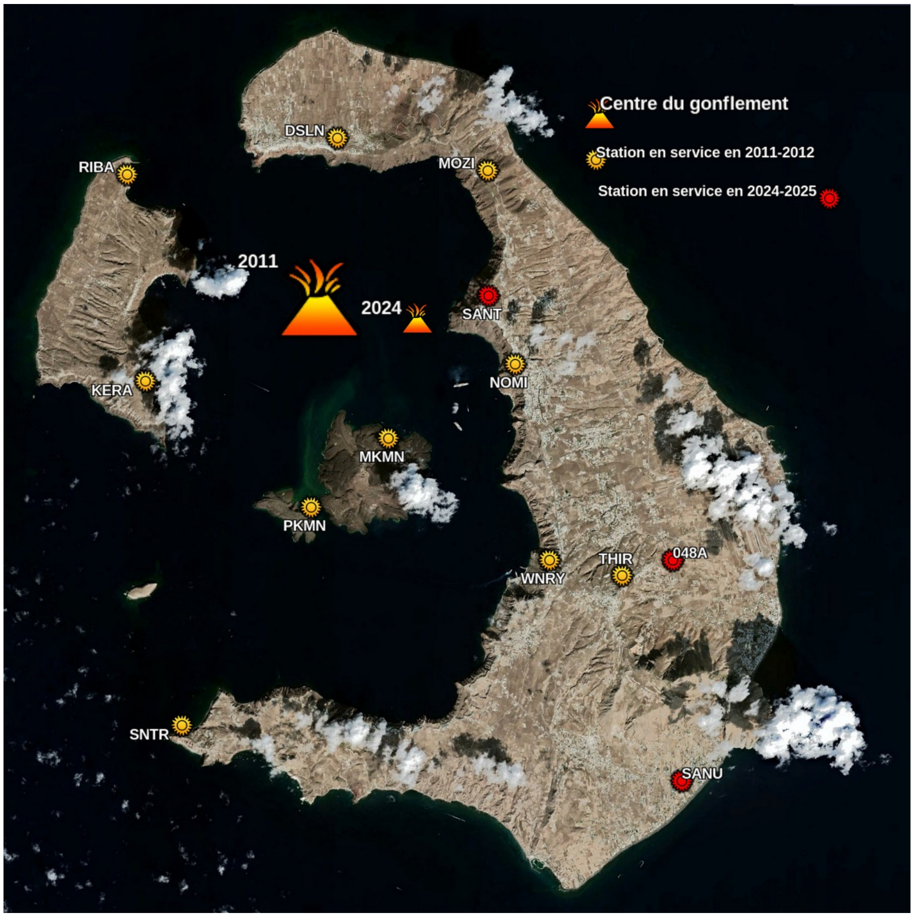

Figure 1. The stations SANT, 048A and SANU are in red. The stations in yellow are those that were existing at the end of the 2011-2012 unrest, they were then removed in the following years

Station	Long. (°)	Lat. (°)	Elev. (m)	Owner	Name of the network	Data available since
SANT	25.42261	36.43360	392.018	Metrica & NKUA	HxGN SmartNet[5]	3/2/2011
048A	25.46350	36.38769	120.832	Hellenic cadastre	Hepos[6]	25/12/2021
SANU	25.46603	36.34905	42.797	Tree Company	Uranus[7]	28/1/2016

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[5] https://info.metrica.gr/index.php/en/smartnet-network-hxgn

[6] https://www.hepos.gr/en/home/

[7] https://www.uranus.gr/

2. Time series 2022-2025 of SANT, 048A and SANU

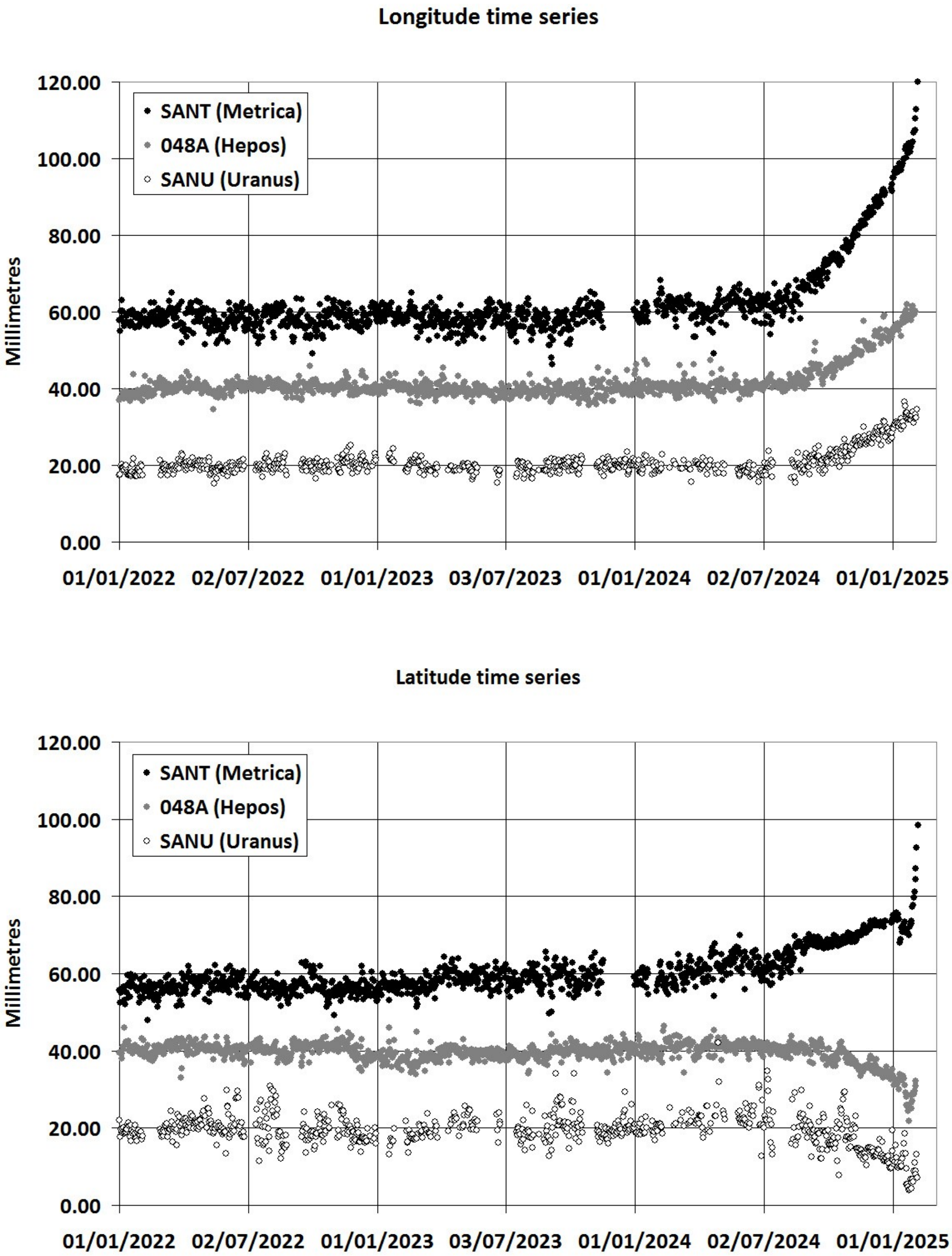


Figure 2. Horizontal (E-W and N-S) time series of SANT, 048A and SANU

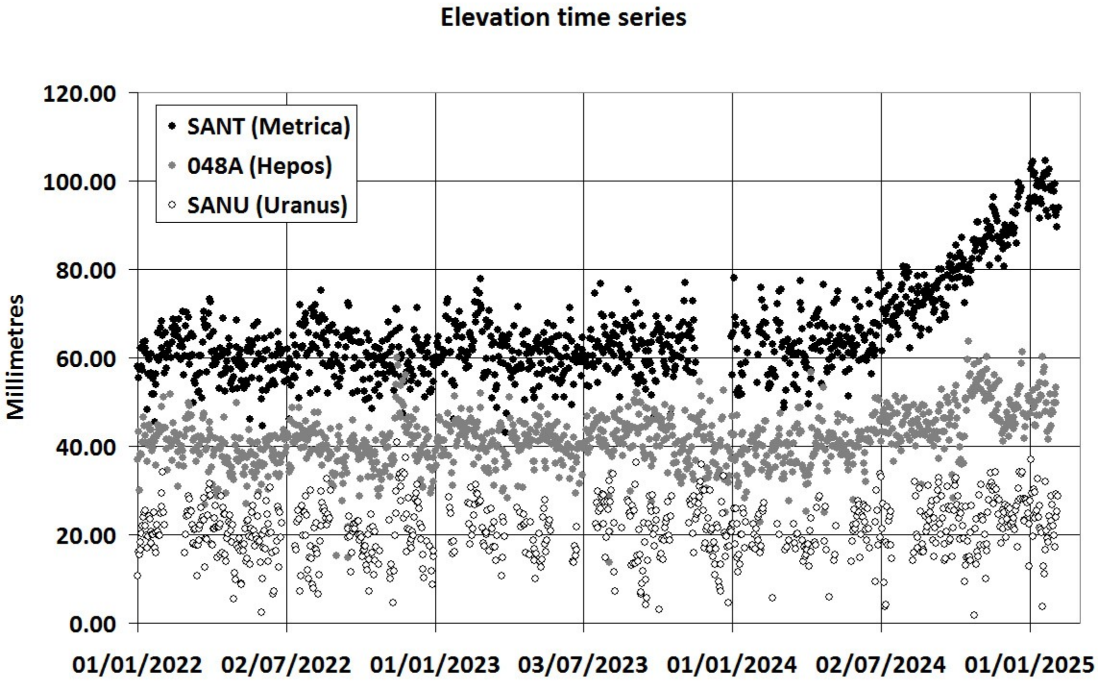
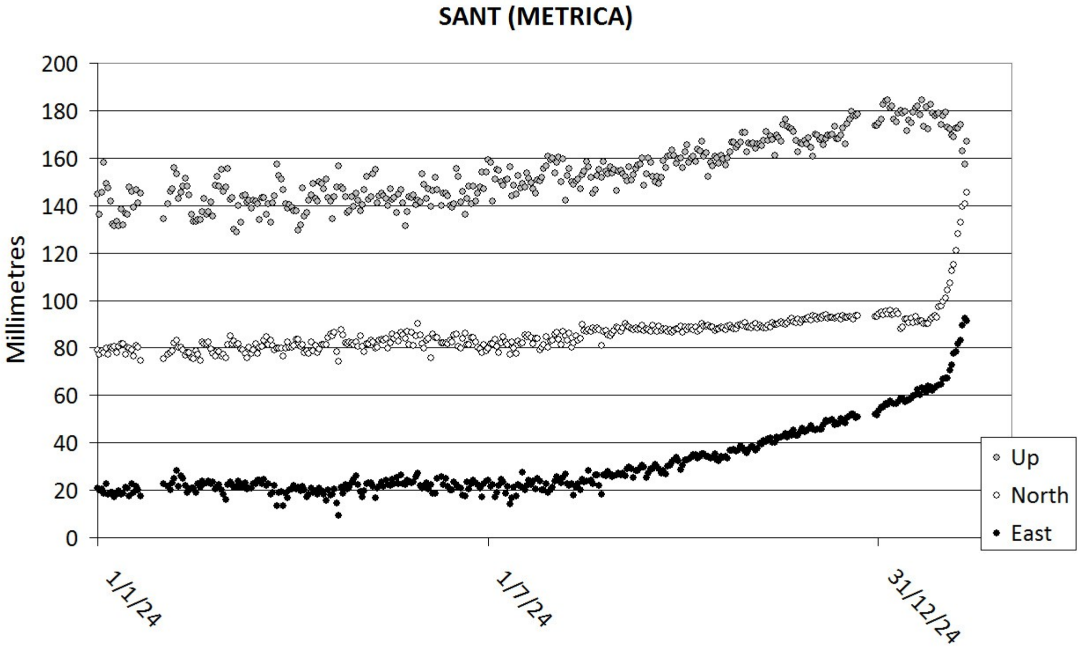


Figure 3. Vertical time series of SANT, 048A and SANU

3. Update of the time series of SANT (latest data February 11)

The deflationary trend that began around 20 January accelerates. The fast movement towards the NNE that began on 29 January is continuing.



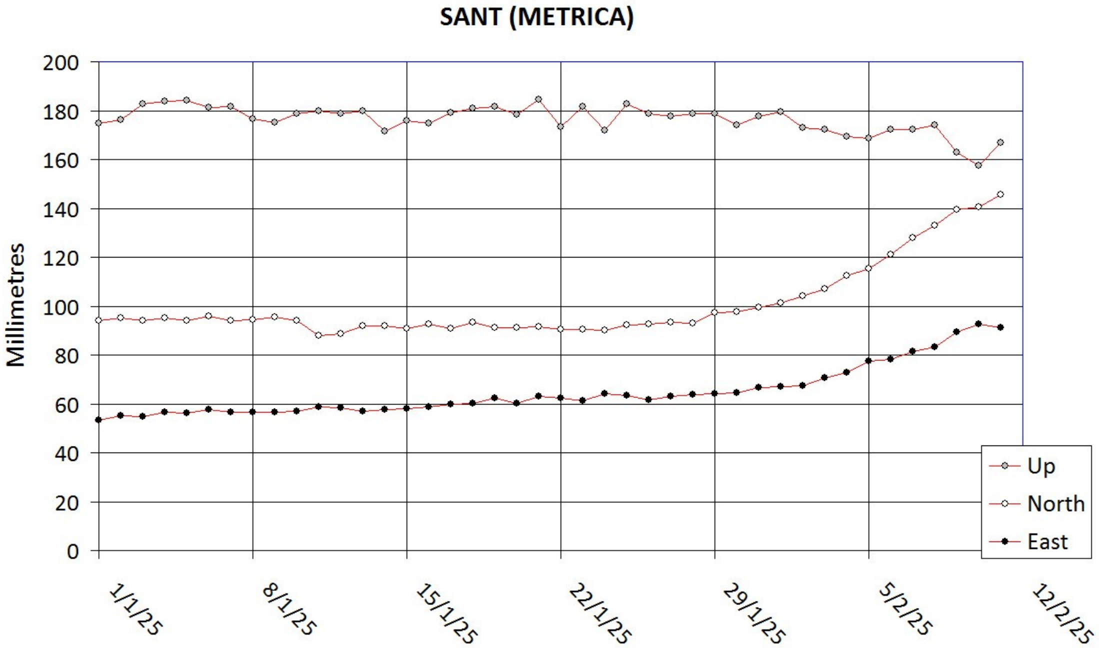
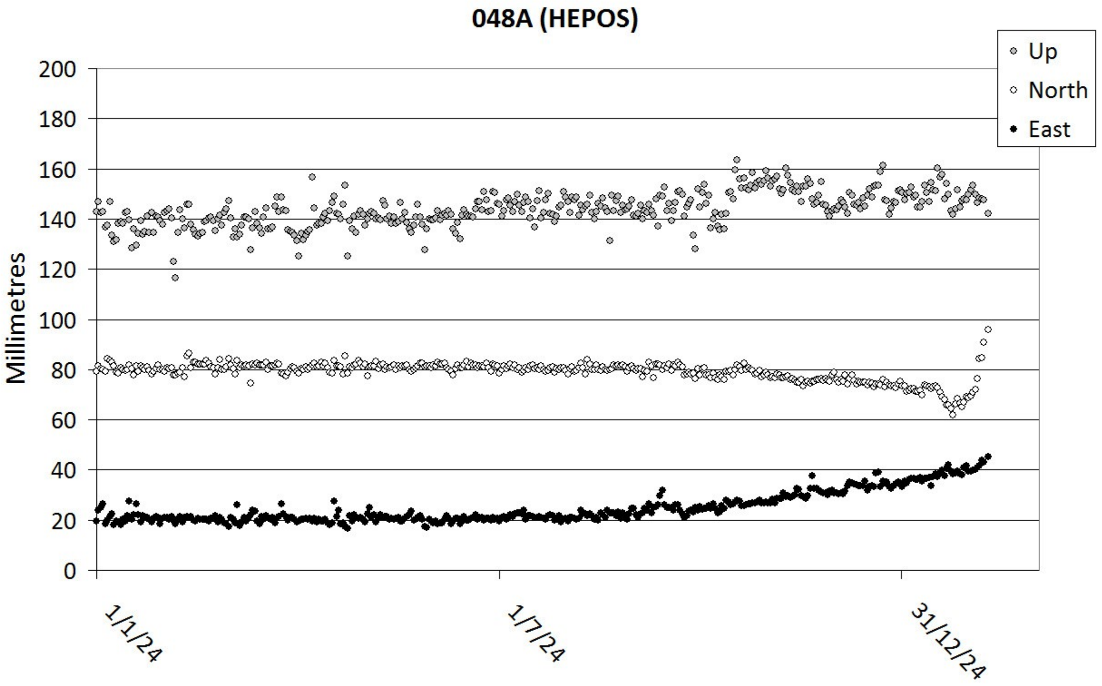


Figure 4. Time series 2022-2025 and 2025 of SANT

4. Update of the time series of 048A (latest data February 9)



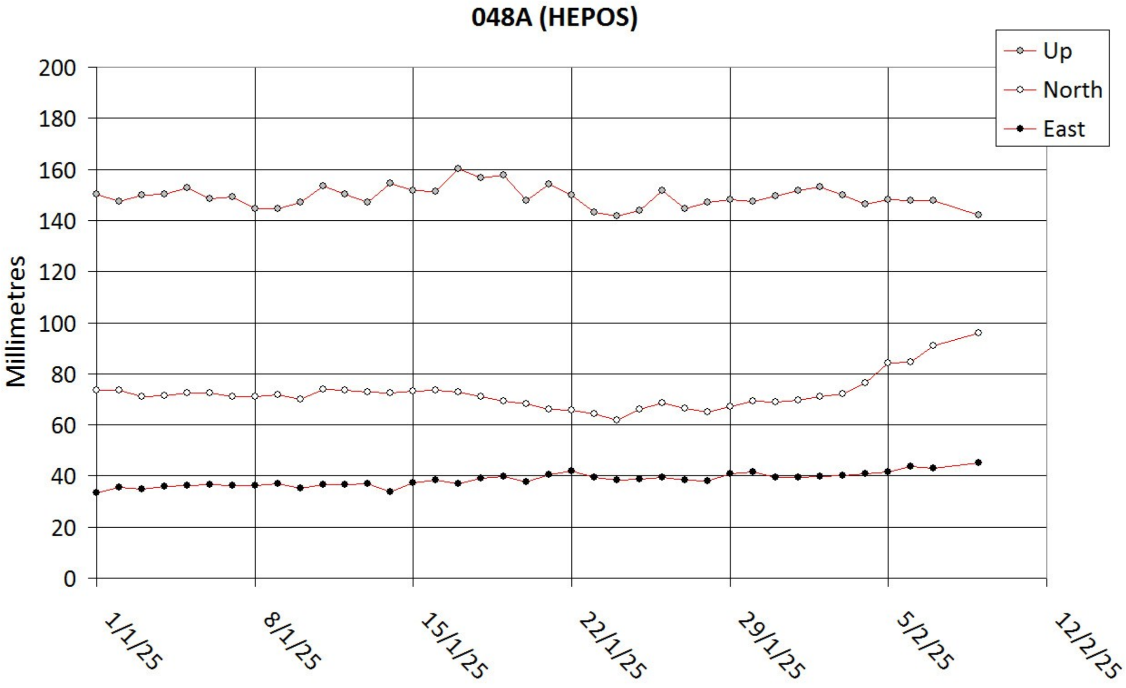


Figure 5. Time series 2022-2025 and 2025 of 048A

5. Stations velocities before and during the beginning of the unrest (until January 19)

The ITRF 2014 average secular velocity of Santorini recommended by Briole *et al.* (2021) for the analysis of the volcanic activity is 7.4, -15.5 and 0.7 mm yr -1 in east, north and up. They noted also that the average uplift rate of 0.7 mm yr -1 exists and after the unrest of 2011-2012.

The anomalies of velocities reported below correspond to the average anomaly for a period that starts during the summer 2024 and ends on January 19. After this date, there are large changes in the horizontal motions of the stations that are not discussed in this section.

Station	Velocity before 2024 with respect to the average island			Anomaly of velocity with respect to the pre-2024 velocity			Period for which the anomaly is estimated		
	v_E(rel)	v_N(rel)	v_U(rel)	v_E	v_N	v_U	Start	End	Days
	mm yr^{-1}								
SANT	-2.1	-0.7	-0.1	50.8	24.9	62.3	1/6/2024	17/1/2025	230
048A	0.6	-2.7	1.0	39.9	-16.1	25.9	15/8/2024	19/1/2025	157
SANU	1.2	-1.9	1.1	36.5	-32.0	13.6	18/9/2024	5/2/2025	123

The start and end dates indicated in the above table are those which minimise, for each of the stations, the differences between observations and modelling, assuming a constant rate of inflation. It should also be noted that, for each particular station, different dates are also obtained for each of the three channels, and it is the one which minimises the average difference of the three channels which has been selected. The inflation period, as deduced from the combination of information provided by the three stations, is 170 days and this period (therefore conventional according to our model) runs from 1 August 2024 to 24 February 2025.

6. Horizontal location of the inflating source according to its azimuth observed from the stations

A simple way to determine the location of the source of the inflation is to triangulate it based on the azimuths from which the inflation is observed from the various stations. This method is, in principle, quite reliable because the uncertainties on the slopes of the drift of the horizontal components of the deformation during the period of inflation are low, and because the topography of the island (in particular at the SANT station which is close to the caldera rim) is less likely to distort the horizontal components than the vertical one (*to be verified*). The table below lists the azimuths from which the source is viewed from the three stations.

Station	UTM-35 coordinates (East and North, in km)		Azimuth of the source (clockwise from the N in °)	Horizontal distance source - station (km)
SANT	358.61	4033.19	N244	5.2
048A	362.19	4028.05	N292	9.0
SANU	362.35	4023.76	N311	11.3

The figure below shows the location of the source deduced from its azimuthal triangulation. The crossing points obtained from the three pairs of stations define a small triangle whose centre we consider to represent the probable epicentre of the inflation centre. The coordinates of this centre are 25.369° E, 36.415° N and we estimate that the uncertainty in our determination is of the order of 0.7 km. This source would therefore be 2 km south-west of the one established by various authors for the 2021-2012 crisis. It should be noted that the azimuth of the source changes slightly during the inflation phase in autumn 2024. This can be clearly seen on the SANT station signal, with a progressive increase in the rate of increase of longitude while the rate of change of latitude remains stable. A progressive movement towards the north-northeast (therefore towards the 2011-2012 source) of the inflation centre during the autumn can help explain this slight curvature of the SANT signal.

Figure 6. Triangulation of the centre of the inflation source using the azimuth of the deformation measured at the three stations SANT, 048A and SANU

7. Depth of the inflating source according to the pitch observed from the stations

As SANT is located close to the rim of the caldera and may suffer from site effects for the amplitude of its vertical displacements, we used only the zenith angles from 048A and SANU, which gives a depth of source of 4.3 km. If SANT had been retained, we would have obtained a depth of 4.8 km, so not very different. With regard to the estimated source for the 2011-2012 crisis, it was 3.7 km. These different estimates are all close.

8. Volume injected in the source according to the observed motions

Here we use only the data of SANT and 048A that are closer to the source. SANU is less sensitive, and therefore has less weight for assessing the volume. Our estimate for the volume stored in the reservoir at 4.3 km depth during the inflation period that lasted until ~ January 1, 2025 is 6.5 millions of cubic meters. This corresponds to a maximum uplift at the vertical of the source of 190 mm. Assuming an average duration of the inflation of 170 days, this gives a daily uplift rate above the center of the reservoir of ~ 1.1 mm/day, thus 33 mm/month, which corresponds approximately to a fringe in C-band Sentinel 1 InSAR, a value consistent with the findings shown by Tsironi and Ganas in their note of February 11 to EMSC.

9. Change of volume in the reservoir between early January 2025 and February 12, 2025

The vertical displacement of SANT shows that the deflation amplitude accounts at the date of this note for approximately half of the inflation amplitude. This means that approximately 3 millions of cubic meters have escaped from the reservoir. Assuming that this magma has filled a lateral dyke, as it is most often the case on volcanoes, and assuming for such a dyke, buried at some depth in the upper crust, a width of 1 km and a length of 30 km, its thickness would then be 0.1 m. Such a value is small for a magma intrusion in a dyke but observed elsewhere and not impossible [*references needed*].

10. Motion towards north of SANT and 048A

Such a motion is not expected in the case an injected dyke is passing to the north of those stations (in such a case, we would expect the opposite). There is still the need to find an explanation for those fast motions towards north.

11. Installation of a GNSS receiver at Anydros on February 12

A receiver Topcon Net-G5 was installed on February 12 by A. Ganas and V. Sakkas on the small island of Anydros. According to the first available data of Feb. 12, the location of the station is the following:

TRD-ITRF2020 (m):	4618597.045	2220590.293	3784545.647
UTM35 (m):	381796.670	4054605.976	89.452
Geographic (°):	25.6779336	36.6296744	89.452
DMS:	25° 40' 40.56093"	36° 37' 46.82789"	89.452

Figure 7. Location of the GNSS station ANYD installed on February 12

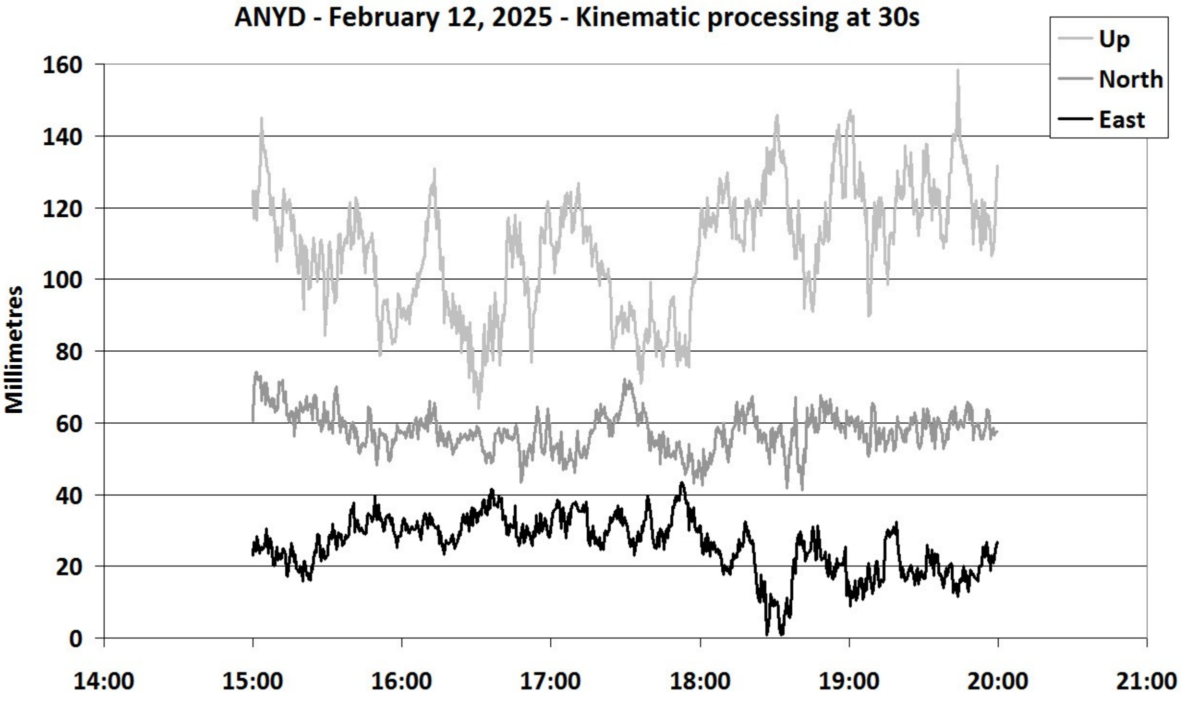


Figure 8. Processing of some data of ANYD in kinematic PPP mode to assess data quality

12. Forthcoming actions

- Inventory of all GNSS stations deployed and operational in the area (regardless the data availability) and prediction of the time series of displacement at those stations (in progress)

- Modelling taking into account topography and non-point source (in progress)

- Inventory of the tide gauges in the area and evaluation of the possibility to install GNSS stations nearby

- Inventory of the campaign GNSS points

13. Acknowledgements

Simon Bufferal (ENS), George Polykretis (TreeComp), …

14. References

P. Briole, A. Ganas, P. Elias, D. Dimitrov, 2021. The GPS velocity field of the Aegean…
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