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Republic of Poland

JAGIELLONIAN UNIVERSITY
IN KRAKÓW

EUROPEAN SPACE AGENCY

15 - 19 June 2026 | Auditorium Maximum of the Jagiellonian University, Kraków, Poland

FRINGE 2026

Unwrapping the phase of a single focused SAR image : application to Sea Level Anomaly

Marcello DE MICHELE[1], Guillaume BACQUES[1] with Remy Asselot [1]

(1) BRGM, French Geological Survey

The phase of a focused SLC

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Key Points of the presentation that I am not presenting today:

-We propose a method to unwrap the phase of a single Synthetic Aperture Radar image, classically assumed to be stochastic noise.

-Our method yields the lengthening or shortening of the optical path from a single Sentinel-1 acquisition.

-This method might enable the use of SAR archives for coastal sea-level measurements, since 1991, a research area where observations are lacking.

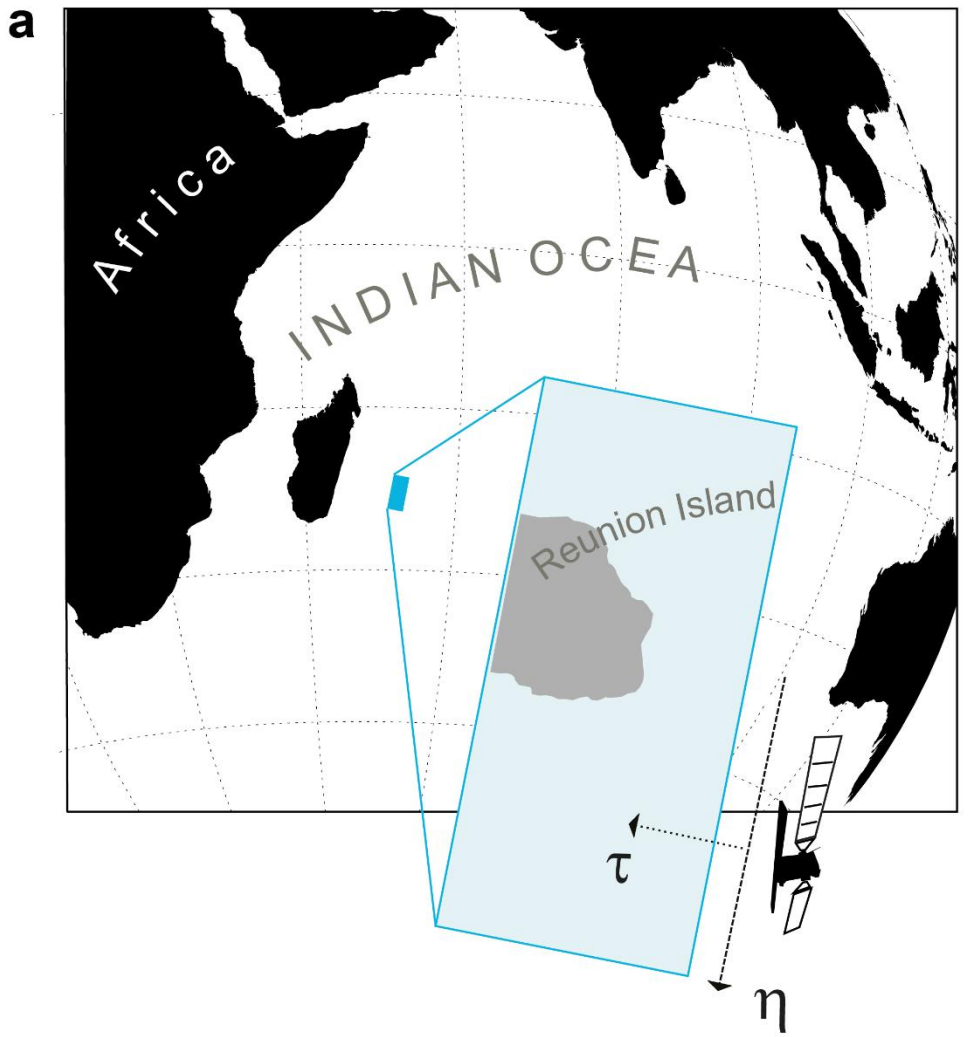
Key Points of this actual presentation:

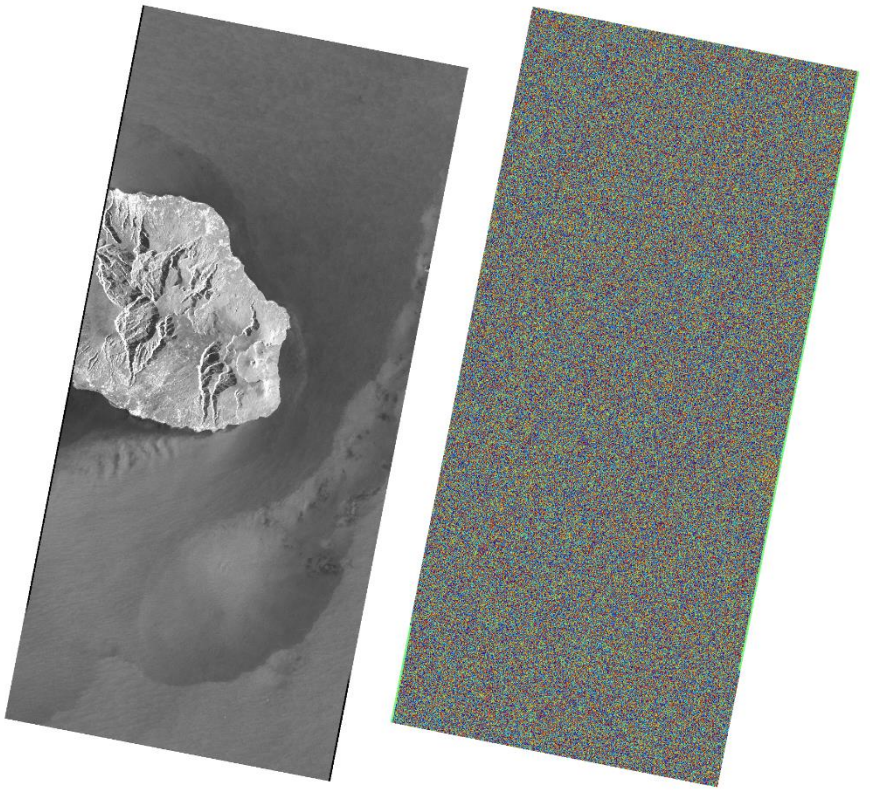
-the phase of a (focused) SLC carries a number of physical information, today not yet fully explored: can we assess them ?

-Can we measure the SAR optical path from a single SLC while we have learned at school and from books that the phase of a focused SLC is “stochastic noise” (quote).

-We are at a point of our research where we feel that we have to open our results to the SAR/InSAR community

Study area / amplitude / phase





Please, if you are inspired by any part of this presentation, cite it as :

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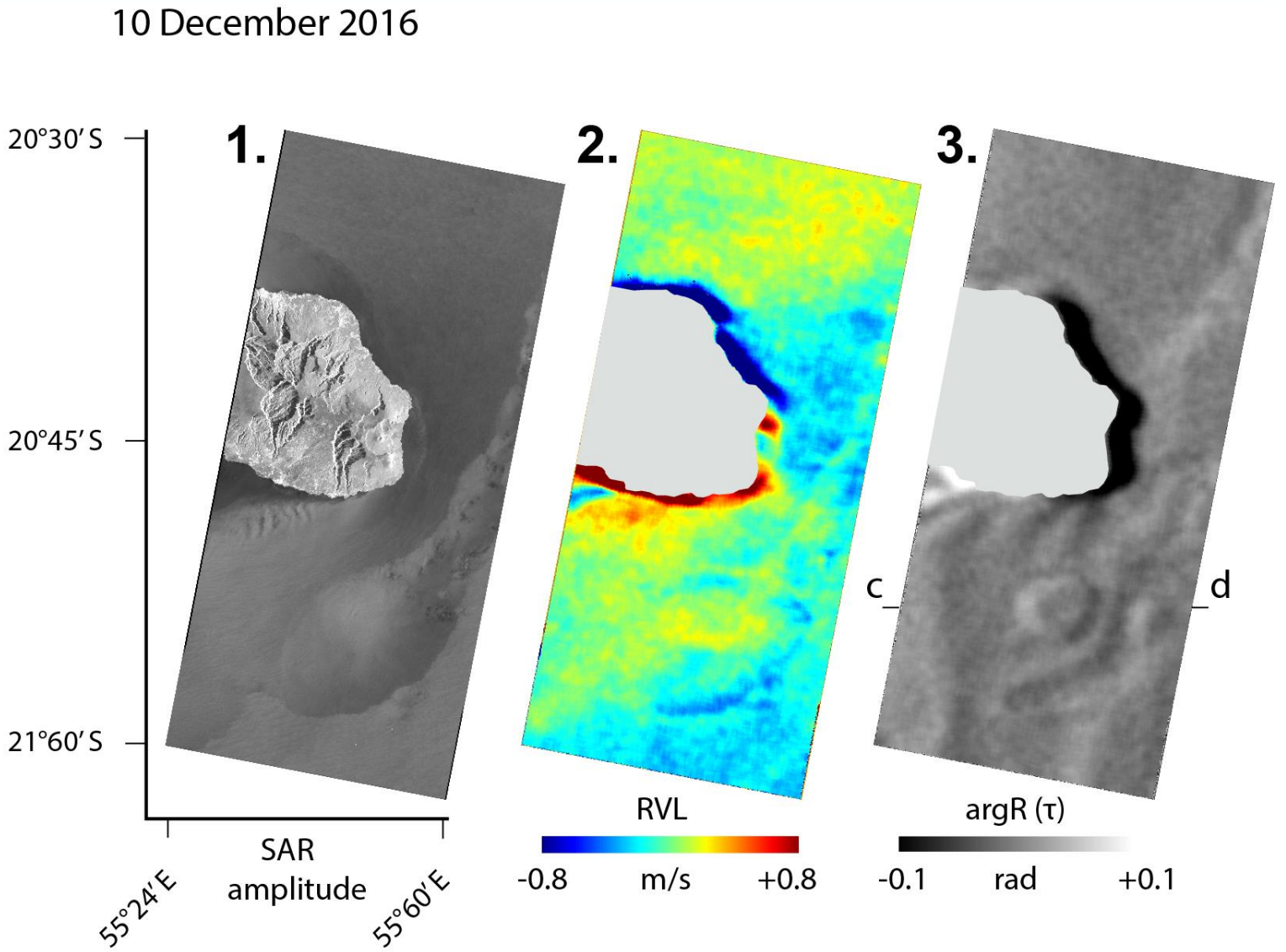
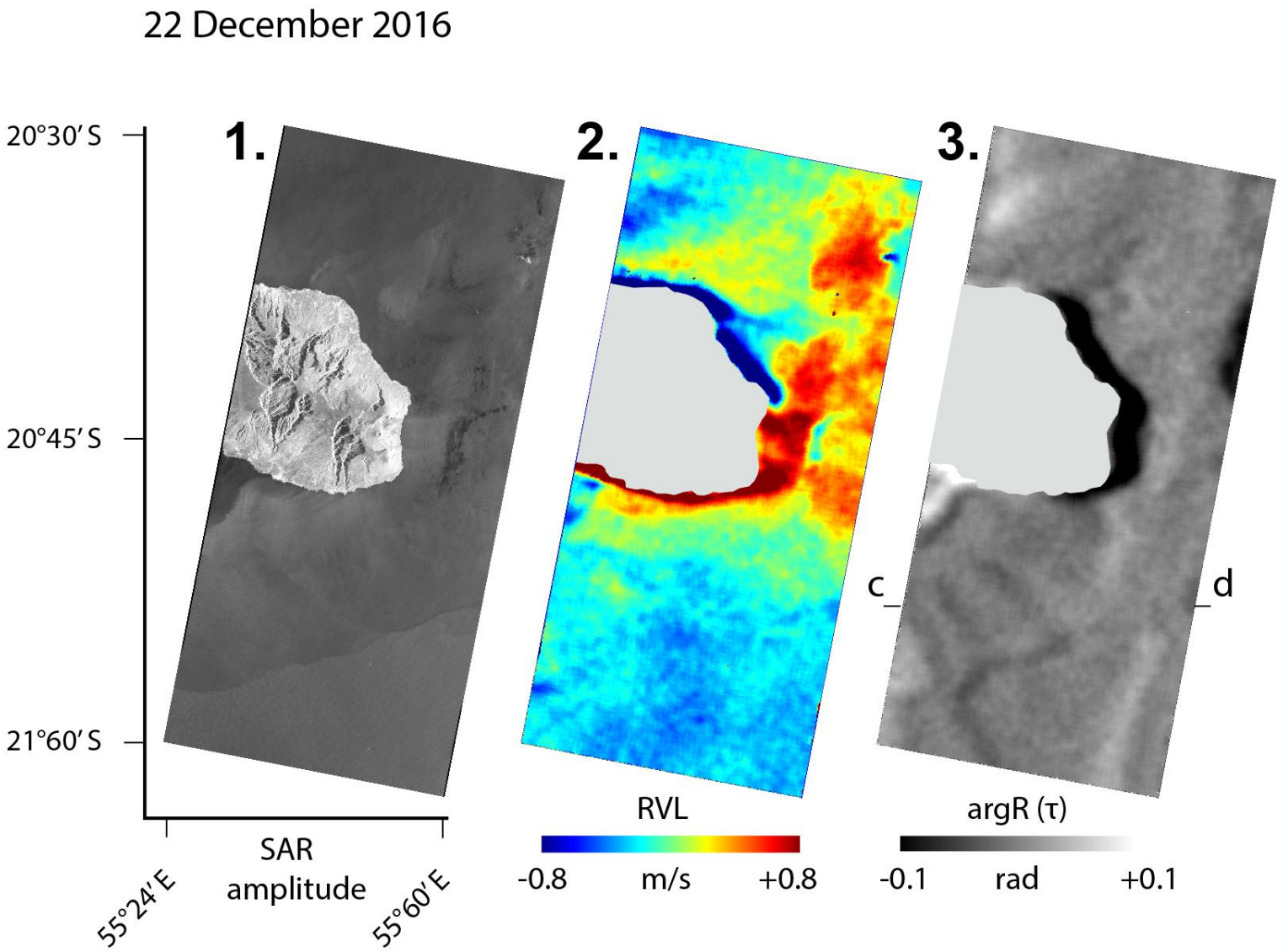
Study area / RVL / argR(τ)



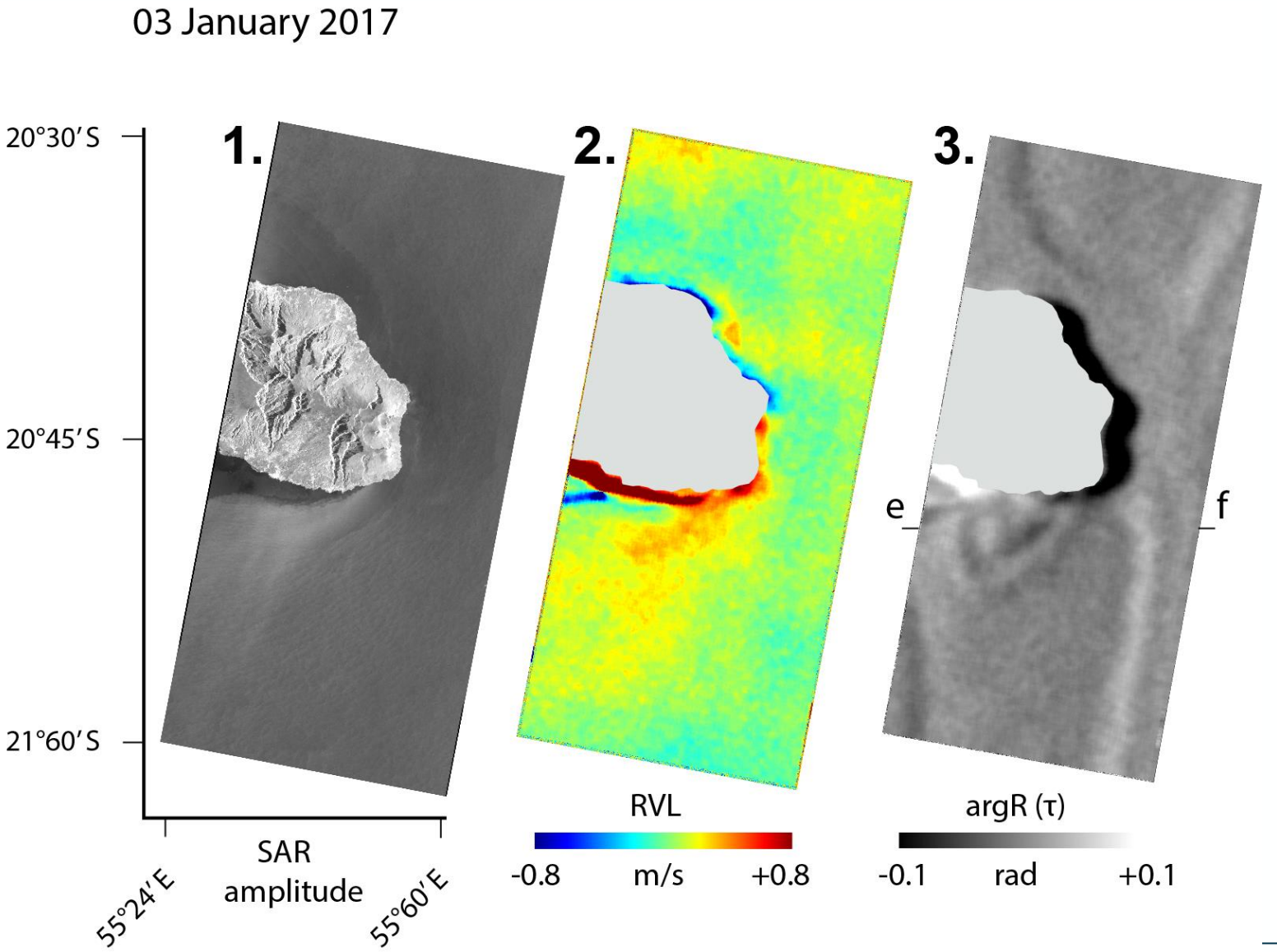
$$\arg R(\tau)$$

$R_{(\tau)}$ is an estimate of the autocorrelation function obtained from *n+1* range pixels.

Study area / RVL / argR(τ)

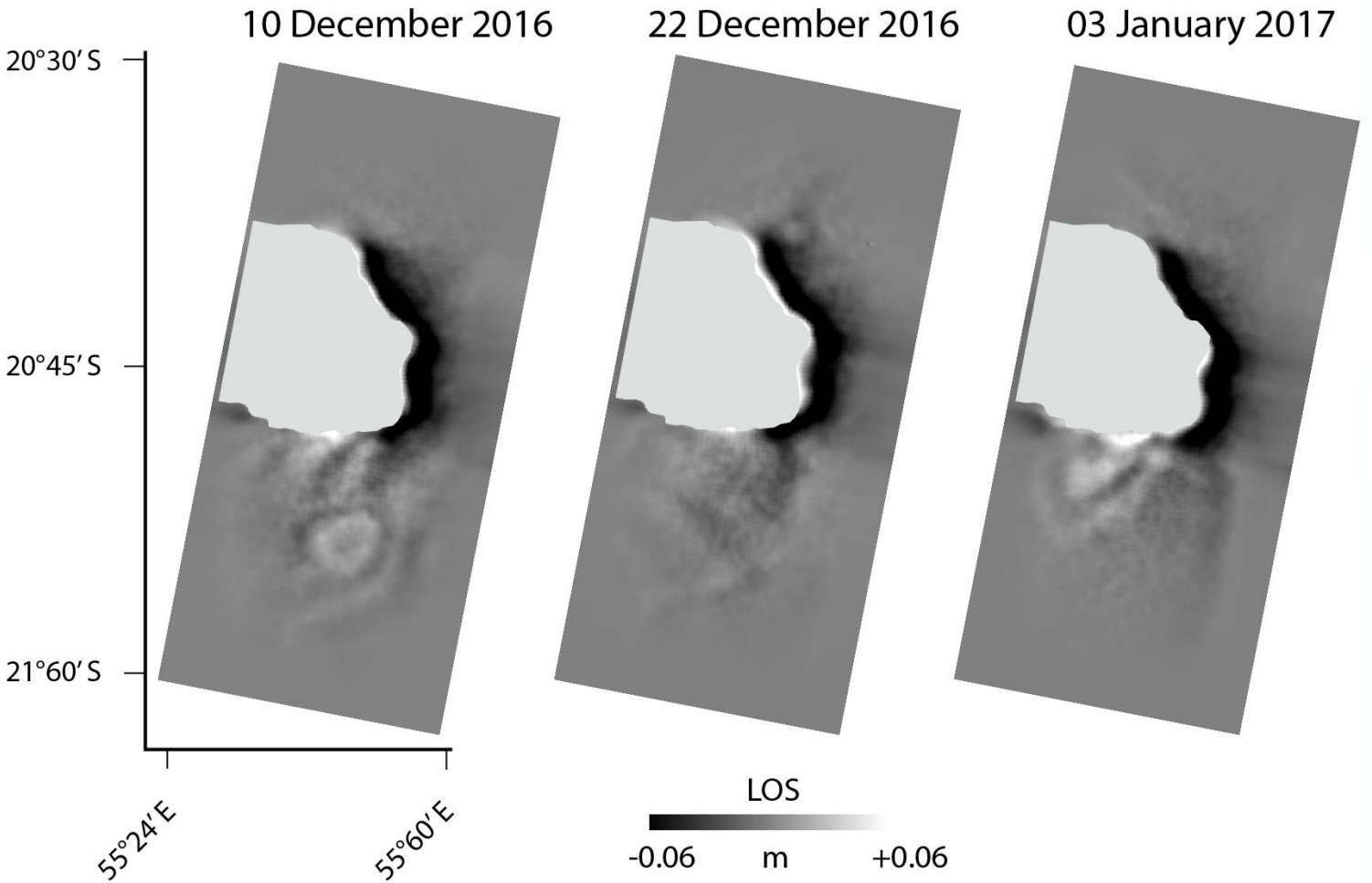


Study area / RVL / argR(τ)



Integrating argR(τ) :

the integram



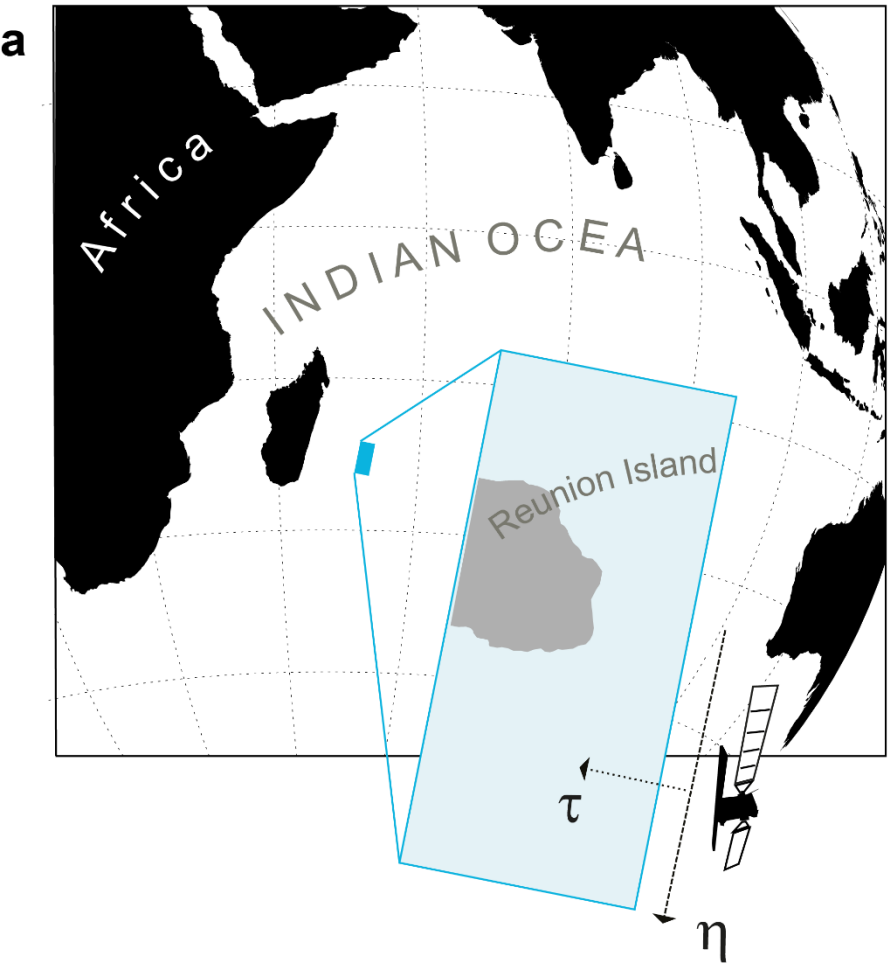
$$dr_\tau = \frac{\lambda}{2}\frac{1}{2\pi}\arg R(\tau) \quad (1)$$

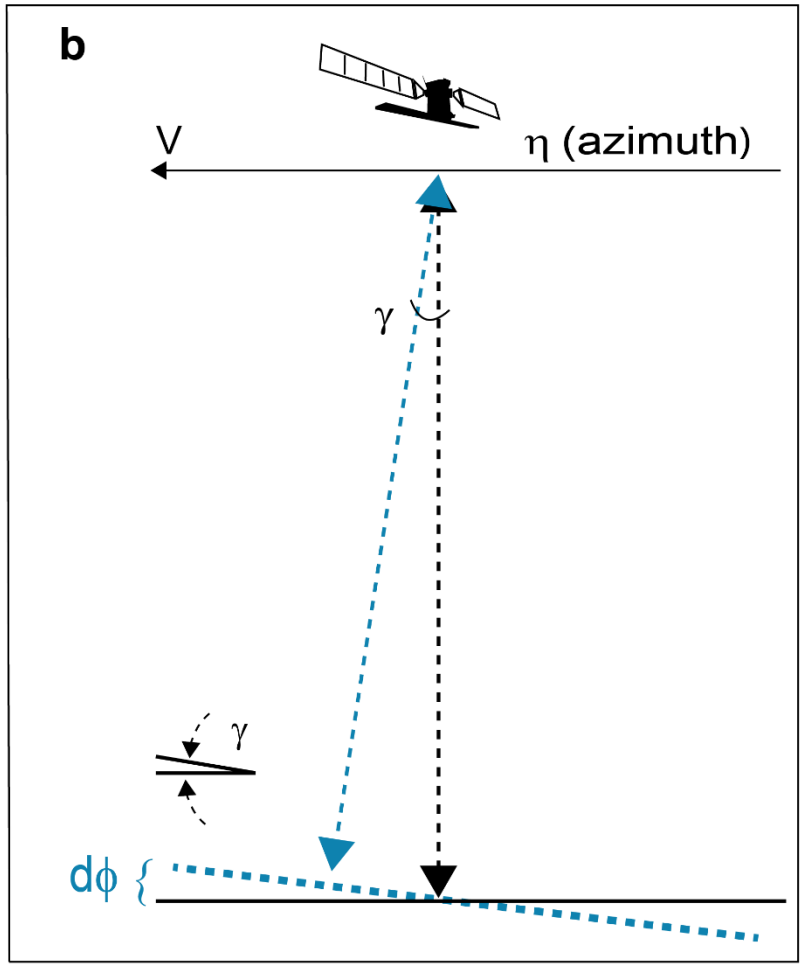
$$= < \text{extra } optical\ path >$$

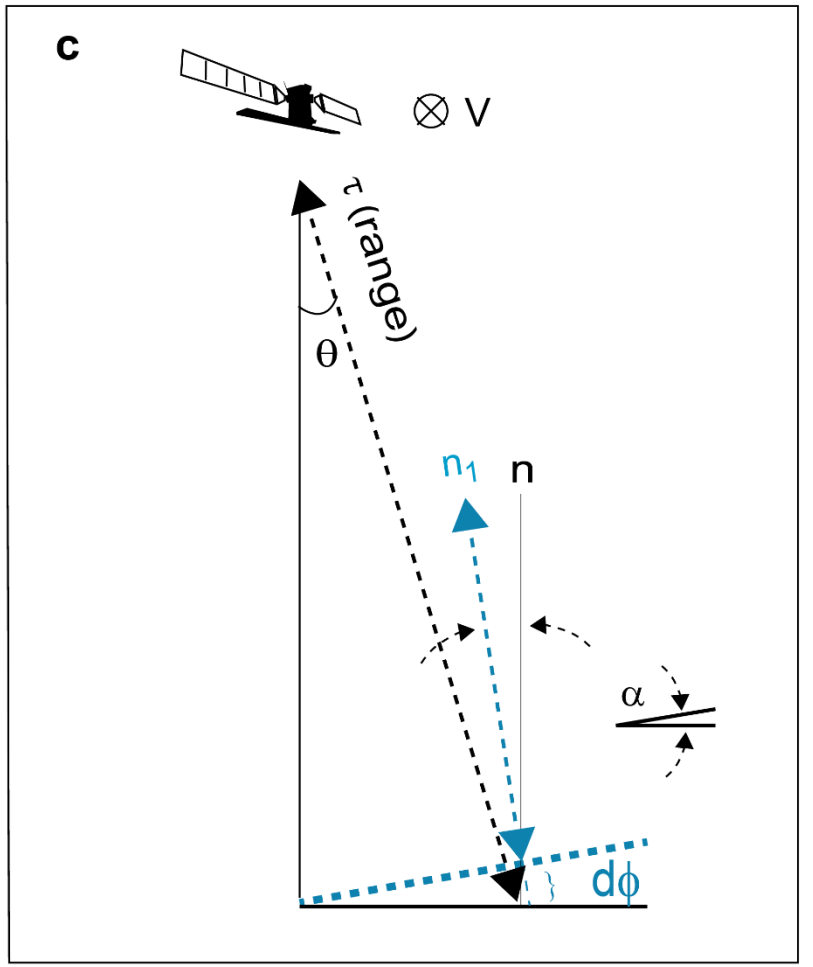
$$dr_\tau \leftrightarrow \Delta R(\omega)$$

$$\int_0^x dr_\tau\, dx + k \leftrightarrow \frac{\Delta R(\omega)}{j\omega}$$

Interpretation: towards a possible geometrical model ?







Interpretation :

Our results, show a time-varying, coherent and spatially correlated SAR phase signal, which is calculated from single SLCs, at different dates at high spatial resolution (166 m). At each SLCs dates, this signal appears to correspond to a physical phenomenon related to ocean dynamics. Since Sentinel-1 focusing processor uses the GETASSE30 DEM to focus the SLC phases, a statistically significant phase variation, dr_τ, within the *integram* could indeed represent a physical discrepancy between the GETASSE30 DEM and the true surface. In this study, a discrepancy between the DEM's mean sea surface and the actual instantaneous sea level, is the sea level anomaly (SLA), at the SLC acquisition date.

Study area / RVL / argR(τ)

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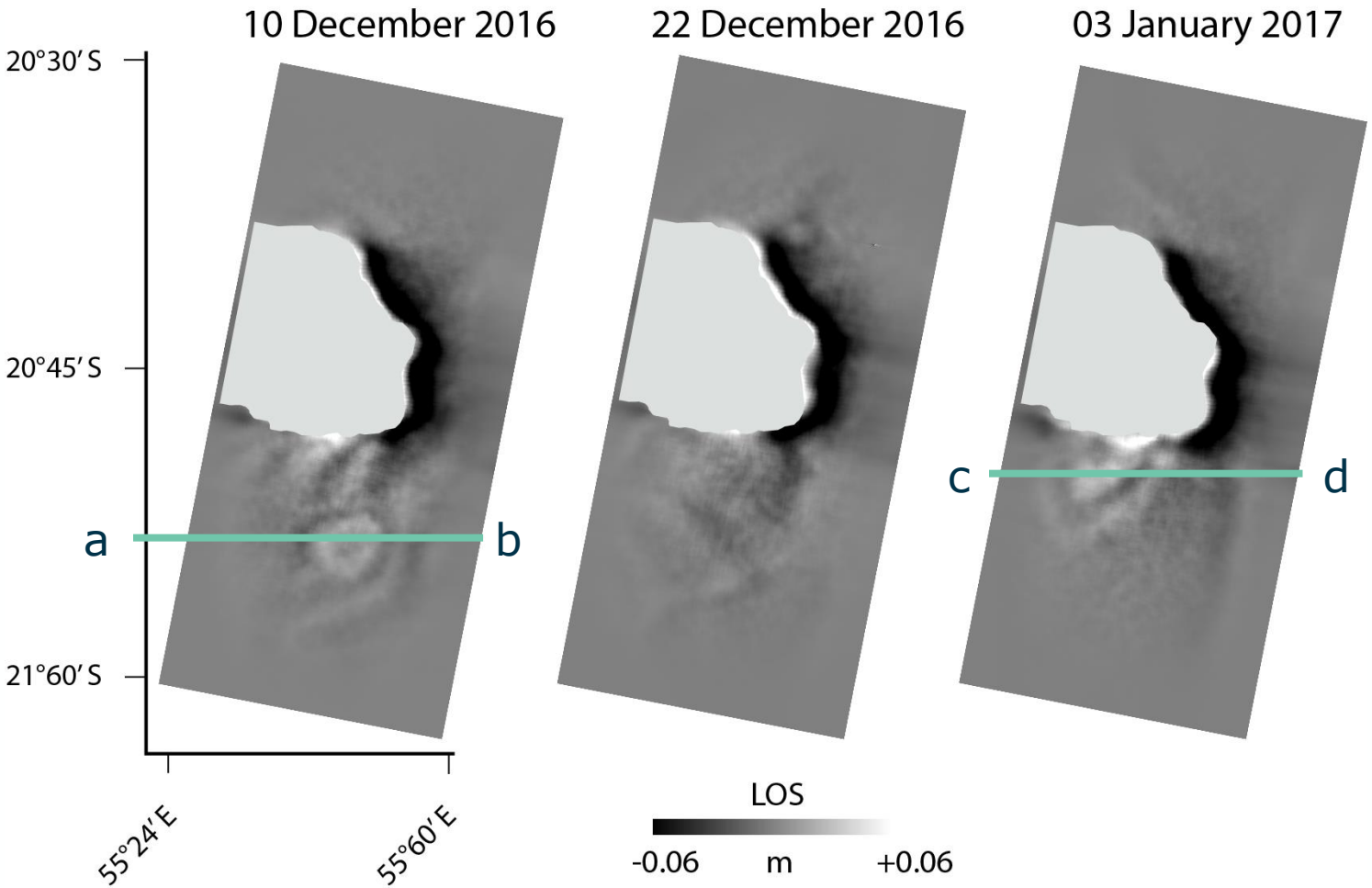
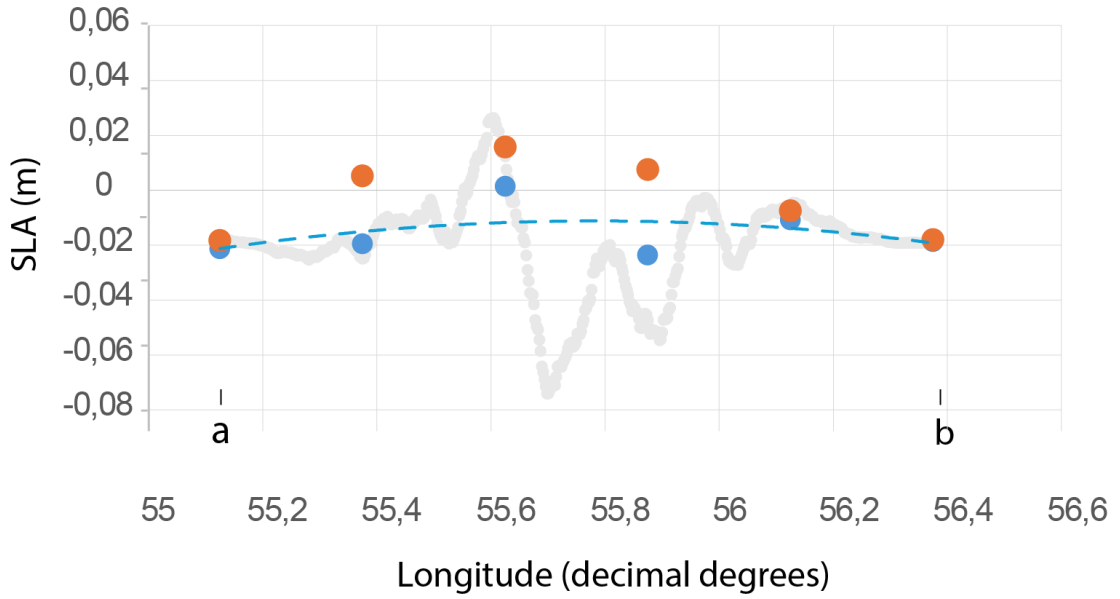
the integram



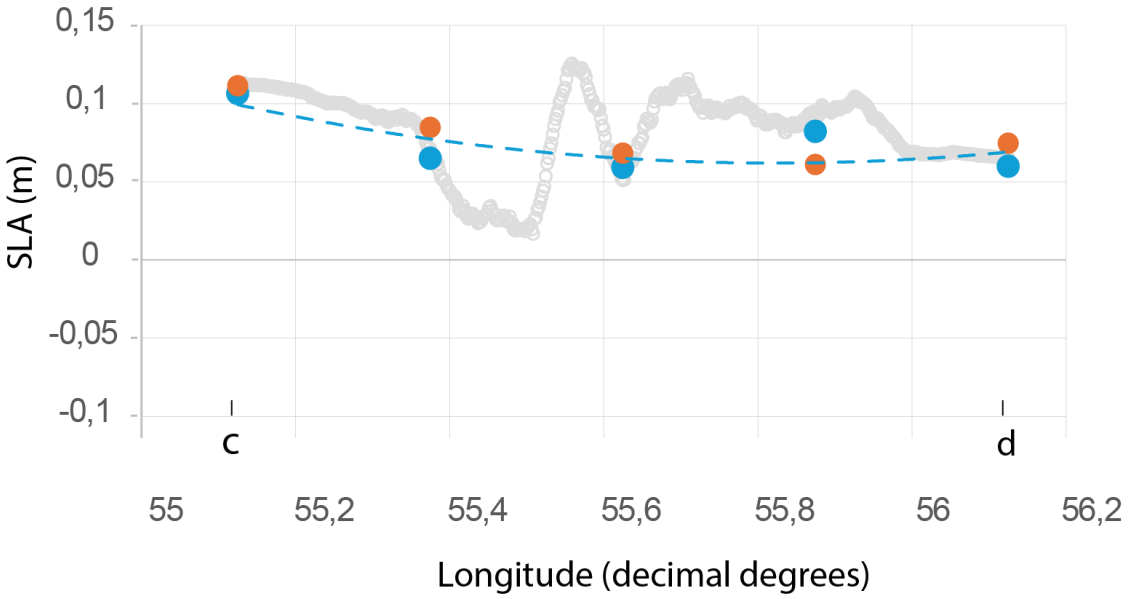
Comparison with altimeters

SLA: Sea Level Anomaly provided by CMEMS
(Copernicus Marine and Environnement Monitoring Service)

a.

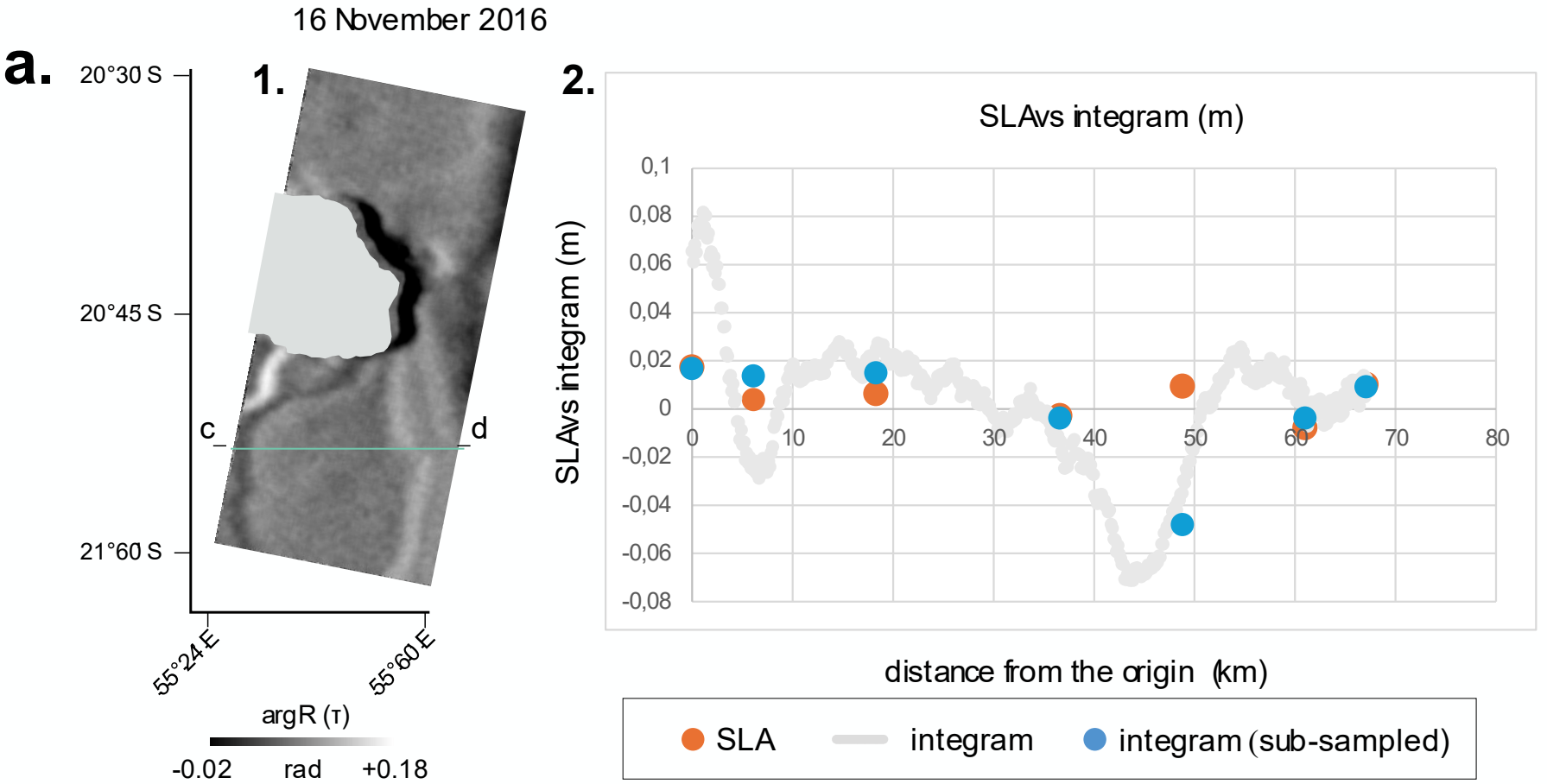


b.

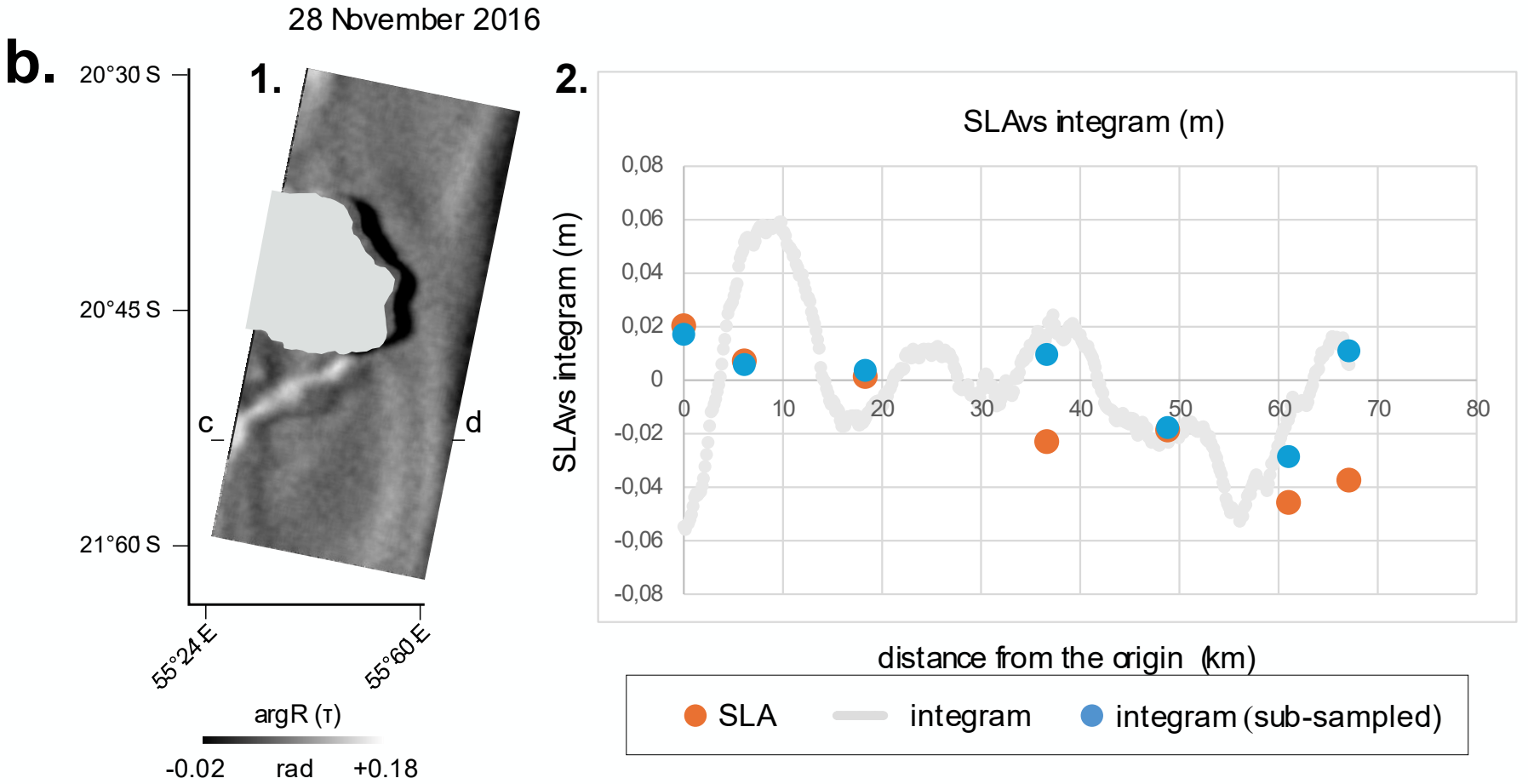


SLA integram integram (sub-sampled)

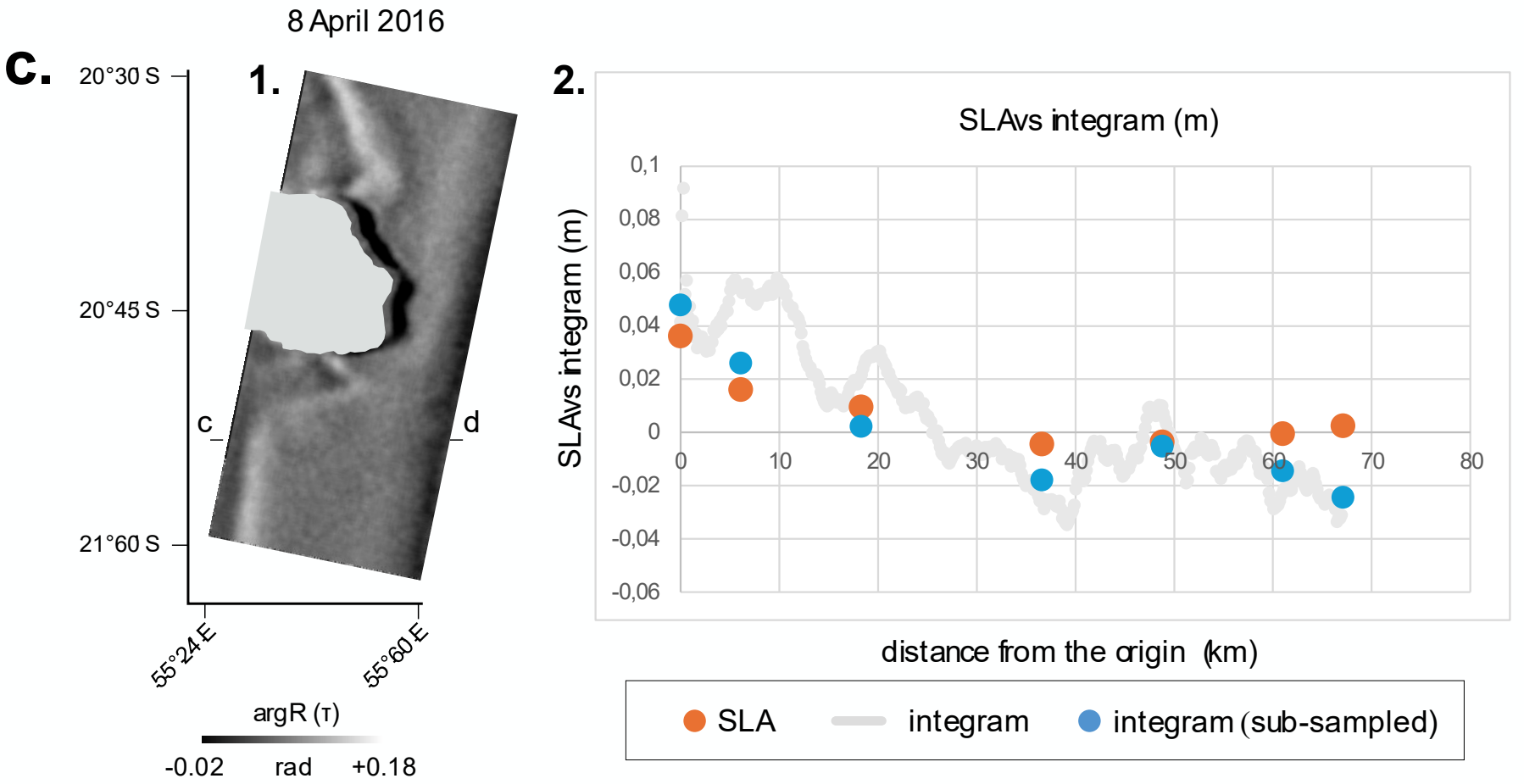
Comparison with Altimeters



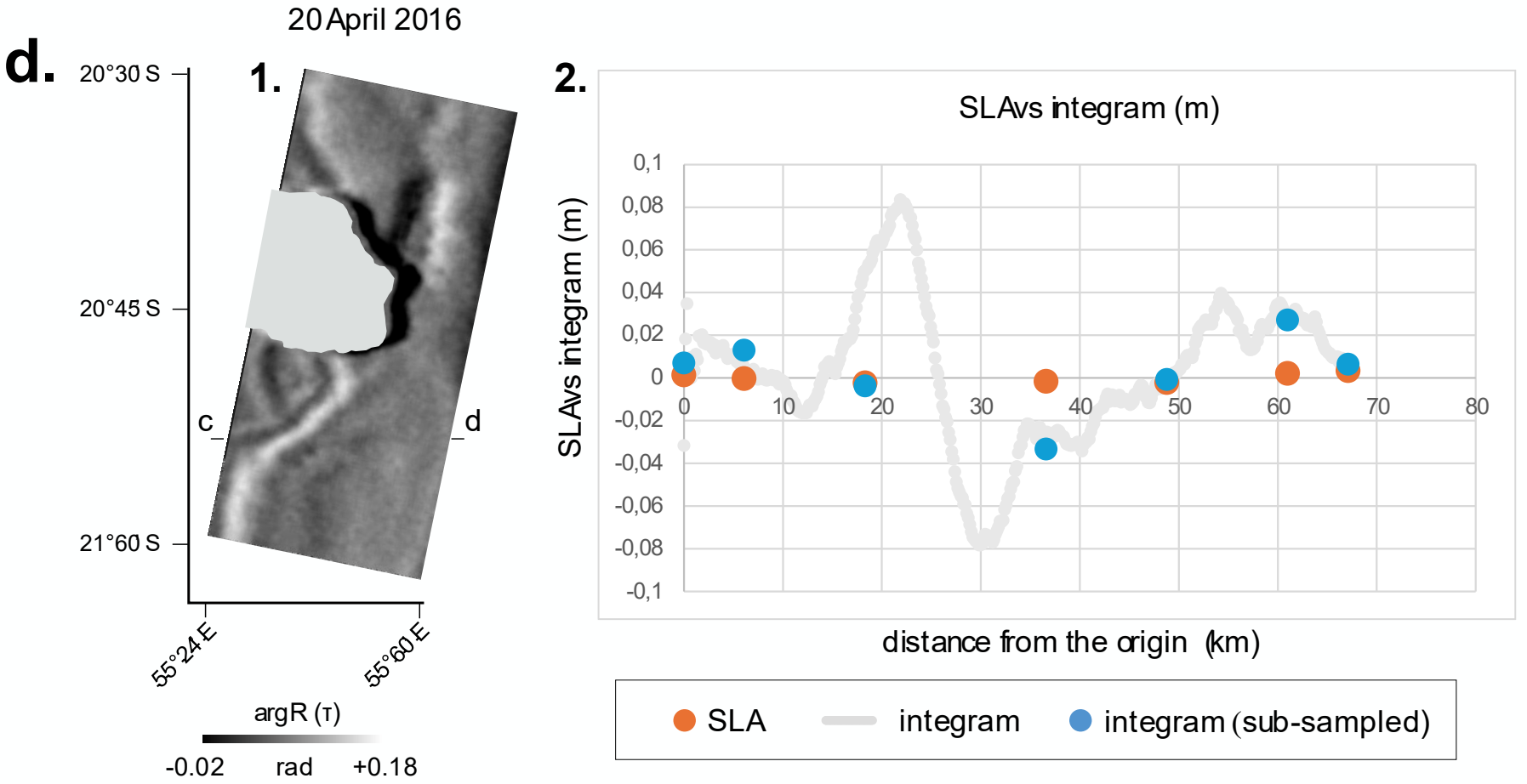
Comparison with Altimeters



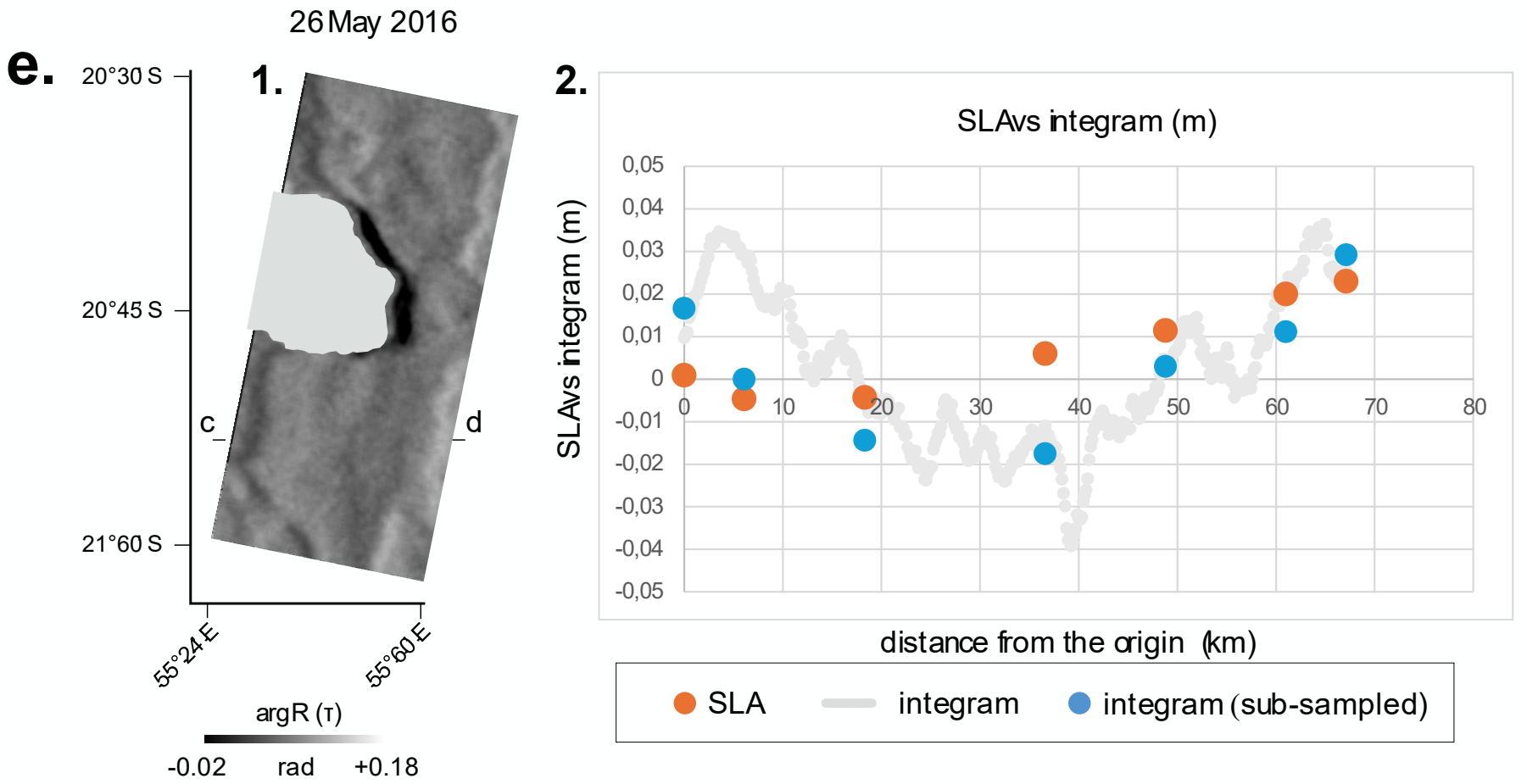
Comparison with Altimeters



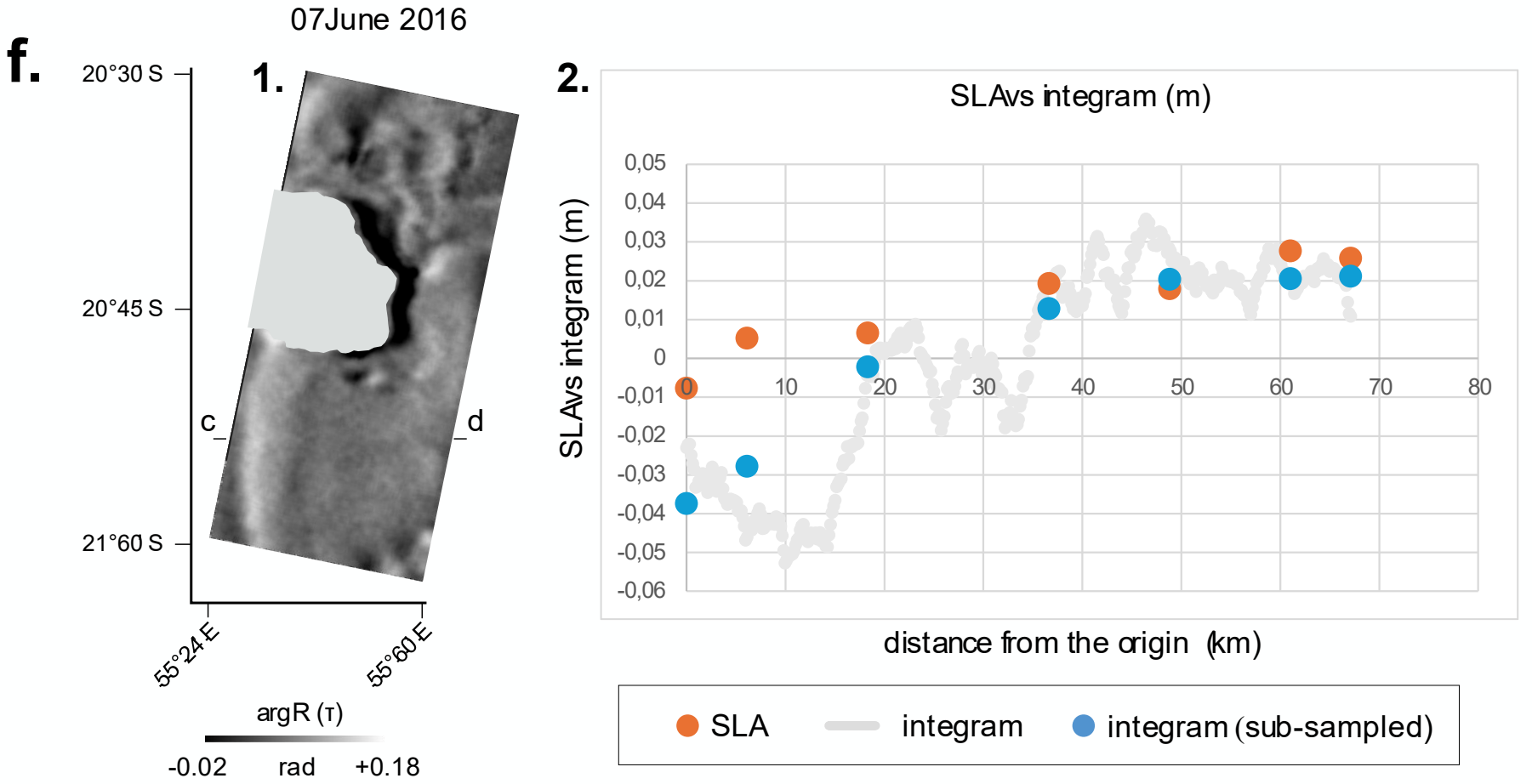
Comparison with Altimeters



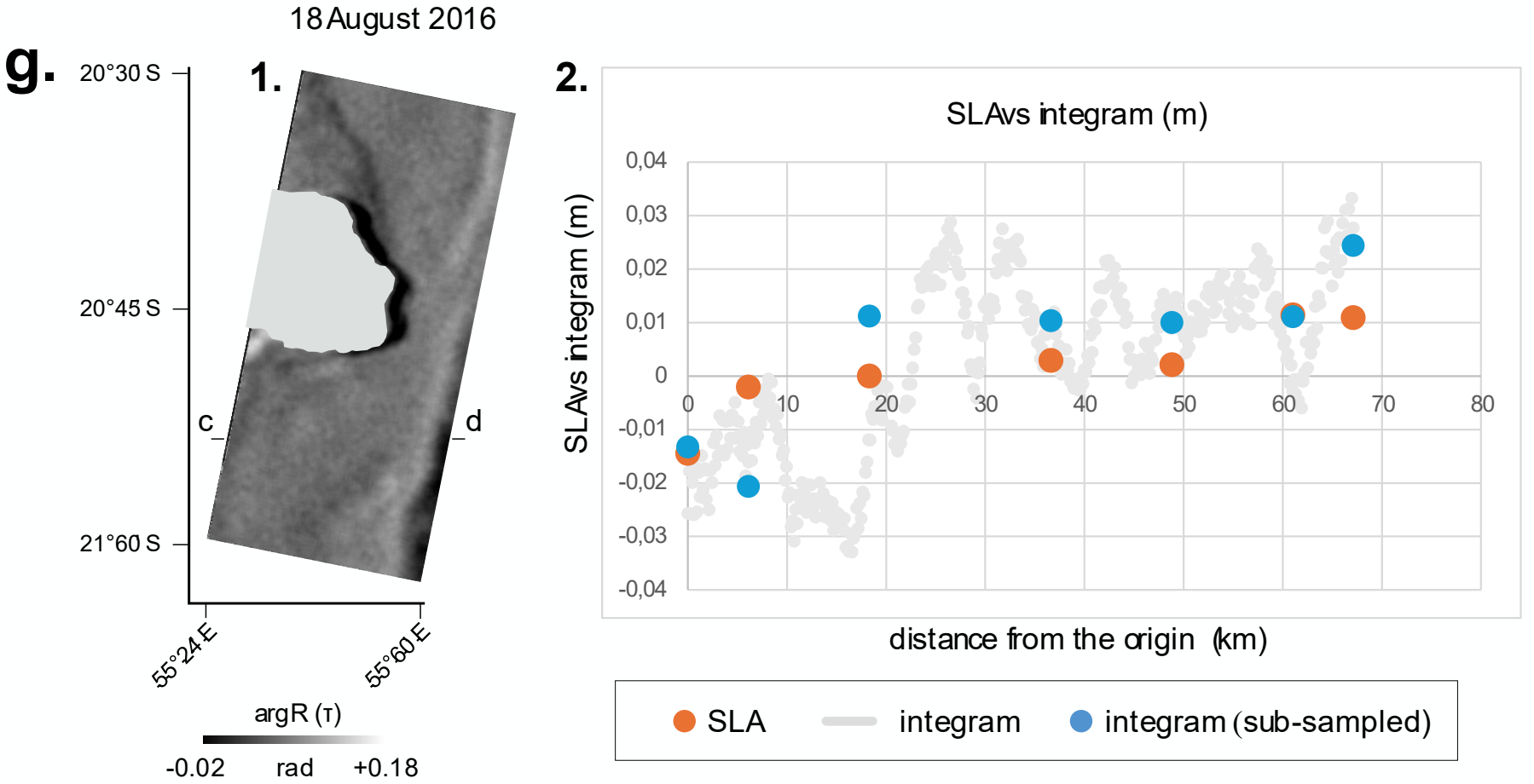
Comparison with Altimeters



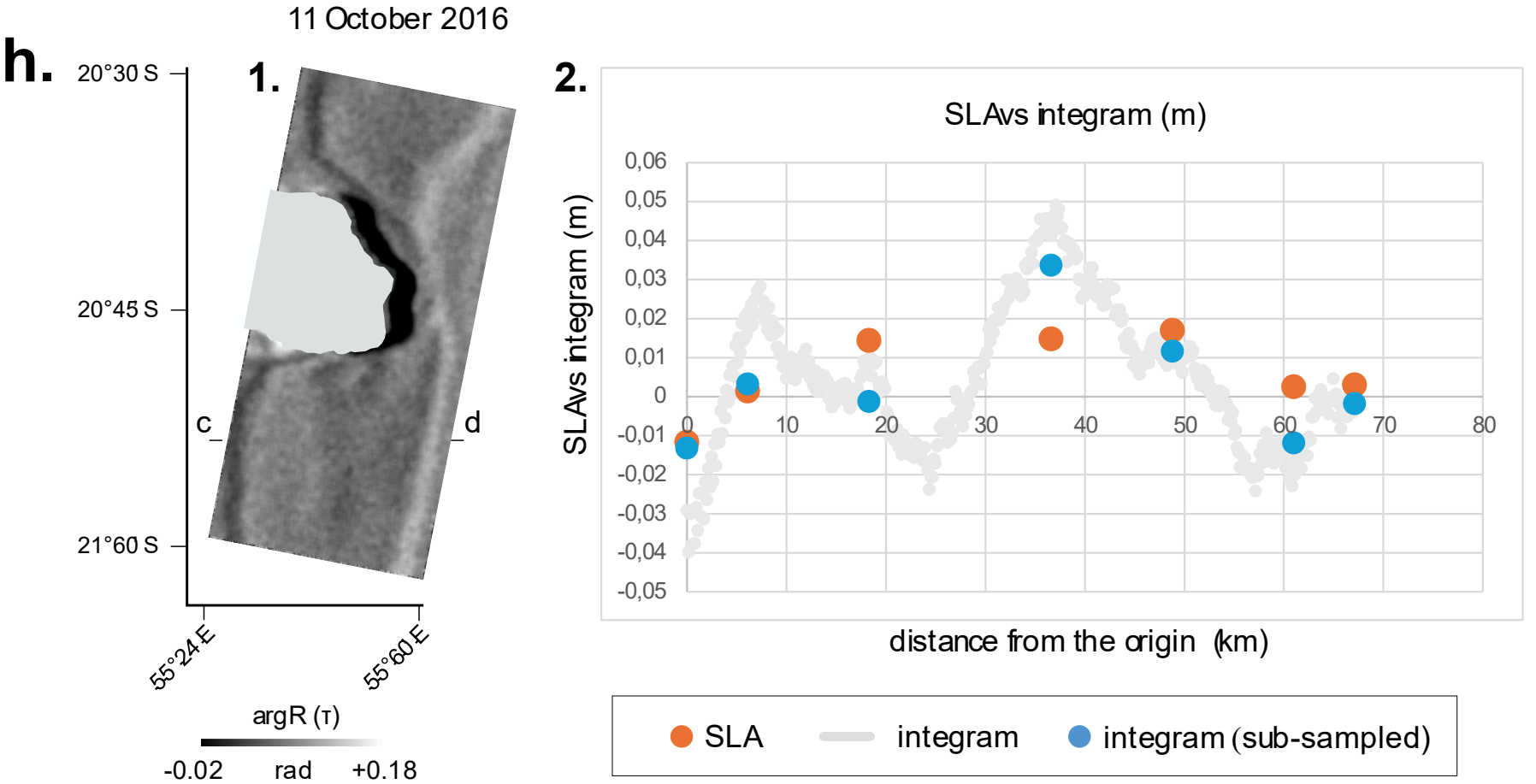
Comparison with Altimeters



Comparison with Altimeters

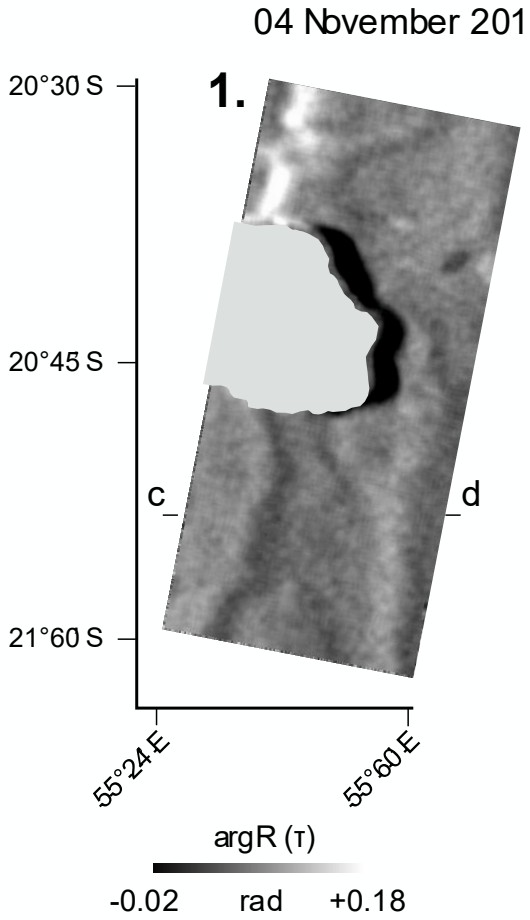


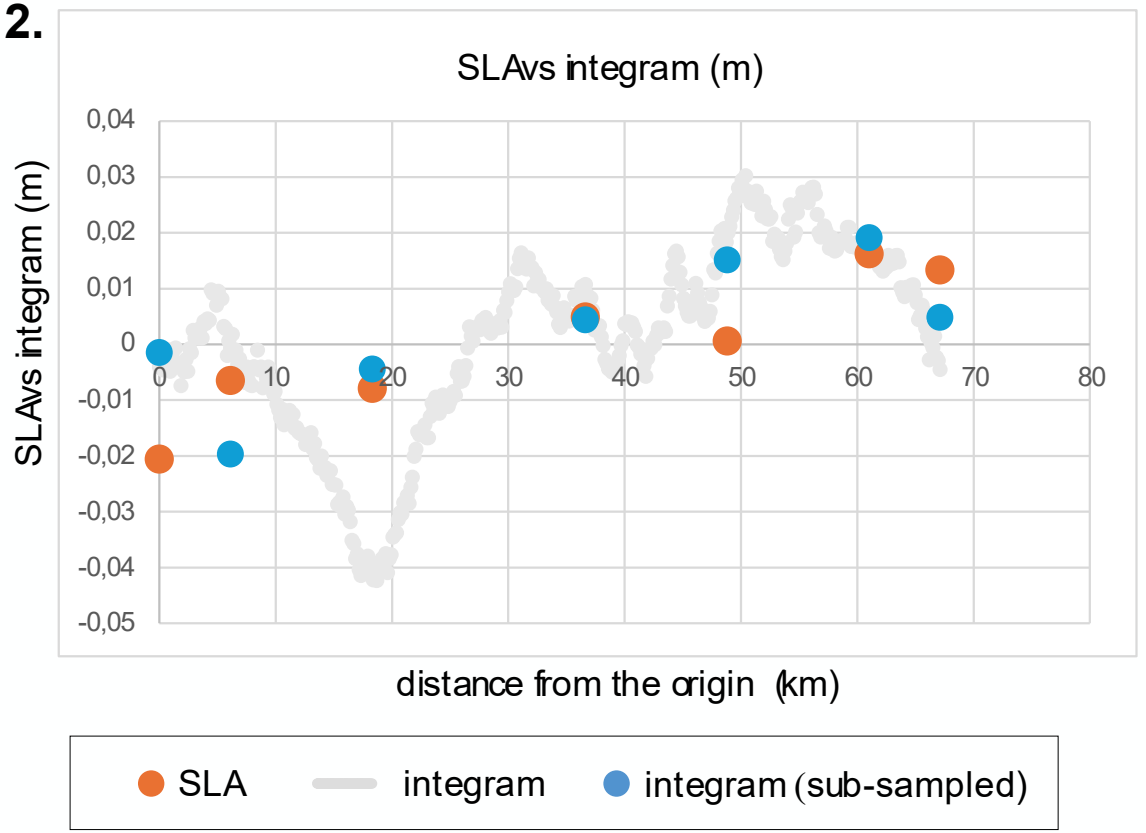
Comparison with Altimeters



Comparison with Altimeters

i.





Comparison with Altimeters

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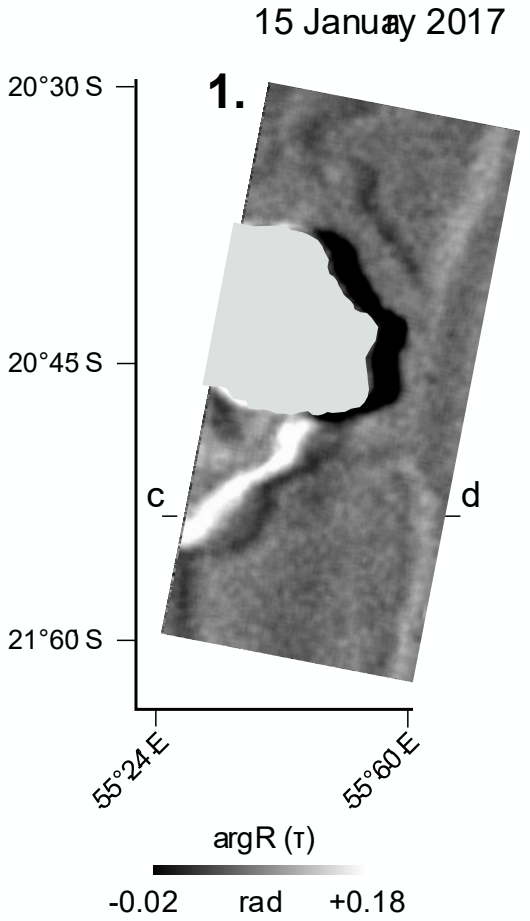
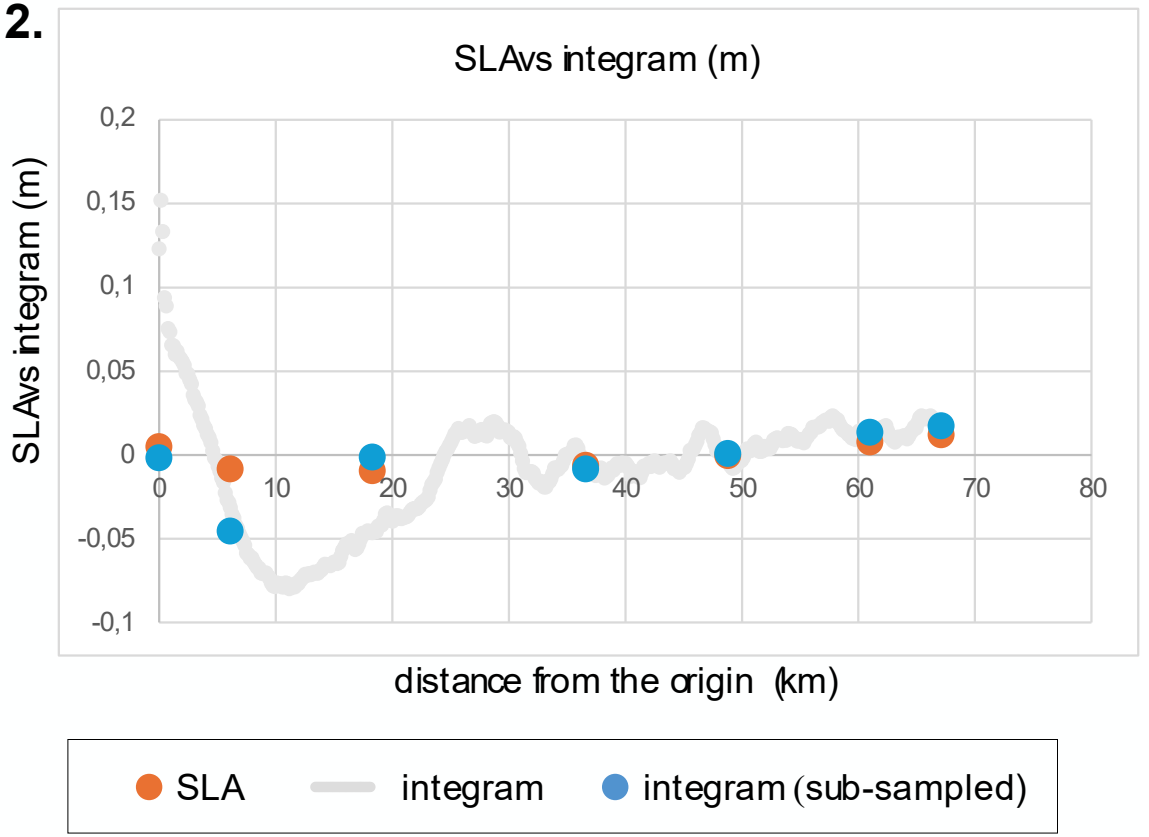
Géosciences pour une Terre durable
brgm

BiOT
Brgm: Initiative en Observation de la Terre

I.





Comparison with Altimeters

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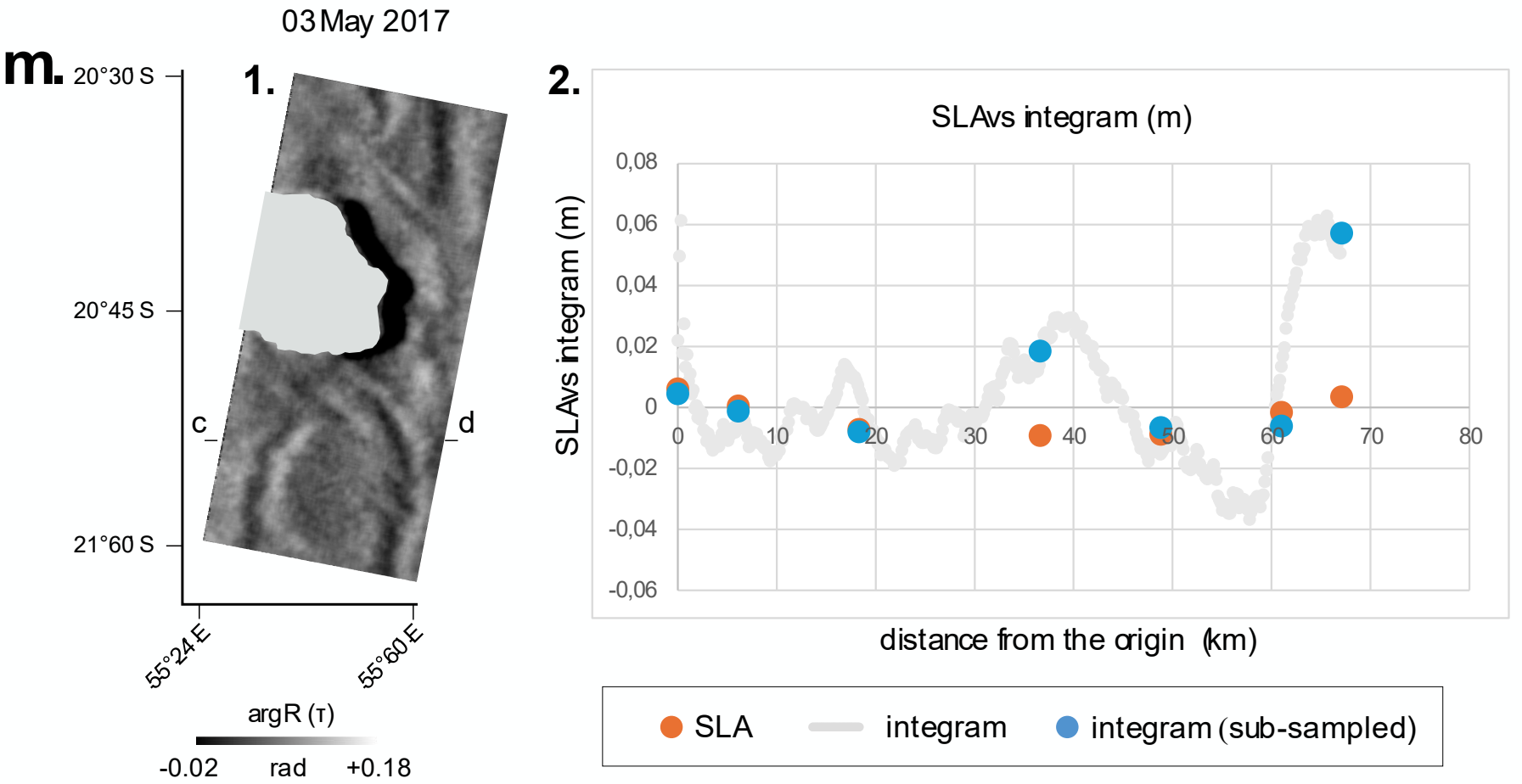


dr(τ): (SOϕ) Sar Original Phase Retrieval

Considering the focused SLC samples of a data-take as $Z(i,j)$, where i represents the range pixels and j represents the pulse lines, the random speckle phase term between a pixel in (i, j) and its neighbour in (i_{+1}, j) is partly correlated. Therefore, when one computes the phase difference between (i, j) and (i_{+1}, j), the difference in speckle is not large. A multi-looking operation is then applied and statistically reduces the speckle term. What remains is the difference in phase return-time between a pixel and its neighbor. Given that at each fast time (τ), the differential is calculated between pixels in the same SLC line i.e. the same Azimuth (j), the geometric effect should be effectively eliminated during SAR focusing. The phase delay can therefore come from a residual phase contribution between neighbouring range pixels. We can evaluate the shift between range radar returns (dr_τ) of a focused SLC as follows:

$$dr_\tau = \frac{\lambda}{2}\frac{1}{2\pi}\arg\left(\frac{\sum_{i=1}^{n} z_i z_{i+1}^*}{n}\right) = \frac{\lambda}{2}\frac{1}{2\pi}\arg R(\tau) \quad (1)$$

where

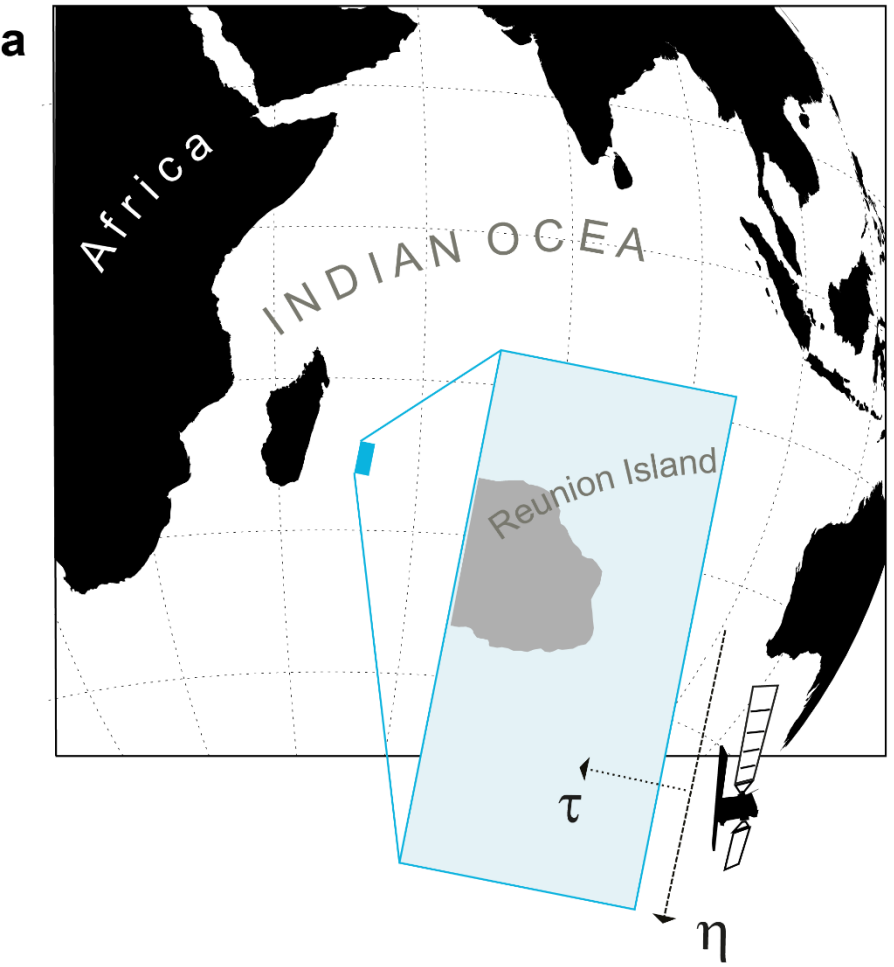
$$\frac{\lambda}{2}\frac{1}{2\pi}\arg R(\tau) = < \text{extra } optical\ path > \quad (2)$$

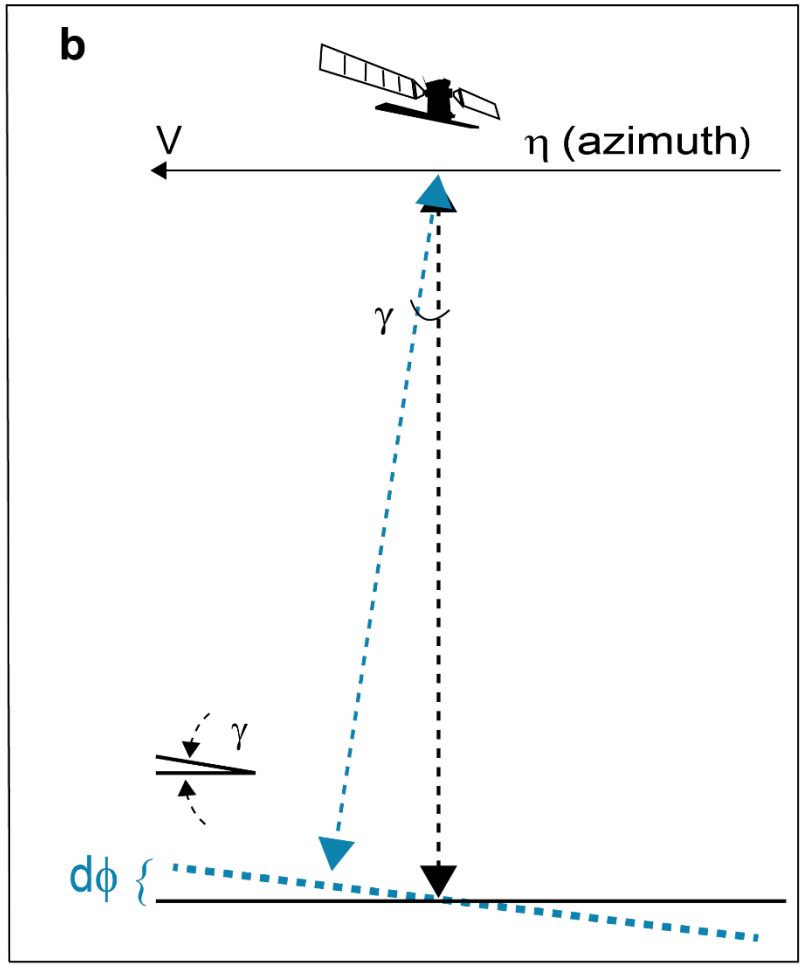
dr(τ): (SOϕ) Sar Original Phase Retrieval

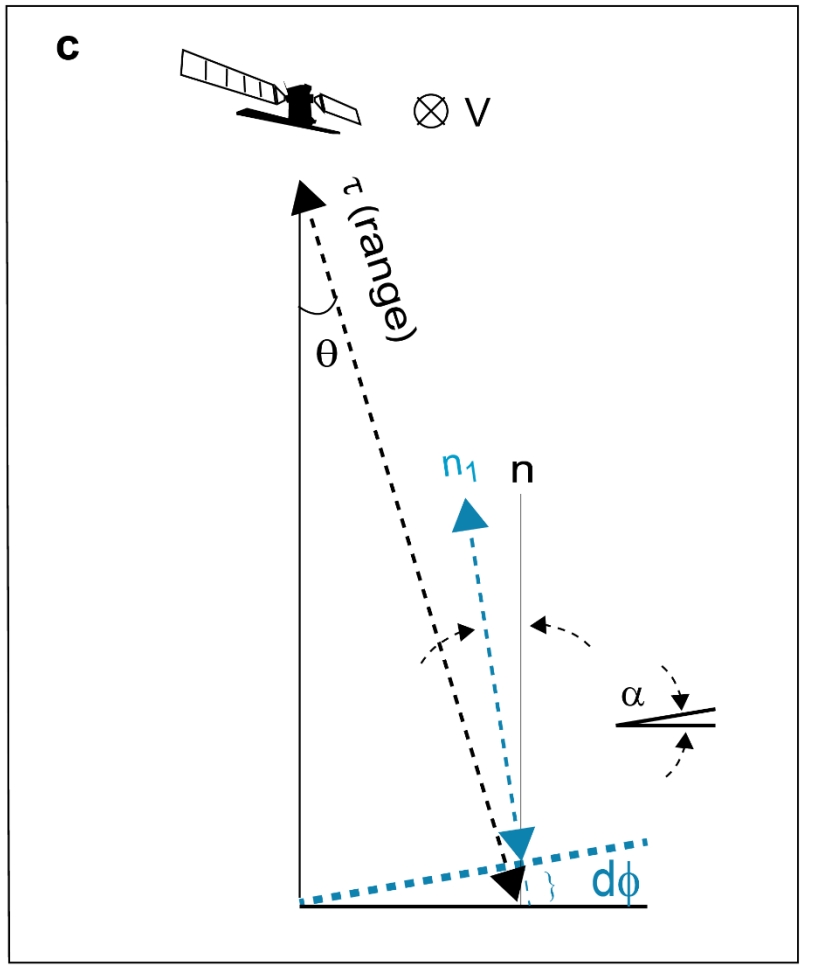
if we apply Equation (1) to the slow time direction , i.e., the azimuth direction, in contrast to the range direction, and multiply Equation (1) by the *prf* (pulse repetition frequency), the residual phase contribution can be associated with an uncompensated Doppler signal due to an “apparent velocity of the target” or the radial velocity of ocean currents (RVL). We can calculate it with the formulation given by Srivastava et al. (1978), also discussed in Madsen (1989) in terms of Doppler centroid f_D estimation, first discussed by Rummler (1968), Benham et al. (1972) and Rochwarger (1972) under the name of time domain velocity estimation, also called the *pulse pair algorithm*, routinely used today to measure ocean currents from space.

In the range direction: we measures angles and their variation in range (i.e. the along track variation of the incident angle –NOT the look angle).

Interpretation: towards a possible geometrical model







(SOϕ) : the integram

dr_τ represent the lengthening or the shortening of the SAR phases in the LOS direction. Hence, if we integrate dr_τ, as follows (for instance):

$$\begin{aligned} \mathrm{d}r_\tau &\leftrightarrow \Delta R(\omega) \\ \int_0^x dr_\tau\, dx + k &\leftrightarrow \frac{\Delta R(\omega)}{j\omega} \end{aligned} \qquad (3)$$

we shall obtain the unwrapped phase of a single SLC, in the LOS geometry.

We call this method ***SAR Original Phase retrieval* (SOϕ)**, and we call the result an ***integram***. In this study, we chose *n*=64. Since Sentinel-1 SM mode pixel spacing is 2.6m, the *integram* resolution is 166 meters.

Conclusions/summary

Two main points : one on the signal, the other on the interpretation of the signal.

1) On the signal:

we measure a time variable, spatially consistent signal from: arg $R_{(\tau)}$ i.e. an estimate of the autocorrelation function in range direction. When we integrate this signal, we obtain the average extra optical path with respect to a reference surface. This latter operation can be assimilated to a “unwrapping” operation on a single SLC. There are many potential applications.

2) On the interpretation of the signal in terms of SLA : it is a conscious over-simplification that I adopted to look for a possible geophysical signal behind the SAR measurement. It doesn’t work too bad !

The ocean is a complex environment. The ocean free surface morphology is the expression of the interaction of multiple phenomena: such as tides, sea floor topography, atmospheric pressure, winds. The <extra optical path> contains all of them, including tropospheric phase delay over the ocean.

acknowledgements

The (long) research behind this presentation was funded by BRGM (the French Geological Survey) via the Contrat d'Objectifs, des Moyens et de la Performance granted by the French Minister of Research to the BIOT group (BRGM: Initiative on Earth Observation).

We are thankful to the EU Copernicus program for providing Sentinel-1 data freely available.

We thank CREODIAS for the Data Information and Access Service to Sentinel-1 archive.

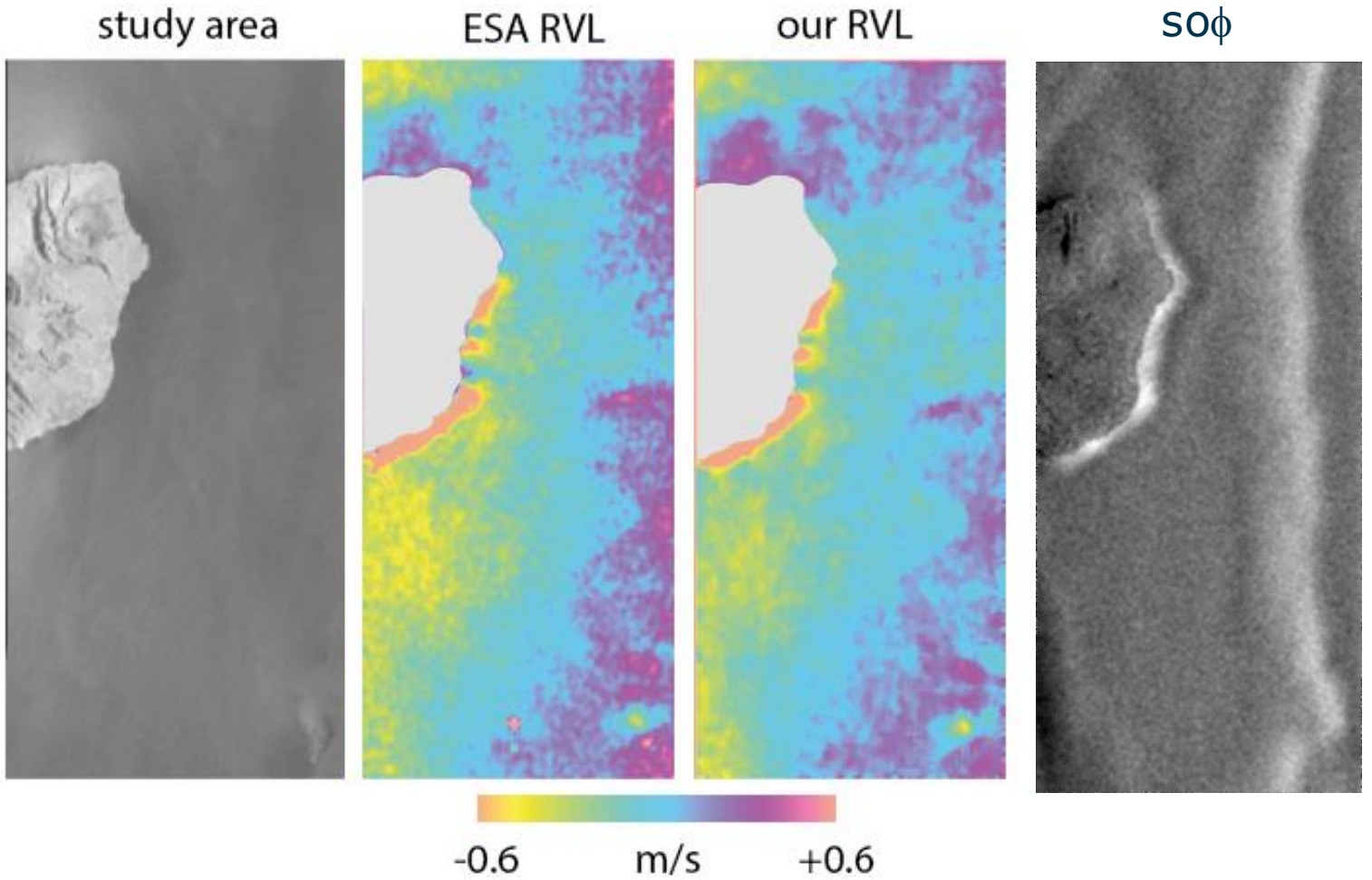
The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (**http://www.marine.copernicus.eu**), with support from the Centre Nationale d'Etudes Spatiales (CNES) (https://www.aviso.altimetry.fr/).

I thank Alessandro Ferretti and Pierre Briole for the constructive feedback on this study.

No AI was used to generate this study, ANY part of it. The code is written in IDL.

ESA RVL /ourRVL/ SOϕ

20 mars 2024 (ascending Sentinel-1 Strip Map mode).



We suggest the use single SAR SLCs for measuring the ocean slope. There is potential for :

→ Geoid mapping from Sentinel-1 SAR

→ Sea floor topography – sea floor tectonics from Sentinel-1 SAR

We open the way to use SAR SLCs to measure the <extra optical path> . There is potential for :

→ measuring tropospheric phase delay from a single SLC

→ Measuring the displacement of the Earth surface from already unwrapped SLCs (goodbye incoherent interferograms).