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Article

FLATSIM: the ForM@Ter LARge-scale multi-Temporal Sentinel-1 InterferoMetry service

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Abstract: The purpose of the ForM@Ter LARge-scale multi-Temporal Sentinel-1 InterferoMetry service (FLATSIM) is the massive processing of Sentinel-1 data using multi-temporal Interferometric Synthetic Aperture Radar (InSAR) over large areas, *i.e.* greater than 250,000 km². It provides the French ForM@ter scientific community with automatically processed products using a state of the art processing chain based on a Small BASeline Subset approach, namely the New Small BASeline (NSBAS). The service results from a collaboration between the scientific team that develops and maintains the NSBAS processing chain and the French Spatial Agency (CNES) that mirrors the Sentinel-1 data. The proximity to Sentinel-1 data, the NSBAS workflow and the specific optimizations to make NSBAS processing massively parallel for the CNES High Performance Computing infrastructure ensures the efficiency of the chain, especially in terms of Input/Output, which is the key for the success of such a service. The FLATSIM service is made of a production module, a delivery module and a user access module. Products include interferograms, surface Line Of Sight velocity, phase delay time series and auxiliary data. Numerous quality indicators are provided for an in-depth analysis of the quality and limits of the results. The first national call in 2020 for region of interest ended up with 8 regions spread over the world with scientific interests including seismology, tectonics, volcano-tectonics and hydrological cycle. To illustrate the FLATSIM capabilities, an analysis is shown here on two processed regions, the Afar region in Ethiopia, and the eastern border of the Tibetan Plateau.

Keywords: InSAR; Sentinel-1; automatic processing; time series analysis; deformation monitoring; tectonics; subsidence

1. Introduction

Since its first development in the 1990's [1–3], the Interferometric Synthetic Aperture Radar technique (InSAR) has now become a mature technique that allows to retrieve surface ground motion associated to a very wide range of processes, such as seismic cycle, gravitational instabilities, volcanic unrest, mining activities, land subsidence, etc.

While InSAR measurements from single interferograms allowed to measure pluri-centimeter deformation events, the advent of Multi-Temporal InSAR (MTInSAR) techniques [4–7] has further broadened up the field of InSAR applications. Low deformation of natural and anthropogenic origin as well as their temporal dynamics can now also be captured by time series analysis of InSAR

30 displacement maps. MTInSAR techniques take advantage of numerous and partially redundant SAR
31 acquisitions both to enhance the reliability of the phase delay measurement and to better separate
32 contributions to the ground displacement from atmospheric perturbations in the radar wave travel
33 time. As a result, MTInSAR has been able to quantify large-scale, slow and transient natural processes,
34 as for example postseismic relaxation following earthquakes, interseismic loading of fault [8–10],
35 fault creep bursts [11–13], slow earthquakes [14], permafrost freeze-thaw dynamics [15], gravitational
36 sliding of volcano flanks [16,17], or the earth visco-elastic response to lake load changes [18,19].

37 Time series analysis of these phenomena were made possible by the availability of numerous
38 repeated SAR images, acquired with the exact same sensor and similar viewing geometries on relatively
39 narrow orbital tubes, and over at least 5 years. This was for example the case for the ERS-1, ERS-2
40 and ENVISAT missions of the European Space Agency in C-band or the ALOS-1 mission by JAXA in
41 L-band. However, due to the limited revisit time or the limitations of the acquisition strategies, the
42 processed time series were in most places made of typically 15 to 20 acquisitions for ALOS-1 (e.g., [20]
43) and up to about 40 to 80 acquisitions for ERS/Envisat (e.g., [11,18]). Data gaps, and/or limited access
44 to the whole data archive, made the continental-wide processing with these data quite challenging.
45 However, a few large-scale studies have shown the feasibility of large-scale InSAR processing for
46 tectonic applications [21–23].

47 Since 2014, the radar satellite constellation of the European Copernicus Sentinel-1 mission (S-1)
48 provides massive amounts of SAR data available free of charge (4 Peta-bytes/year today). Continental
49 regions are systematically covered by acquisitions in the Interferometric Wideswath (IW) mode, with
50 continuous 250 km-wide tracks. With the launch of Sentinel 1-B in April 2016, the revisit time in Europe
51 has dropped to 6 days. Therefore, beginning of 2021, after 5 years of mission, about 300 images per
52 viewing geometry are available. In tectonically active regions outside Europe the sampling frequency
53 is about 12 to 24 days. The retrieval of ground deformation at continental scale, with unprecedented
54 temporal sampling, is now providing new observables leading to major scientific discoveries and
55 enabling operational applications in the fields of environment, risk and asset management. However,
56 taking advantage of this extraordinary data set requires the development of fully automated processing
57 chains, as well as large computational and storage facilities coupled with the ability of software to
58 scale up while processing thousands of SAR scenes, all of which require significant human resources.

59 The S-1 **imaging is done by Terrain Observation with Progressive Scans (TOPSAR) technique [24]**
60 **which** is based on antenna forward-backward sweeping inside each burst, and on the switching the
61 radar footprint between three overlapping sub-swaths. Its specificity strongly increases the complexity
62 of the processing workflow, the number and size of intermediate files written on disk requiring
63 intensive input/output (I/O) operations and the usage of "scratch" disk space. A number of InSAR
64 processing chains now handle S-1 SAR data, and are freely available (e.g., **SNAP -SentiNel Application**
65 **Platform- [25], ISCE -InSAR Scientific Computing Environment- [26], GMTSAR -Generic Mapping**
66 **Tools (GMT) for SAR- [27]**), or delivered by commercial agreement (e.g., Gamma, [28]).

67 Implemented strategies for MTInSAR processing of large stacks of S-1 data differ from one group
68 to another. Some rely on permanent scatterers (PS, [5]) or distributed scatterers (DS) techniques, i.e. the
69 phase delay information is extracted from reliable points or from sets of neighboring points, sharing
70 common statistical properties (e.g. SqueeSAR, [7]), for each secondary acquisition with respect to
71 a single reference acquisition. Unwrapped phase time series are then obtained on a mesh made of
72 PS or DS points, that can be associated with a defined, single feature on ground. Another class of
73 processing strategy is the **SBAS (Small BAseline Subset)** approach depicted in [4], in which redundant
74 differential interferograms between images separated by a small baseline are constructed, multi-looked
75 and spatially filtered. Unwrapped phase time series are then continuous in space, with an improved
76 signal to noise ratio in non-urban areas, but a mixing of ground targets by the multi-looking and
77 filtering steps.

78 Whether based on PS, PS-DS, or relying on SBAS approach, on-demand services or remote
79 massive data processing have been implemented on high performance computers or on cloud

80 computing environments. For example, an on-demand MTInSAR service has been installed on
81 the ESA **Geohazards Exploitation Platform** (GEP) based on the **Parallel-SBAS** algorithm [29,30].
82 PS or PS-DS algorithms have also been employed for ground motion mapping at country-scale,
83 based for example on SqueeSAR [31,32] or on PSI techniques [33–35]. In a fairly limited number
84 of cases, national geological survey agencies have made the PS or PSDS ground velocity maps
85 and displacement time series available for the public and free of charge through a web portal (e.g,
86 <https://bodenbewegungsdienst.bgr.de/> for Germany, <https://insar.ngu.no/> for Norway). Other
87 groups are making systematic small baseline differential interferograms over large areas available
88 on-line, as in the framework of the **Advanced Rapid Imaging and Analysis project** (ARIA) from **Jet**
89 **Propulsion Laboratory, California Institute of Technology** (JPL-Caltech) for California, Tibet and Afar
90 areas [36], or of the **Looking Into Continents from Space with Synthetic Aperture Radar** (LiCSAR)
91 project for the whole Alpine-Himalayan belt [37]. In these last two cases, the delivered interferograms
92 can be used to recover, after network inversion, the tectonic ground deformation at large-scale, as no
93 high-pass spatial filtering of the phase is performed [23]. Open source time series analysis packages
94 can even be directly integrated with the interferograms production services as for LiCSBAS [38].

95
96 In France, the development of InSAR services adapted to Sentinel-1 data for the Earth sciences
97 research community is among the objectives of ForM@Ter, a data and services centre for the study
98 of the Solid Earth. ForM@Ter is one component of the national research infrastructure Data Terra
99 (<https://www.data-terra.org/>), which aims to promote an integrated approach for the study of the
100 Earth System through multi-type observation data and services, in particular by enforcing data
101 interoperability. ForM@Ter helps developing high-performance tools and services to access, process
102 and analyze satellite and in-situ data on the Solid Earth, as well as their value-added products, in
103 a unified and simplified way. In particular, ForM@Ter sets up a meta-catalog for unified search
104 and access to data as well as a web portal to make data, products and services available. Two
105 services dedicated to the measurement of ground motion by InSAR using Sentinel-1 data are being
106 developed within ForM@Ter : the GDM-SAR and FLATSIM services. **GDM-SAR (Ground Deformation**
107 **Monitoring-Synthetic Aperture Radar)** is an on-demand processing service, which will be accessible to
108 the national and European scientific community as part of the Thematic Core Service Satellite Data of
109 the European solid earth research infrastructure, EPOS (<https://www.epos-eu.org/>). In this paper, we
110 focus on the FLATSIM service. **FLATSIM stands for ForM@Ter Large-scale multi-Temporal Sentinel-1**
111 **InterferoMetry. This service**, dedicated to massive, automatic, multi-temporal InSAR processing over
112 large continental areas (250,000 km² minimum per study site), with an emphasis on the recovery of
113 large-scale deformation processes. The FLATSIM service delivers interferograms, line of sight average
114 ground velocity maps, time series of ground displacements, and numerous auxiliary information. The
115 processed areas are selected through a series of call for scientific proposals presently open to the French
116 scientific community.

117 In the following, we first present the main processing steps implemented in FLATSIM, based on
118 the MTInSAR NSBAS software [39,40]. The FLATSIM parallel implementation on the CNES High
119 Performance Computing infrastructure is then described together with the production and delivery
120 modules. Next, we present the main products, including the auxiliary data that are provided for
121 assessment of the products' quality. Finally, two FLATSIM case studies among the first selected ones
122 are presented to discuss the qualification of the results.

123 2. The NSBAS processing chain used in the FLATSIM service

124 2.1. Main steps

125 The FLATSIM service runs the New Small BASeline (NSBAS) processing chain. The NSBAS chain
126 is versatile, allowing for the user to choose different processing options and parameters, for example
127 for coregistration, selection of image pairs, multilooking, atmospheric or Digital Elevation Model

128 (DEM) corrections, filtering, unwrapping, or to decide the order in which steps are performed. Here,
129 we only describe the specific steps, workflow and parameters implemented in FLATSIM. They are
130 included in the 2.02 version of the NSBAS processing chain.

131 NSBAS partly relies on a set of modified scripts and libraries originating from the legacy InSAR
132 processing software **Repeat Orbit Interferometry PACkage** (ROI_PAC) [41], expanded to allow for the
133 processing of a stack of SAR images, using a set of parallelized steps, as described in [19,39,42]. The
134 NSBAS chain was further adapted to accommodate the specificities of Sentinel-1 images, acquired in
135 the novel TOPS mode [40,43]. It is inspired by the "Small Baseline Subset" (SBAS) approach defined
136 in [4,6]. As for all SBAS methods, a series of small baseline differential interferograms are computed,
137 multilooked, filtered and unwrapped, before being inverted to obtain phase time series of each pixel.
138 The main steps of the fully automatic workflow are the following:

- 139 • Import all available S-1 data with VV polarization for a given track in a given region of interest
140 defined by its maximum and minimum latitudes (ROI).
- 141 • Import and assemble the **Digital Elevation Model** (DEM) encompassing the area covered by the
142 downloaded S-1 data. **We use the DEM from the Shuttle Radar Topography Mission (SRTM)** [44]
- 143 • Select bursts for each subswath independently and retain only complete acquisitions within the
144 chosen latitude range.
- 145 • Download precise orbits, compute perpendicular and temporal baselines and choose a single
146 primary date common for the three subswaths.
- 147 • For each subswath, assemble bursts into **Single Look Complex data (SLC)**, transform the DEM in
148 the primary date radar geometry, and compute the geometrical transformations of all secondary
149 SLCs on the geometry of the primary acquisition, combining orbit, DEM and correlation offsets
150 information.
- 151 • For each subswath, reassemble secondary SLCs using the position of the burst limits from the
152 primary image and an improved deramping function, and resample secondary SLCs on the
153 primary geometry.
- 154 • Define the interferometric network and computes differential interferograms for each subswath.
- 155 • For each subswath, evaluate spectral diversity parameters and correct interferograms.
- 156 • Merge the subswaths of all interferograms and of some auxiliary images using available metadata
157 and inverted phase jumps in subswath overlaps.
- 158 • Correct interferograms from stratified atmospheric effects, multilook, filter, unwrap, remove
159 phase ramps in range and azimuth and reference.
- 160 • Discard possible low quality interferograms based on their phase variance or unwrapping
161 fraction.
- 162 • Invert interferograms into time series and provide quality indicators.
- 163 • Prepare products in tiff or geotiff format, together with metadata, previews, and text files.

164 We detail below a few selected steps, necessary to understand the FLATSIM products.

165 2.2. Burst selection

166 The Sentinel-1 standard acquisition mode (TOPS) consists in sweeping the antenna beam from
167 the aft to the fore, thereby illuminating a portion of the ground called a "burst". Three sub-swaths are
168 successively covered to broaden the swath. The Sentinel 1-A and 1-B satellites are tasked to maintain
169 synchronicity of burst acquisition, which is essential to ensure an optimal interferometric coherence.
170 However, Sentinel-1 acquisitions do not necessarily cover the same burst coverage. In other words, the
171 acquisition start/stop times (w.r.t. the ascending node crossing time, or ANX time) may vary from one
172 acquisition to another. As input, FLATSIM is given the north and south latitude limits of the area of
173 interest. Then, starting from these a priori limits, an optimization step is required to select the best set
174 of acquisitions that simultaneously maximizes the latitudinal extent of the data set and the number of
175 acquisitions, without including gaps in the processing. The FLATSIM strategy consists in an iterative
176 search for the optimal number of consecutive bursts that achieves the largest number of complete

177 acquisitions on the chosen set of consecutive bursts (Figure 1). Note that dates of acquisition which are
 178 incomplete from one or more of the three sub-swaths are discarded. Up to about 40 contiguous bursts
 179 can be selected.

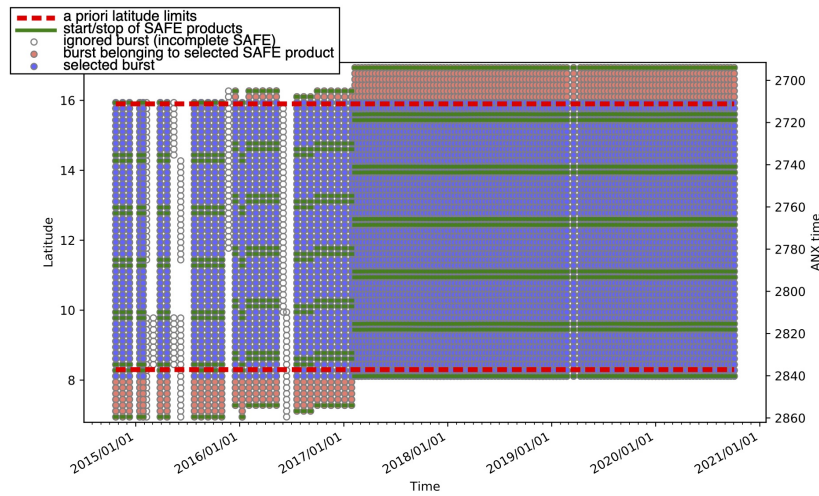


Figure 1. Distribution of bursts as a function of acquisition dates (X-axis) and latitude (Y-axis). Empty circles represent bursts that have not been kept, whereas blue circles correspond to bursts that have been selected for processing. Pink circles are bursts that have not been selected, but belong to the beginning or the end of a partially selected SAFE product (standard product produced by ESA that typically includes 9 bursts per sub-swath).

180 2.3. Coregistration and interferometric network selection

181 Image correlation is performed between the amplitude image of the primary acquisition and an
 182 amplitude image simulated from DEM and orbit information. Found offsets are fitted by a second-order
 183 polynomial in range and azimuth. This modeling and further adjustment serve to build lookup tables
 184 from radar to ground geometry and vice-versa. We then precisely coregister all secondary images
 185 with respect to the primary acquisition (Figure 2, top), as explained in [19]. A simulated topographic
 186 phase map (in radar coordinates) is calculated for each of the secondary images, using the precise
 187 orbital parameters of the secondary and the primary acquisitions. This simulation is used to predict the
 188 distortion in range between secondary and primary images, supplemented by an additional constant
 189 offset in range and an affine offset function in azimuth derived from amplitude image matching. The
 190 affine offset function depends linearly on range and azimuth. Prior to resampling, a deramping is
 191 performed, cancelling most of the azimuthal phase modulation pattern inherited from the TOPS mode
 192 pre-processing, taking the azimuth spectral properties of the primary image as a reference for the
 193 deramping function and taking into account the affine offset function in azimuth [40].

194 The chosen network of interferograms includes all $n/n+1$, $n/n+2$, $n/n+3$ couples independently
 195 of their perpendicular baselines, and systematic pairs with temporal separation of ~ 2 to 3 months and
 196 ~ 1 year with restricted perpendicular baselines (Figure 2, bottom). The inclusion of 2 to 3 months and
 197 1 year interferograms is essential for the mitigation of bias due to fading signals [45]. The computed
 198 differential interferograms are multilooked by a factor 8×2 in range and azimuth.

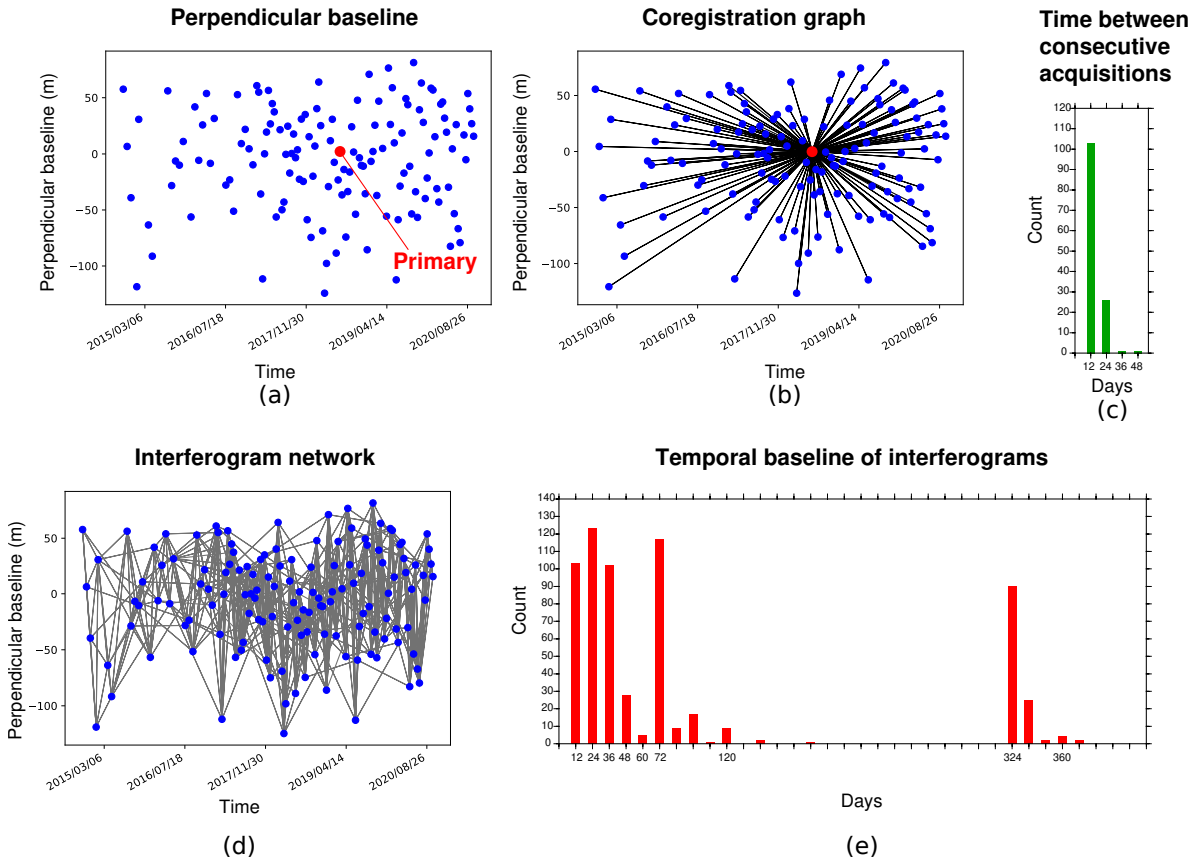


Figure 2. (a) perpendicular baseline versus time for the Sentinel-1 descending track D079 on the Afar region (red dot indicates the primary date); (b) coregistration network; (c) histogram showing the distribution of time interval between consecutive acquisitions; (d) small-baseline interferogram network; (e) histogram showing the distribution of temporal baselines between acquisitions used for the calculated interferograms.

199 2.4. Enhanced spectral diversity correction

200 The S-1 TOPSAR default acquisition mode [24] for IW Sentinel-1 data, while enhancing the swath
 201 width and then the revisit time, required to adapt the InSAR processing chains to take into account the
 202 antenna forward-backward sweeping inside each burst, and the division of the full wide-swath into
 203 three overlapping sub-swaths. Slight inaccuracies in azimuth positioning of the images also result in
 204 phase jumps across bursts that are accounted for using the Enhanced Spectral Diversity method (ESD,
 205 [46]), while subswath merging is facilitated by the accurate timing of subswath SAR SLC **removed def**
 206 **of SLC as provided before** data and a high quality ESD correction.

207 Here, enhanced spectral diversity is computed on the selected network of interferograms, using
 208 forward and backward SLCs of all burst overlaps. The SLCs overlaps are coregistered using the same
 209 function as described above, and differential backward-forward interferograms are multilooked by
 210 a factor 64×16 , using colinearity [47] in the multilooking operation to enhance the signal to noise
 211 ratio. The differential forward-backward wrapped phase screens for all overlaps are then fitted by
 212 a four-parameters function: a constant, two linear coefficients describing the range and azimuth
 213 change, and a coefficient describing the average linear phase change in azimuth within the bursts.
 214 For long tracks, a fifth coefficient, modelling a quadratic phase change across bursts in azimuth
 215 was also found necessary. To obtain consistent and stable parameter values for each secondary
 216 image, all these parameters, estimated on interferograms, are inverted within the network by a
 217 least-squares minimization with outliers removal (Figure 3, left). Using these estimated phase screens,
 218 a sawtooth-shaped phase screen is subtracted to the original interferograms to cancel phase jumps
 219 across burst boundaries.

220 The above strategy is applied independently to each sub-swath, and all sub-swaths are then
 221 mosaicked, correcting for any phase jumps between the sub-swaths by computing the phase difference
 222 in the overlap between sub-swaths, and inverting for these phase differences within the interferometric
 223 network (Figure 3, right).

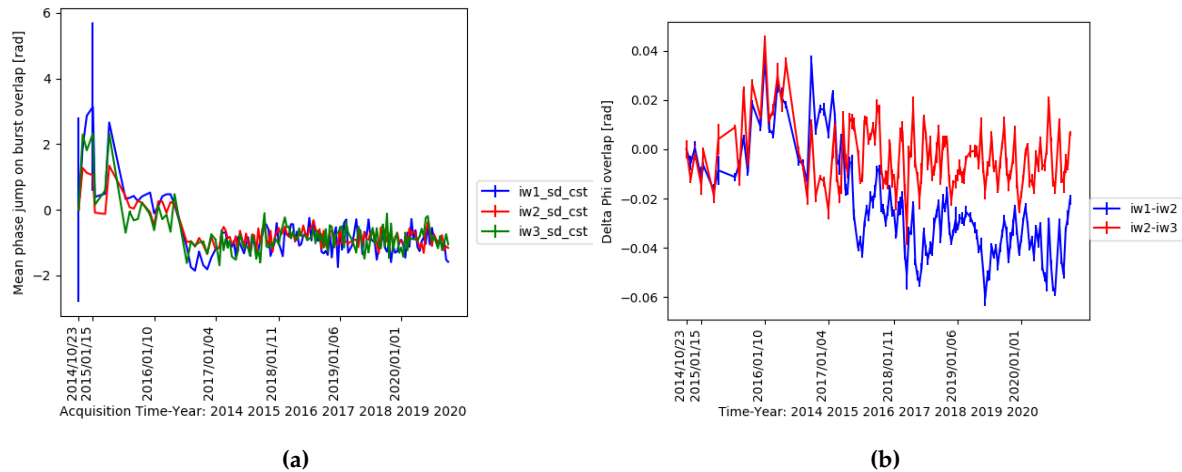


Figure 3. Network-inversion of Spectral diversity (a) and overlap between sub-swath (b). Error bars correspond to the averaged network discrepancy per acquisition. These two figures are part of the delivered products.

224 2.5. Stratified atmospheric correction

225 The final steps are performed on the mosaicked interferograms. The atmospheric phase screen of
 226 interferograms can be divided into a pseudo stratified contribution, that is at first-order dependent
 227 upon elevation, and a more random contribution often named "turbulent". The dry and wet stratified
 228 atmospheric delays, that derive from the temporal variations of the layered atmospheric variables
 229 (pressure, P , temperature, T , humidity, q), can be easily predicted from global atmospheric models
 230 with the assumption of a mainly horizontally layered atmosphere [48,49]. The turbulent contribution
 231 is difficult to model from independent atmospheric information as it requires to place the atmospheric
 232 patterns at the right place in space and time.

233 In the FLATSIM service, the stratified atmospheric phase screen is computed in 8x2-looks using
 234 the geopotential height of pressure levels, and T and q given for each of the 37 pressure levels by the
 235 [European Centre for Medium-Range Weather Forecasts](#) (ECMWF) ERA-5 meteorological reanalysis [50].
 236 The delay is first interpolated as a function of elevation with a very fine vertical spacing at regularly
 237 spaced ERA-5 nodes (every 0.25 degree). Then, for each pixel in radar coordinate, characterized by
 238 its elevation, latitude, longitude and look angle given in separate grids, we compute the delay by
 239 bilinear interpolation of the surrounding four ERA-5 nodes. This procedure is very efficient and easily
 240 parallelized.

241 Beside an elevation dependent contribution, the stratified APS also includes large-scale phase
 242 delay gradients along range and azimuth. The correction before unwrapping (e.g., [51]) strongly
 243 reduces fringe rates in areas of high relief (figure 4). The ERA-5 model, given with a temporal sampling
 244 of one hour, is found more accurate than other global atmospheric models (e.g., the high resolution
 245 global analysis of ECMWF, given every six hours). However, the ERA-5 modelled surface elevation is
 246 a smooth surface that stands above deeply incised valleys. As a result, the phase delay as a function
 247 elevation below the smooth surface is an extrapolation that is not very well constrained.

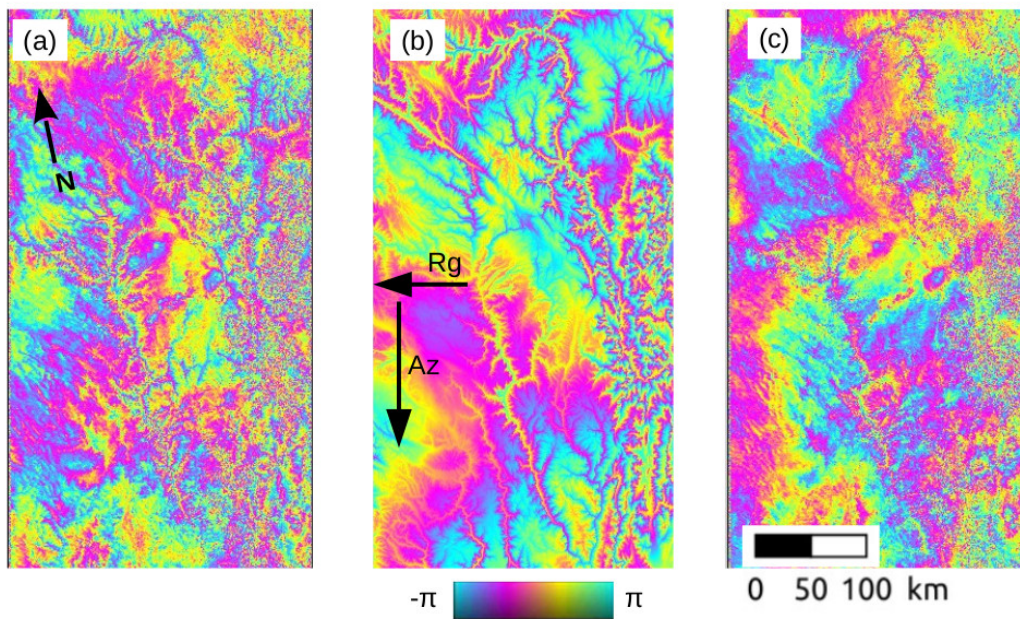


Figure 4. Example of a wrapped interferogram in 32 looks and in radar geometry, before (a) and after (c) correction by the prediction from ERA-5 atmospheric model (panel (b)). For the 250 km wide southern segment of track D135 at the border between the Tibetan plateau and the Sichuan basin. One color cycle = 2.6 cm of delay. First date : 2020-06-08; second date : 2020-06-20.

248 2.6. Interferogram multilooking, filtering and unwrapping

249 After atmospheric correction, we take further looks to obtain 64x16 or 32x8 looks interferograms
 250 (this choice, fixed for a given region of interest, is left to the PIs of the scientific proposals). Filtering is
 251 performed by averaging on a 12x12 triangular sliding windows weighted by spatial coherence.

252 Unwrapping of multi-looked interferograms uses the coherence associated to the filter averaging
 253 process on complex values to guide the unwrapping integration path [19,51]. The unwrapping path is
 254 also set to avoid crossing large topographic gradients in radar geometry. Its seed point is automatically
 255 chosen in an area with good coherence over the interferogram stack. These choices for the filtering and
 256 unwrapping procedure are quite suitable for an automatic processing over mountainous and vegetated
 257 areas with limited displacement gradients, but is not adapted to large deformation gradients.

258 After unwrapping, coefficients of a linear phase ramp in range and azimuth are computed for each
 259 interferogram, together with the residual phase standard deviation. The coefficients are inverted over
 260 the interferometric network in order to get a consistent flattening of each interferogram. The phase
 261 standard deviation is also inverted for each time step, as in [18]. All interferograms are referenced by
 262 setting the averaged phase in a small area adjacent to the unwrapping seed point to zero.

263 Finally, the unwrapping fraction (proportion of the pixels unwrapped in one interferogram), the
 264 residual phase standard deviation per interferogram and the residual phase standard deviation per
 265 date are used to automatically discard anomalous interferograms or anomalous acquisitions. This step
 266 is very important in the automated FLATSIM procedure to ensure the quality of the final products. It
 267 typically discards from 0 to 20 interferograms and 0 to 3 acquisitions per processed track.

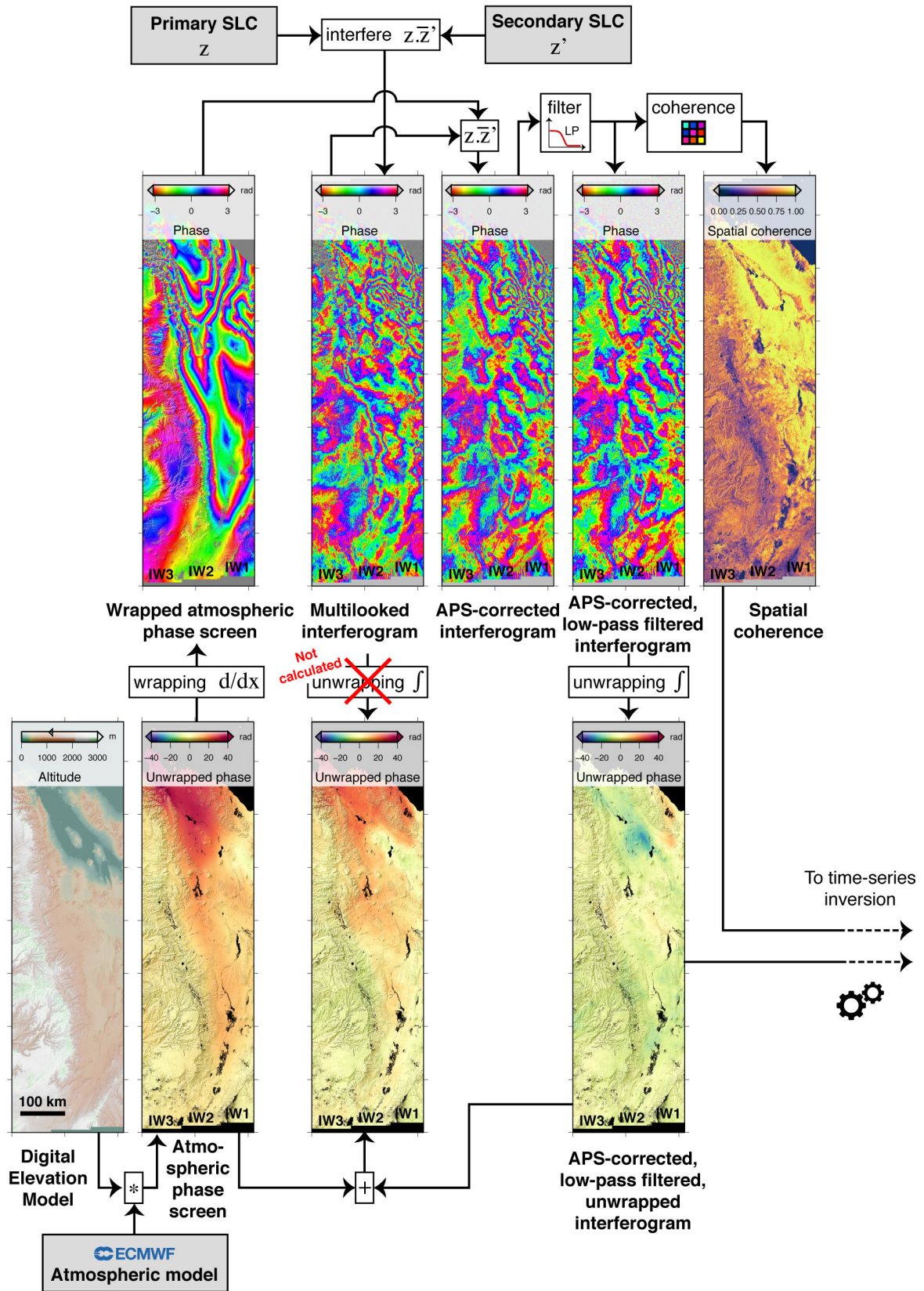


Figure 5. Processing steps for each interferogram.

268 *2.7. Time series inversion*

269 The time-series inversion of the line-of-sight displacement follows the principle described in
 270 [18,19,52], and depicted in Figure 6. We jointly solve for both the total phase delay time series and a
 271 temporally smoothed time series. The first one, delivered by FLATSIM, includes both LOS (**Line of**
 272 **Sight**) displacement and residual atmospheric phase screen, whereas the second, for which temporal
 273 fluctuations at short time scales induced by atmospheric turbulence are filtered out, only serves as a
 274 regularization, in case we get disconnected data subsets in the unwrapped interferograms network.
 275 Unwrapping errors are corrected iteratively, by searching for the optimal integer number of phase
 276 cycles to be added in areas detected as incorrectly unwrapped. For this step, the correction is prioritized
 277 on interferograms characterized by a large residual between the initial and reconstructed line-of-sight
 278 displacement maps. After a few iterations, the root mean square misclosure map is computed for
 279 the whole data set, together with a root mean square misclosure for each interferogram, and for each
 280 acquisition [52]. Using the total phase delay maps at each time step, an average LOS velocity map is
 281 calculated by a simple pixel-by-pixel linear least-square regression in the temporal dimension. The
 282 velocity map is then slightly improved by iteratively reducing the weight of the acquisitions with large
 283 deviations from the trend of the mean displacement.

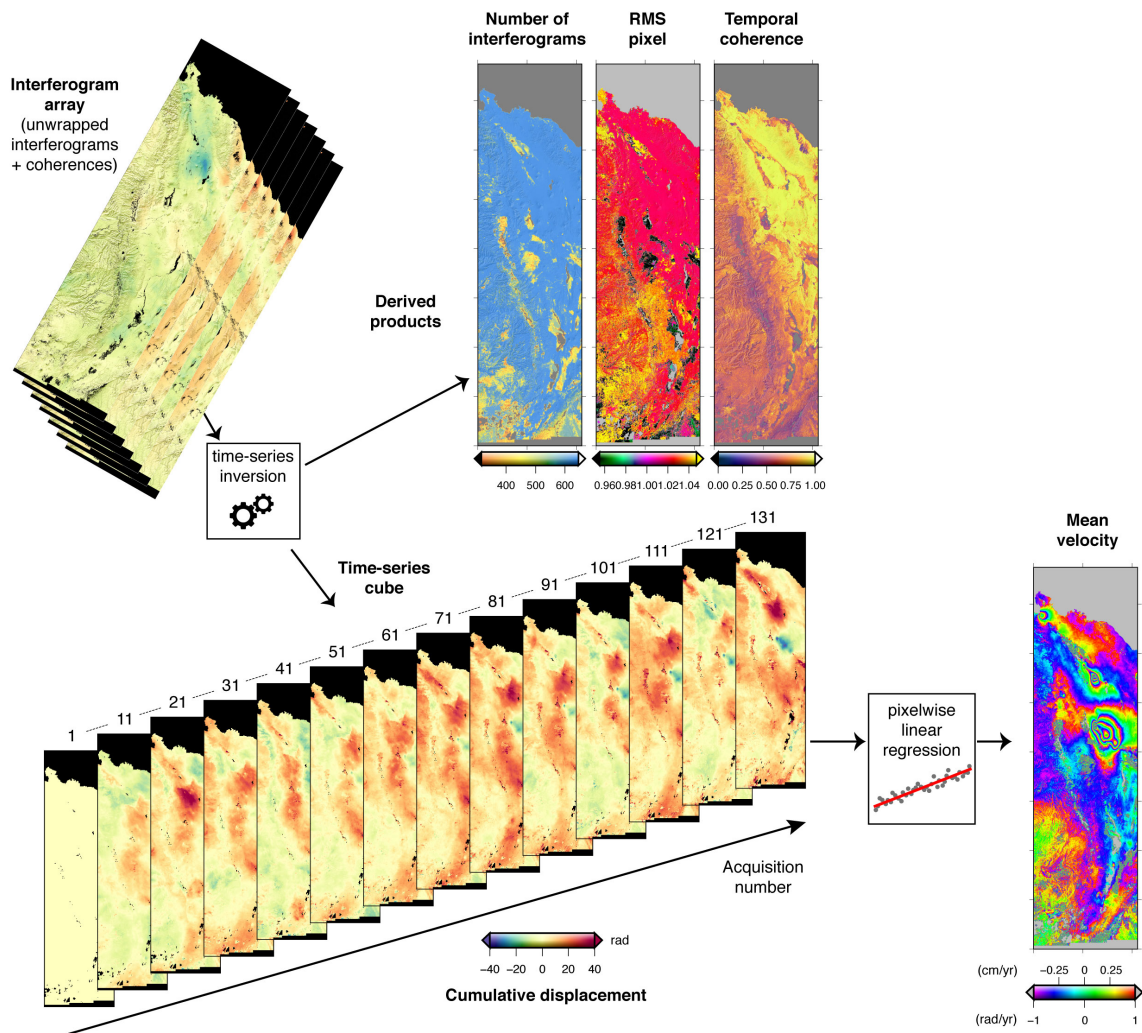


Figure 6. Time-series processing. The time series inversion provides, from the input stack of interferograms, maps of cumulative displacement, together with quality indicators. The mean velocity, obtained by linear regression through the time series, is shown in a wrapped color scale.

284 3. FLATSIM architecture

285 The goal of the FLATSIM project was to integrate the NSBAS chain in the CNES High Performance
 286 Computing (HPC) infrastructure to benefit from its computing power and from the fact that CNES
 287 mirrors locally the Sentinel-1 data from ESA. FLATSIM is thus able to process up to 6 years of Sentinel-1
 288 data over large geographical areas (up to 7 million km² per year in total). FLATSIM is designed to
 289 automatically access and process Sentinel-1 radar images and to distribute interferometric products
 290 which cover worldwide areas of interest. As shown in Figure 7, FLATSIM is composed of two main
 291 components: a Production Module and a Delivery Module.

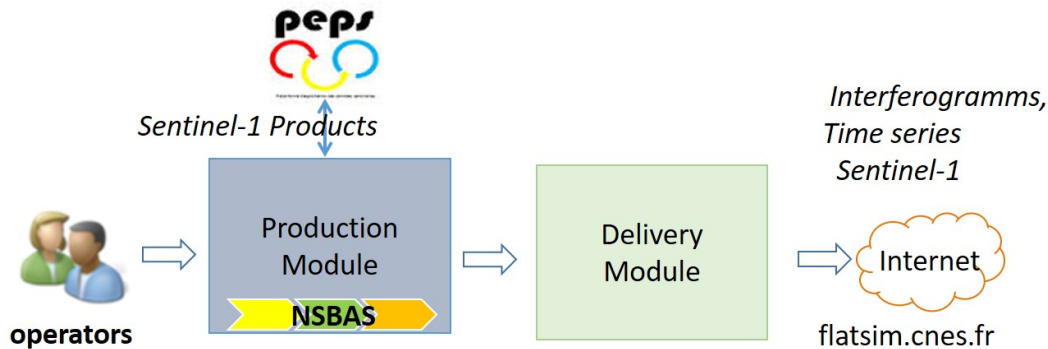


Figure 7. General architecture for production and delivery

292 3.1. Architecture of the FLATSIM project: distributed and scalable by design

293 The strategy behind the integration of NSBAS in the FLATSIM project was to make NSBAS
 294 processing massively parallel. Even if most of its steps can be run in a parallel way, NSBAS was
 295 conceived as a global processing chain running on a single-node, monolithic workspace, in which
 296 all the data generated during the NSBAS workflow are stored, from acquisition of the Sentinel-1
 297 SLC (Single Look Complex), to production of the time-series and formatting of distributed data.
 298 The integration of NSBAS in FLATSIM is based on a different logic, that consists in splitting the
 299 NSBAS chain in a set of unitary processes for which the inputs and outputs are clearly identified and
 300 catalogued. This way, it is possible to create for each unitary process its own workspace, from the
 301 cataloged data, including only the data necessary for its execution. It then becomes easier to dispatch
 302 these treatments on the computing resources.

303 3.2. Architecture of the CNES HPC infrastructure

304 The CNES HPC infrastructure is a shared facility at the disposal of CNES projects and partners.
 305 It is composed of more than 480 batch servers for a total of 12288 cores (725 Tflops) and a 8.2 PB
 306 General Parallel File System (GPFS) with 300TB burst buffer offering a bandwidth up to 100GB/s. This
 307 large computing capacity should enable FLATSIM to meet its production objectives. The integration
 308 of NSBAS should also be optimized to the CNES HPC, to avoid FLATSIM deteriorating the level of
 309 service for all the other users of this computing center.

310 FLATSIM also relies on various services offered by CNES computing division, such as different
 311 types of data storage, database management system (DBMS) hosting services and web-site hosting
 312 mutualised services.

313 3.3. Architecture of the FLATSIM Production Module

314 The technical environment of the production module includes the HPC and the GPFS, a shared
 315 postgresql DBMS, and the mutualized datalake (composed of several data storage spaces). The
 316 architecture of the Production Module (Figure 8) is based on 2 sub-components:

- 317 • The FLATSIM application server which includes catalog and orchestrator capabilities,
 318 • The FLATSIM unitary treatments that integrate NSBAS as a library and run as unitary jobs on
 319 nodes of the HPC center.

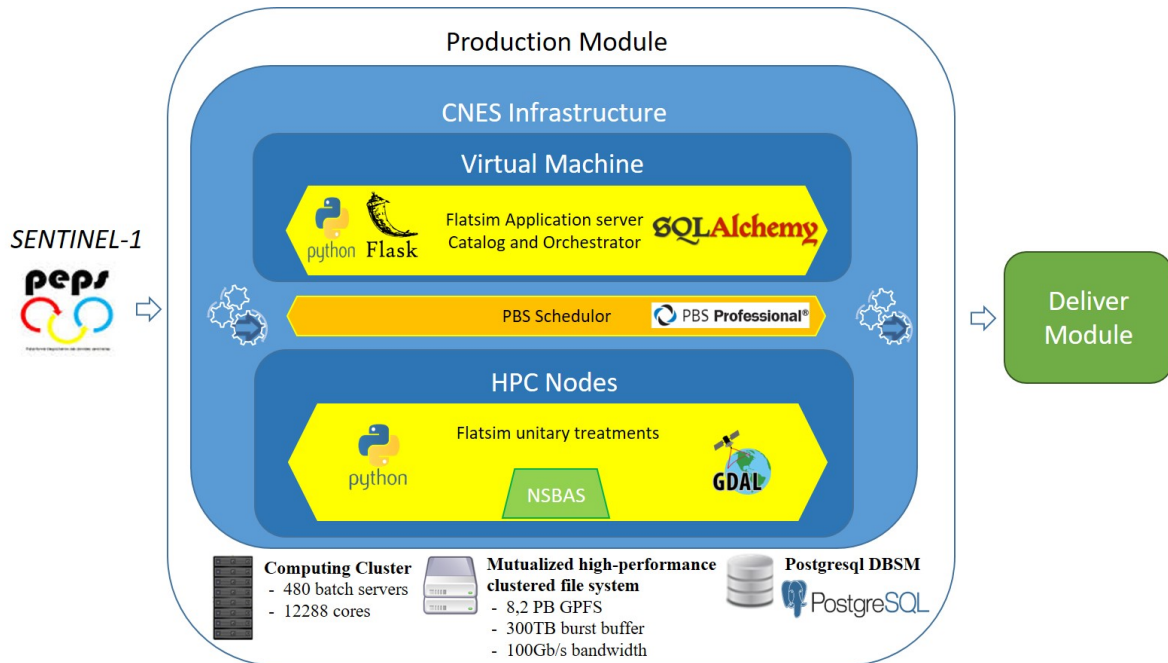


Figure 8. Production Module architecture and components

320 The FLATSIM application is in charge of referencing data, orchestrating processing steps and
 321 submitting them as unitary jobs to the scheduler. The data cataloged by the application server are
 322 stored on the GPFS, while their metadata and status of processing steps' jobs are registered in the
 323 postgresql database.

324 Through the integration, each step of the NSBAS workflow has been divided into unitary
 325 processes, which can be performed in isolation and parallel for each unique data (SLC or
 326 interferograms) in different jobs spread on the HPC's nodes. During their execution, job's temporary
 327 data are written on the local storage of the node, and, at the end of the execution, output data are
 328 transferred and cataloged by the FLATSIM application server, to be used as input of the next step jobs.
 329 Once the output data are cataloged, the job also updates its status in the application server.

330 The FLATSIM application server is also responsible for the processing sequencing. It monitors
 331 the production status of each step, and when one step is completed, based on its parametrization, its
 332 internal logic, and the data cataloged, it identifies the jobs to process for the next step, and submit these
 333 new jobs to the Distributed Resource Manager (DRM) PBS-PRO, that will dispatch them on the HPC
 334 nodes. At any time during the production, the operators can interrogate the FLATSIM application
 335 server to request information on the production status, and act on products or jobs if necessary.

336 During the first step of the production, FLATSIM gets SENTINEL-1 Level-1C products via
 337 direct privileged access on the PEPs platform (developed by CNES in the context of collaborative
 338 ground segments of Copernicus program) and stores them in the application server catalog. After the
 339 packaging step, the FLATSIM output products are transferred on the mutualized datalake, which is
 340 accessible by both the production module and the delivery module. At the same time, these products
 341 metadata are sent to the delivery module to be registered in its database.

342 By default, the scheduling system in the CNES HPC allows a project to submit jobs on up to 800
 343 cluster cores. Under these conditions, processing a Sentinel-1 swath covering 5.5 degrees of latitude to
 344 generate a 8 looks resolution (about 100 meters pixel size) time series over 5 years' time depth requires
 345 approximately 10,000 hours of CPU time and 60 hours of real time.

3.4. Architecture of the FLATSIM Delivery Module

The role of the Delivery Module is to diffuse the FLATSIM products to the scientists and public community. The products are first made available to scientific experts for validation before being distributed to end users.

The FLATSIM Delivery Module is composed of Web services and Websites. The web services and the expertise website are packed in an Apache HTTP server hosted in the CNES infrastructure in a VM (Virtual Machine) provided by the CNES web-site hosting mutualised services called Web-NG. In the CNES infrastructure, the delivery module uses a shared postgresql DBMS and the mutualized datalake to store the data. Depending on their types, the data are stored on different technical means:

- Downloadable products on the GPFS part of the datalake,
- Visualization data on the NAS (Network Attached Storage) part of the datalake,
- Metadata in the postgresql database.

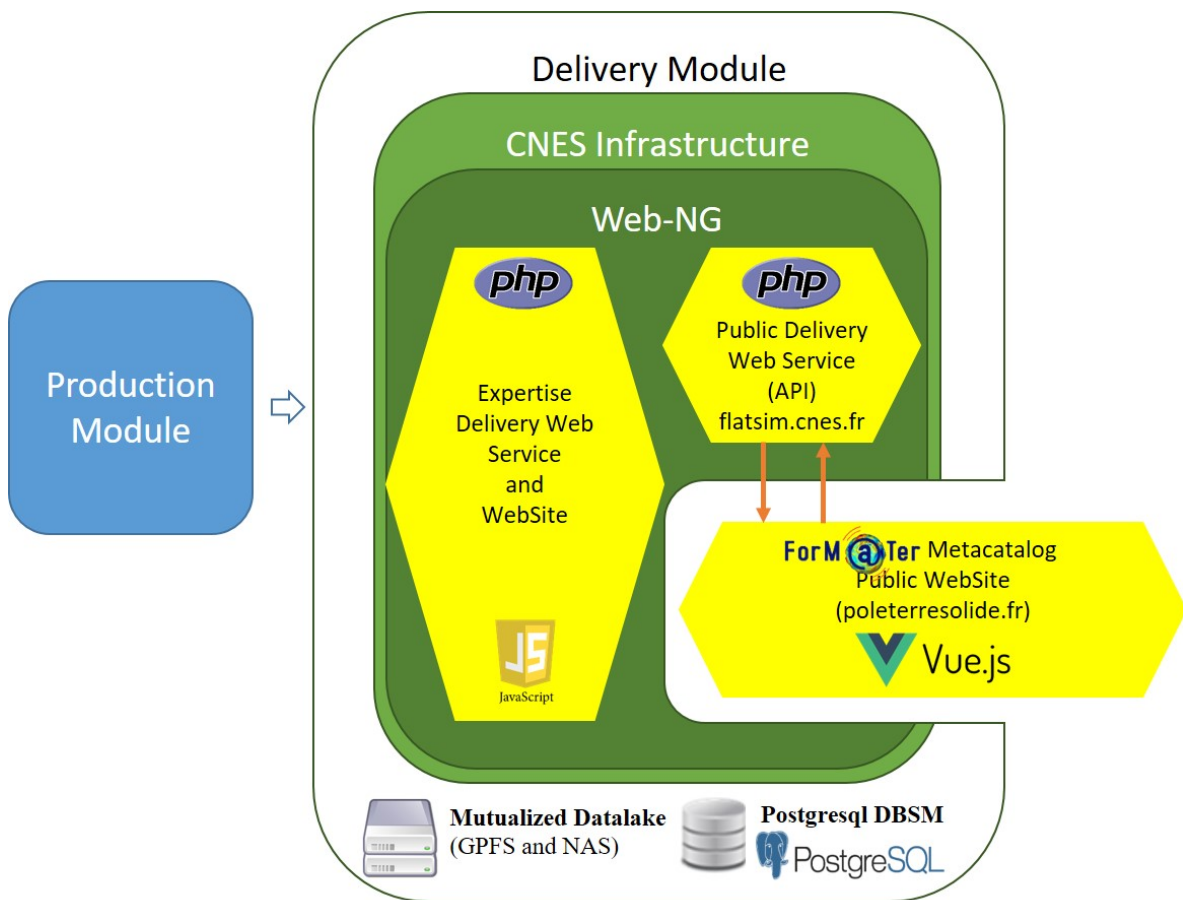


Figure 9. Delivery Module for user access

3.5. User access interface

The public data access is made via the ForM@Ter Website, on the "Terre Solide" metacatalog page (<https://www.poleterresolide.fr/>), which is a Vuejs (javascript) application embedded on a page of a Wordpress site. The CNES public delivery web service provides an Opensearch Application Programming Interface (API) which allows access to the catalog of distributed products. The metadata of the FLATSIM collections (for each study area) are recorded by the ForM@Ter metacatalog in a Geonetwork catalog under the ISO19139 standard. Downloading and viewing products with WMS (warehouse management system) is reserved for authenticated ForM@Ter users. Authentication is done with the ForM@Ter Single Sign-On (SSO).

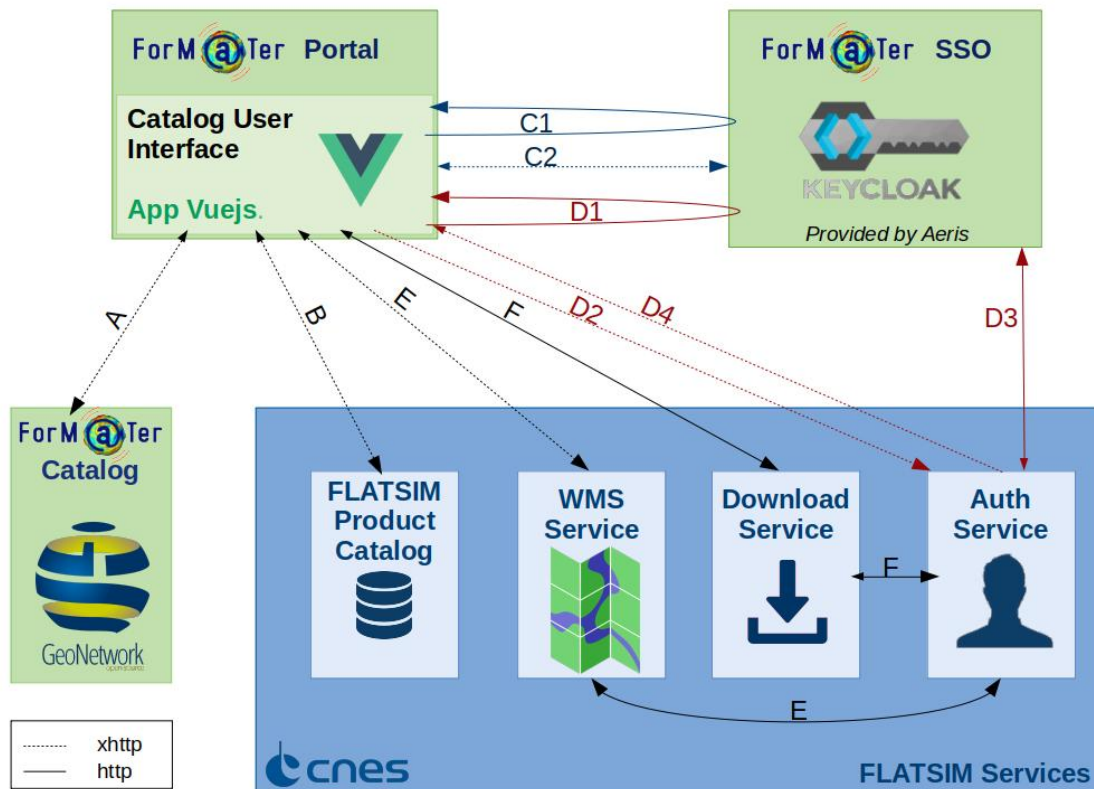


Figure 10. Catalog access architecture

367 In Figure 10, we display the requests made at the interface between the ForM@ter portal, the
 368 ForM@ter SSO, the Form@ter Catalog and the CNES FLATSIM services :

- 369 • Request A : Geonetwork's Q Search API is used for user searches among collections. These
 370 searches can be spatial, temporal, by data center, open term, variable or platform. The requests
 371 are xhttp requests, invisible to the user.
 372 • Request B : The metacatalog's Opensearch API allows searches among the granules of a FLATSIM
 373 collection. The requests are xhttp requests, invisible to the user.
 374 • Requests C1 and C2 (User authentication for the metacatalog) :

375 C1, the user authenticates with the Keycloak SSO and is redirected with a code to the
 376 metacatalog page.

377 C2, the Vuejs metacatalog application queries the SSO with the code to obtain an access
 378 token and user information (invisible to the user).

- 379 • Requests D1 to D4 (Authentication with FLATSIM) :

380 D1, the user authorizes FLATSIM to access his user data and is redirected to the metacatalog
 381 page with a code for FLATSIM Authentication.

382 D2, the metacatalog application transmits the code to the FLATSIM authentication service
 383 (invisible to the user).

384 D3, FLATSIM's authentication service queries the SSO with the code, to get user data
 385 (invisible to the user).

386 D4, the authentication service transmits a FLATSIM data access token to the metacatalog
 387 application (invisible to the user).

- 388 • Request E : The user now has a FLATSIM access token, he can query the WMS Flatsim service
389 by transmitting the token. The service checks that the token is valid with the FLATSIM
390 authentication service and sends the images back (invisible to the user).
- 391 • Request F : The user now can request a download by transmitting the token. The service checks
392 that the token is valid with the FLATSIM authentication service and then returns the archive
393 (invisible to the user).

394 3.6. Service access

395 Processed areas are selected through a series of call for research proposals, with an independent
396 committee evaluating the scientific objectives, feasibility and team skills, bearing in mind that the
397 amount of square kilometer processed per year is limited. This call is currently dedicated to the
398 French scientific community. Products are freely available for the french scientific community. The
399 international community will access the final displacement rate maps (after thorough validation,
400 possible partial reprocessing, tying up to geodetic reference frame, and a first data analysis by scientific
401 teams) through peer-reviewed publications with a reference to the FLATSIM service.

402 4. Description of Products

403 4.1. General description

404 The choice of the number of products and their processing level delivered by the FLATSIM service
405 was a trade-off between providing only a few small-size high-level products ready-to-use for users
406 non-expert in InSAR and providing the huge amount of all intermediate and final products along with
407 processing logs, most of which are only potentially useful to user experimented in InSAR processing
408 and require large storage and download capabilities on both the provider and user sides.

409 Compared to other MTInSAR services like LicSAR or P-SBAS on GEP, we have chosen to put the
410 slider more on the side of a rather large product set giving great flexibility for post-processing and
411 analysis of results. This choice results from our long InSAR processing experience showing that starting
412 from the coregistered stack of wrapped interferograms (that is a large burden of the processing) some
413 processing steps can be optimized a-posteriori based on the analysis of the first time-series results.

414 The details of the products made available by FLATSIM are described here: [https://formater.
415 pages.in2p3.fr/flatsim/](https://formater.pages.in2p3.fr/flatsim/). Here, we give insights on the main types of products that are delivered,
416 including quality assessment products and auxiliary products useful for controlling how successfully
417 the automated workflow proceeded. Except for the DEM which is provided only in radar geometry, all
418 the products are delivered in both radar and ground geometries. For instance, this allows the user to
419 re-run with his own computing resources the unwrapping step, or the time series inversion, before
420 geocoding. We give all the necessary information so that the user can redo the processing from the
421 merged, 2-looks, wrapped interferograms, if needed.

422 The products are delivered **separately for each processed track** as three types of packages:
423 interferogram, time-series, and auxiliary data. Filenames are formed according to the naming
convention depicted in table 1

Table 1. Product naming convention for interferogram packages

<code>CNES_TYPE_GEOMETRY_[DATE1_DATE2]_LOOKSrlks.EXT</code>

424 in which
425

426 **TYPE** points toward the file type (i.e., wrapped interferograms, coherence, etc..). See hereafter for a
427 more detailed description.

428 **GEOMETRY** is set either to *radar* for radar geometry or *geo* for ground geometry.

429 **DATE1** (DATE2, respectively). These optional fields corresponds to the date at which the first (second
430 or last, respectively) image has been taken.

431 **LOOKS** is the number of looks used to downsample the image (note there is a factor 4 between the
432 number of range and azimuth looks, i.e., 2 looks means 8 looks in range and 2 looks in azimuth).

433 **EXT** is the extension of the file that defines its type:

434 **tiff** contains the data;

435 **png** a preview file. It comes with a *legend* file, typically a colorbar with the scale information.

436 **meta** a file that contains additional metadata. It contains for example information about the
437 parameters of the processing chain, or about the product itself like its DOI, or about the
438 satellite geometry, like the orbit direction, the relative orbit number, etc.

439 In each package, in addition to the main products, previews, graphs and small text files that
440 contains statistics allow a quick quality assessment of different processing steps. **The size of large
441 products is also given in the next subsections. Although some files can be particularly large (>10Gbytes),
442 GDAL (Geospatial Data Abstraction Library) or GDAL API for example can easily manipulate them
443 and extract sub-grids with lower spatial or temporal resolution. These sub-grids can be used in data
444 analysis packages performing, for example, principal or independent component analysis, if these
445 packages have data size limitations.**

446 4.2. Packages of interferogram products

447 There is one package per interferogram. It contains a set of files related to a given interferogram
448 that are synthesized in table 2.

Table 2. Products of the interferogram package

FILE TYPE	DESCRIPTION
APS	Interferogram Atmospheric Phase Screen from Global Atmospheric Model
InW/InU	Wrapped/Unwrapped Differential Interferograms
InWF	Wrapped Differential Filtered Interferograms
Coh	Spatial coherence

449 • **Wrapped/Unwrapped Interferogram**

450 InW (InU, respectively) is the wrapped (unwrapped, respectively) merged interferogram.
451 Wrapped interferograms in radar geometry are provided both in 2 and 8 (or 16) looks. The initial
452 number of looks of the interferograms before they are geocoded is given in their names and
453 metadata. The ground pixel spacing is chosen according to the initial pixel spacing in radar
454 geometry. The InWF and InU products are spatially filtered. All interferograms have been
455 corrected using spectral diversity and the ERA5 atmospheric model.

456 • **Spatial coherence**

457 Coh is the spatial coherence of the wrapped interferogram. It can thus be considered as a proxy
458 of the quality/reliability of the signal. Typically, the spatial coherence will be very low (close to
459 zero) at points located on water – e.g. sea, lakes, rivers, snow – and close to one at locations with
460 stable backscattering properties where there is no vegetation – e.g. deserts, rocky mountains
461 without snow, roads, buildings, etc.

462 • **Atmospheric phase screen**

463 APS is the phase delay induced by the atmosphere as predicted by the ERA-5 atmospheric model
464 [50] and mapped on the DEM [48,49].

465 Each zipped interferogram package is about 2.2Gb for 25 processed consecutive bursts (450 km
466 long segment). This large size is partly due to the interferogram product in 2 looks and in radar

469 geometry (i.e., with a spatial resolution of about 30 m, 1.3Gb), whereas 8-looks interferograms, APS or
 470 coherence maps in ground geometry (pixel spacing of 0.00111 degree, 124Mb) and in radar geometry
 471 (resolution of 120 m, 82Mb) are less heavy.

472 4.3. Time-series package

473 This package corresponds to products generated at the time series inversion step (see 2.7). Map
 474 products are given in 8 (or 16) looks, in radar geometry and in ground geometry. Table 3 summarizes
 475 the time series products.

Table 3. Main timeseries products

FILE TYPE	DESCRIPTION
DTs	Time series of total LOS phase delay (data cube)
MV-LOS	Mean LOS Velocity
Net	Auxiliary maps for the assessment of the time series quality
Stk-In	List of the interferograms file names

476 • DTs: time-series

477 This product is a data cube that contains the cumulated total phase delay images at each
 478 acquisition with respect to the first date. In practice, the reference is set to the origin of a
 479 linear fit through the time series for each pixel. This representation avoids for the APS of the
 480 first image to appear in negative on all other dates. Note however that it is not ideal in case of
 481 strongly non linear deformation. The time series may be incomplete for some pixels and for
 482 some dates, and values are then replaced by NaN. We choose to deliver the total phase delay,
 483 that includes both residual atmospheric phase screens and displacement signals, without any
 484 attempt by us to separate both contributions. This allows the user to perform its own separation,
 485 possibly guided by his knowledge of the expected deformation signal properties.

486 The geotiff file includes as many bands as time steps. The unit is in radians along LOS, positive
 487 away from satellite. Each band is named by the acquisition date. The associated preview file
 488 displays the cumulated displacement at the last time step.

489 • MV-LOS: LOS velocity

490 The mean LOS velocity is given in a geotiff product with two bands :

- 492 – band 1 is the mean velocity in rad/yr, positive away from satellite
- 493 – band 2 is a shaded view of the topography, with an illumination simulated to match the
 494 radar backscatter amplitude.

495 • Net: Quality assessment product

496 This geotiff product gives various indicators of the quality of the time series inversion, provided
 497 in radar and in ground geometry.

- 498 – band 1: RMS misclosure of the interferogram network for each pixel, in rad.
- 499 – band 2: Number of interferograms used in the time series inversion for each pixel.
- 500 – band 3: Number of images used in the time series inversion for each pixel.
- 501 – band 4 : Proxy for the temporal coherence, computed as the norm of the average of all
 502 successive interferometric triplets (between 0 and 1).
- 503 – band 5: Proxy for a possible bias in the timeseries, computed as the argument of the average
 504 of all successive interferometric triplets (in rad).

505 • Stk-In: interferogram list product

506 It gives information on the timeseries, as for example the list of dates and interferograms used as
 507 input to the time serie inversion and the reference image that was selected.

508

509 • **Additional txt files**

510 The "RMSinterfero.txt" and "RMSdate.txt" files, together with their png previews, are very
 511 useful to check possible problems on interferograms or on acquisitions. They provide the RMS
 512 interferometric network misclosure averaged either by interferogram or by date. For example,
 513 the RMS value for some interferograms will be large in case of uncorrected unwrapping errors.
 514 Specific errors associated with one image, for example in case of snow, strong atmospheric
 515 or ionospheric perturbations, or bad azimuth frequency modulation corrections, can also be
 516 detected.

517 The zipped time-series package is about 6.7 Gb for 25 processed consecutive bursts (450 km
 518 long segment) and 100 processed images. The package size will increase linearly with the number
 519 of processed bursts and images. The data cube has a larger size in ground geometry (6.1 Gb, pixel
 520 spacing of 0.00111 degree) than in radar geometry (4.1G, resolution of about 120 m).

521 *4.4. Auxiliary data package*

522 This set of products (table 4) provides the user with auxiliary information common to the whole
 523 data set, including LookUp Tables (LuT), LOS unit vectors, and processing parameters, etc.

Table 4. Main auxiliary products

FILE TYPE	DESCRIPTION
CosENU	LOS unit vector expressed in local reference frame (East, North, Up components).
DEM	Elevation in meter in radar geometry. Comes in two resolutions.
LuT	Lookup Tables used to do the mapping between radar and ground geometry.
TCoh	Backscatter properties in 2 looks.

524 • **CosENU : LOS unit vector**

525 The three-bands geotiff product in either radar or ground geometry gives the LOS unit vector
 526 $\vec{u} = (u_E, u_N, u_U)$, along the satellite to ground direction, such that the LOS velocity, V_{LOS} , can be
 527 related to the ground velocity vector, $\vec{V} = (V_E, V_N, V_U)$, by $V_{LOS} = V_E u_E + V_N u_N + V_U u_U$

528 • **LuT: Lookup Tables**

529 The provided LuT tables allows to project 2-looks or 8-looks products in radar geometry in
 530 ground geometry and inversely.
 531

532 • **TCoh: Radar backscatter properties**

533 This product assembles at about 40mx40m resolution backscatter properties averaged over the
 534 complete data stack. It includes (1) the averaged SLC amplitude, (2) the amplitude dispersion
 535 index (σ_A / \bar{A}), (3) the norm of the complex average of all successive interferogram triplets, (4) the
 536 argument of the complex average of all successive interferogram triplets.
 537

538 • **Auxiliary text files**

539 Numerous text files are added in the package for users wanting to verify some crucial processing
 540 steps. They include perpendicular baseline information, parameters for enhanced spectral
 541 diversity corrections for each sub-swath, interferogram unwrapping fractions, and interferogram
 542 phase standard deviations.
 543

544 The zipped auxiliary package is about 11 Gb for 25 processed consecutive bursts (450 km long
 545 segment). The package size will increase linearly with the number of processed bursts. The largest
 546 product sizes are for auxiliary information in 2-looks. LuT in 2-looks have a size of 2.2 Gb in ground
 547 geometry (pixel spacing of 0.000277 degree) and of 1.3 Gb in radar geometry (resolution of 30 m). They

548 allow to geocode the wrapped 2-looks interferograms. The TCoh product is larger in ground geometry
 549 (3.9 Gb, pixel spacing of 0.000277 degree) than in radar geometry (2.6 Gb, resolution of 30 m). The LOS
 550 unit vector in 2 looks is only given in radar geometry (2.0 Gb), whereas in 8-looks it is only 186 Mb in
 551 ground geometry and 123 Mb in radar geometry.

552 5. Results and products qualification

553 5.1. First processed areas

554 In May 2020, a first call for proposals was open to the French scientific community to identify
 555 priority regions for FLATSIM processing. Figure 11 presents all the regions of interest retained for this
 556 first call. Nine projects were selected covering different scientific interests. An InSAR expert from the
 557 FLATSIM project was attributed to each project. The role of this expert is to interact beforehand with
 558 the user to define the key processing parameters. At the end of the processing, the expert helps the
 559 user to assess the quality of the generated products.



Figure 11. Map of the selected regions of interest

- 560 1. The *Ozark aquifer* project covers a region located in North America. It focuses on the study of the
 561 deformations associated with the Ozark aquifer (south of the Mississippi basin), subject to strong
 562 variations in groundwater level, and in neighboring regions where significant seismicity is
 563 observed, with a strong seasonal component (New Madrid), or related to wastewater injections
 564 (Oklahoma). The objective is to better understand the geodetic signature of the hydrological cycle.
- 565 2. The *Central Andes, Peru-Chile* project aims at (1) better understanding the seismic cycle of the
 566 Andean subduction zone in Peru and Chile and of the crustal faults in the Andes, (2) monitoring
 567 the dynamics of the large active volcanoes in the region (and to detect possible precursors to
 568 eruptions), and (3) at studying the seismic, climatic and anthropogenic forcing on the dynamics
 569 of landslides in the Andes.
- 570 3. The *Balkan region* is one of the most seismically active zones in Europe, with intense industrial
 571 and demographic development. The purpose of the project is to better quantify the deformations
 572 of tectonic origin in this region (kinematics and localization of active faults, study of earthquakes).
 573 It also aims at quantifying the deformations of anthropogenic or climatic origin (linked to the
 574
 575

576 exploitation of natural resources or to variations in sea level).

- 577
- 578 4. *Turkey*: The objective of this project is to characterize the seismic and aseismic behavior of
- 579 the North Anatolian and East Anatolian faults, in order to better assess their seismic hazard
- 580 and understand the physical processes governing the dynamics of a fault. It also includes
- 581 the monitoring of deformations in the grabens of western Turkey, which are major geological
- 582 structures with high seismic potential.
- 583
- 584 5. The *Afar* project aims at characterizing the spatial and temporal distribution of the deformation
- 585 in the region of the Afar depression. The purpose is to better understand the large-scale tectonics
- 586 (localization of divergent borders, kinematics of the triple point), but also the dynamics of
- 587 volcanic, seismic and aseismic events, and the mechanics of active faults. The issue of landslides
- 588 hazard will also be addressed.
- 589
- 590 6. *Okavango delta*: This project aims at better understanding the deformations of tectonic origin
- 591 in the area of the Okavango Delta (associated with the functioning of the Okavango rift and
- 592 the East African rift), or of hydrological origin (linked in particular to the flood cycle), and the
- 593 possible interactions between tectonics and hydrology in this region.
- 594
- 595 7. The *Tarim* project focuses on the analysis of tectonic deformations along the Western Kunlun
- 596 Range, on the northwestern edge of the Tibetan Plateau. This region is marked by the
- 597 interaction between large strike-slip and thrust faults, with in particular the existence of one
- 598 of the largest thrust sheet in the world, whose interseismic loading and capability to produce
- 599 “mega-earthquakes” will be investigated.
- 600
- 601 8. *Eastern border of the Tibetan plateau*: The objective of the project is to quantify and model the
- 602 current deformations on the eastern edge of the Tibetan plateau. It focuses on deformations of
- 603 tectonic origin, at the scale of active faults as well as at the continental scale, to address issues of
- 604 the seismic cycle and uplift mechanisms of the Tibetan plateau. This project is also interested in
- 605 monitoring non-tectonic signals present in the time series (hydrological overloads in particular).

606 In the following sections, the Afar and the Tibetan case studies will be taken as examples to

607 illustrate the processing results and the quality of the products of the FLATSIM-NSBAS processing

608 chain (Figure 12). For Tibet, we will display the results of a very long track, A070, from the Tarim

609 basin to the North down to the southern part of Tibet. For the Afar case, the focus will be put on the

610 descending track D079, which extends from the Red Sea down to the Main Ethiopian rift, and covers

611 the western part of the Afar depression and the eastern edge of the Ethiopian plateau.

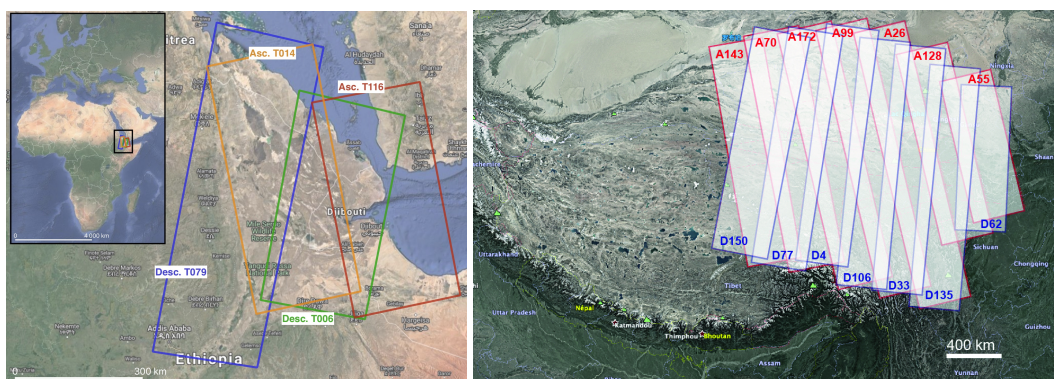


Figure 12. Sentinel-1 tracks footprint of (a) the Afar case study, (b) the Tibetan case study.

612 5.2. Result discussion in Tibet area

613 The LOS velocity products obtained separately for 15 ascending tracks segments in East Tibet are
 614 displayed in Figure 13. A simple velocity offset is added to each map to enhance visual continuity.
 615 However, a proper assembly of the 15 velocity maps should also take into account additional ramps in
 616 azimuth and range, varying incidence angles from near range to far range, and referencing using GNSS
 617 data. Despite these strong limitations, the figure shows a very good across-track consistency of the LOS
 618 velocity features. It highlights interseismic deformation in Tibet along major faults, as the Altyn Tagh
 619 fault and the Kunlun fault [22]. The deformation gradient across the Kunlun fault is particularly sharp
 620 and strong, due to continuing post-seismic deformation after the 2001 Mw7.8 Kokoxili earthquake
 621 [53,54]. A number of other geophysical signals can be seen, especially large subsidence patches due
 622 to permafrost degradation [15,19] south of the Kunlun fault, and smaller-scale, strong, round-shaped
 623 subsidence patterns in the Qaidam basin of probable hydrological origin.

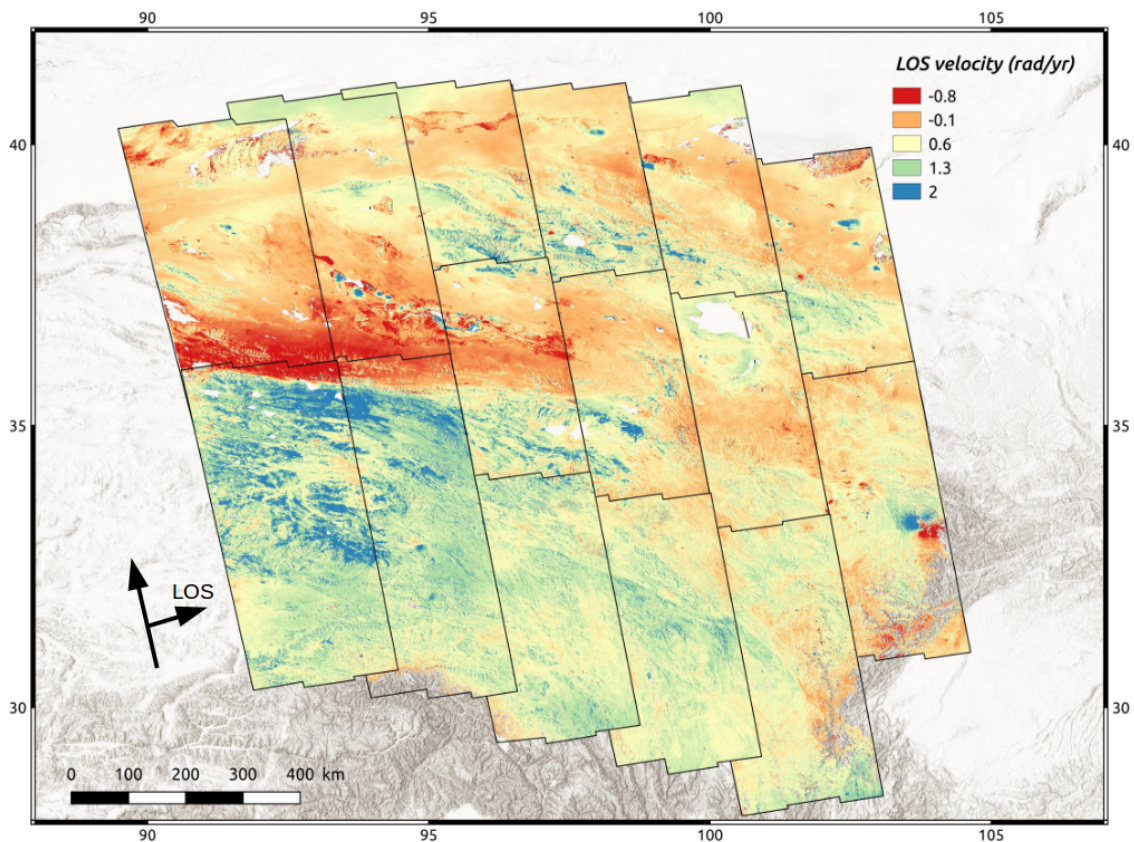
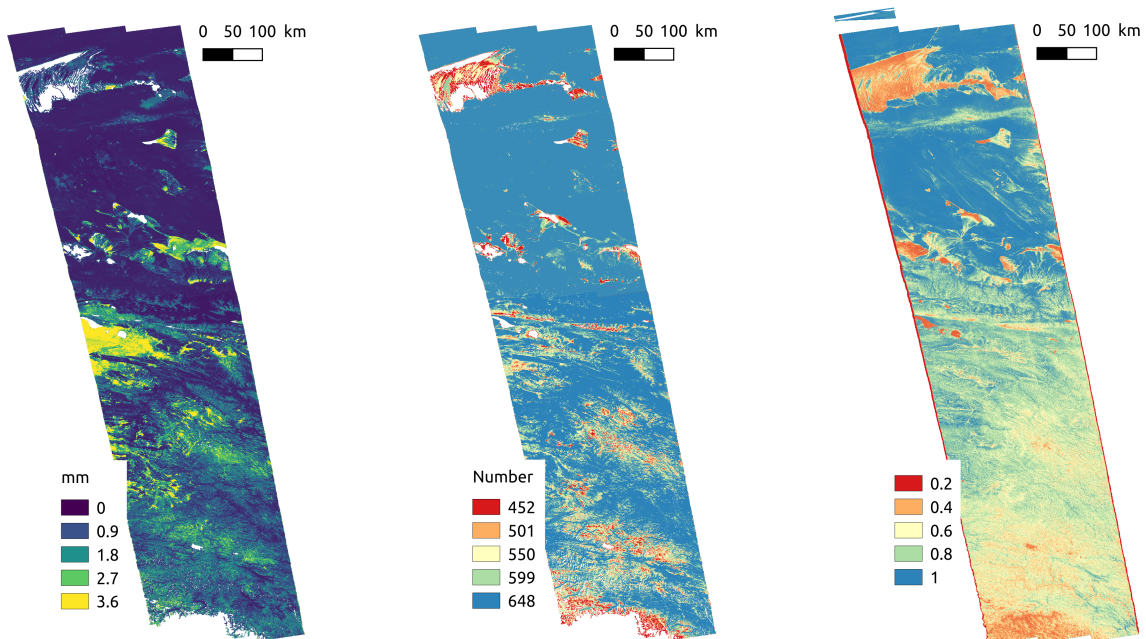


Figure 13. LOS velocity maps provided by automated FLATSIM processing in eastern Tibet over 15 separated track segments. The color scale is in rad/yr, positive away from satellite. The color scale amplitude from minimum to maximum, of 2.8 rad/yr, corresponds 12.5 mm/yr. The maps are overlying each other, from north to south and from east to west, i.e., only the segment on the south-west corner is displayed in its entirety. A constant velocity is added to individual maps to enhance visual continuity across the segments.

624 In order to assess the quality of the velocity maps, we provide additional indicators either as
 625 maps (figures 14 or as averaged values per date or interferograms 15). The unwrapping fraction (figure
 626 15a) is given for each interferogram. It allows to automatically discard interferograms with the lowest
 627 unwrapped fractions (here interferogram 285 for example), or for the users to detect possible problems
 628 with specific periods of time or interferogram durations. The RMS network misclosure (figures 14a,
 629 15b and 15c) combines effects due to phase noise and to unwrapping errors. Typical values of up to 2
 630 mm (~ 0.4 radians) are good and typical of a negligible contribution of residual unwrapping errors.

631 The variation is then associated with temporal decorrelation. It can be seen here (figure 15c) that the
 632 temporal decorrelation has on average a semi-seasonal behavior, with peak decorrelations in winter
 633 and in summer, larger in the southern section than in the northern one, mostly desert, region. A few
 634 acquisitions in the southern part of the study area may be affected by snow. Interferograms with
 635 large RMS misclosure (e.g., numbers 415, 430, 521 of the southern section) are most probably affected
 636 by residual unwrapping errors covering a non negligible fraction of their surface. Pixels with RMS
 637 misclosures larger than 3.5 mm (in yellow on figure 14a) denote areas with unwrapping ambiguities
 638 too frequent to be automatically and consistently corrected by network inversion. Their origin in the
 639 present case is due to freeze-thaw cycles that create strong phase gradient and phase ambiguities across
 640 basin borders [15]. Finally, the number of inverted interferograms per pixel (figure 14b) is also useful
 641 to map lateral variations in the quality of the velocity map. It is strongly correlated with the temporal
 642 coherence (figure 14c). Here, sand dunes in the Tarim basin for example result in a low coherence
 643 and a low fraction of unwrapped interferograms. As including long temporal baseline interferograms
 644 strongly reduce possible bias due to fading signals [45], we cannot exclude a bias in areas with a
 645 significantly reduced number of interferograms. Therefore, combining the three quality maps shown
 646 in figure 14, using different thresholds, allow to mask pixels for which we have less confidence, before
 647 performing a geophysical interpretation of their displacement behaviour through time.



(a) RMS misclosure

(b) Interferogram number

(c) Proxy for temporal coherence

Figure 14. Examples of quality indicators merged for the two segments of track A070 in Tibet

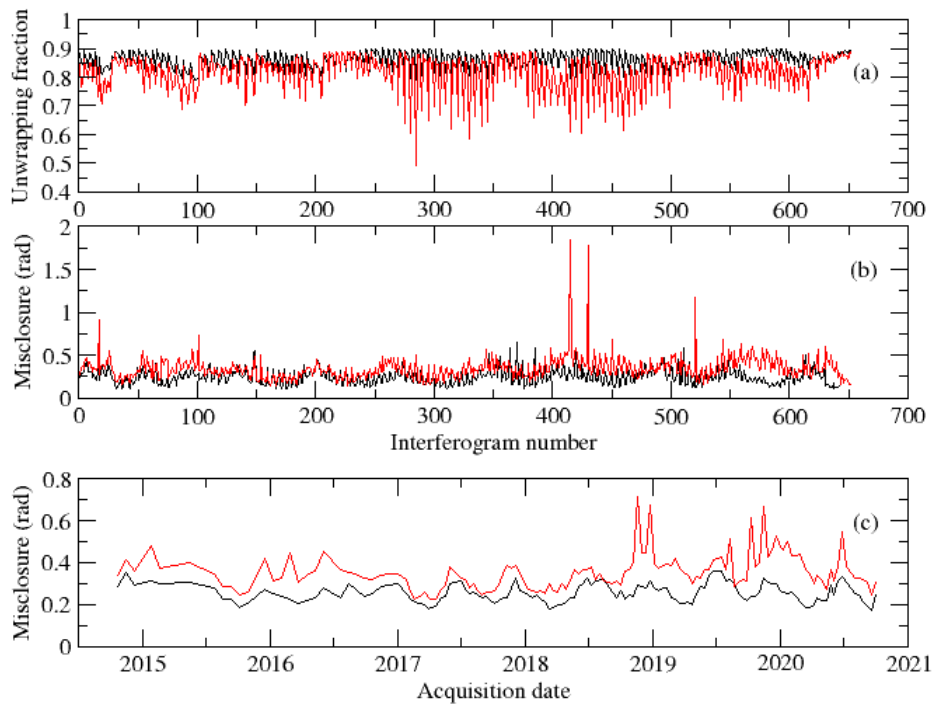


Figure 15. Quality indicators for track A070 in Tibet: (a) percentage of unwrapped area for all interferograms; (b) RMS misclosure for all interferograms; (c) RMS misclosure per date. Black curves : northern section. Red curve: southern section.

648 The merged proxy for the temporal coherence (Figure 16) shows, at the scale of eastern Tibet,
 649 pixels where we can expect good signal to noise ratio. Areas of very low coherence include lakes, rivers,
 650 highly vegetated areas and moving sand dunes. A zoom on the northern rim shows the potential of
 651 temporal coherence for mapping interesting features. Here for example, areas of stabilized sand dunes
 652 by the effect of anthropic action have a marked signature on the coherence map.

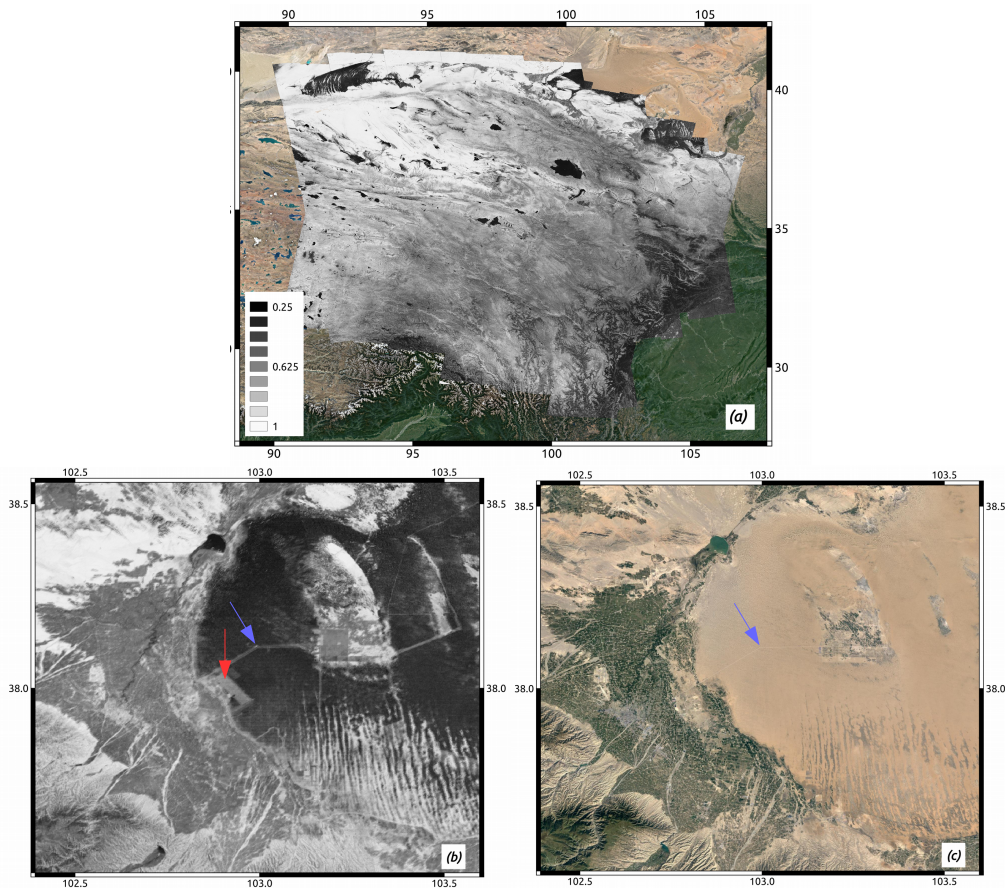


Figure 16. Proxy for temporal coherence, merged for all tracks that have been processed in eastern Tibet. (a) Global map. (b) Zoom on the rectangle shown in (a). (c) Associated optical image. The red arrow points toward a large geometrical field of stabilized sand dunes. The blue arrow shows how dirt roads increase the coherence in desert sand dunes.

653 5.3. Discussion of results in the Afar area

654 In Afar, beside the three quality indicator maps shown in figure 6, the quality of the results can be
 655 discussed through a comparison of the velocity maps along overlap areas, and through the analysis
 656 of the various observed surface deformation signals and their temporal behavior. The accuracy of
 657 the signals detected in the final mean velocity maps can be tested by comparing the results in the
 658 overlap region between the two adjacent descending tracks D079 and D006 (Figure 17, right). Despite
 659 different incidence angles ($\approx 44^\circ$ for track D079 versus $\approx 36^\circ$ for track D006), the excellent agreement
 660 indicates the reliability of the resulting velocity maps across a broad range of spatial wavelengths.
 661 Furthermore, we can detect signals that arise from different geophysical processes involving magmatic
 662 and/or tectonic drivers (Figure 17, left). Relatively strong deformation rates due to magmatic deflation
 663 or inflation characterize different volcanoes (e.g., Nabro, dabbahu, Erta 'ale). Also, a tenuous extension
 664 signal is visible across the Asal rift, as previously shown thanks to Radarsat InSAR timeseries [10].

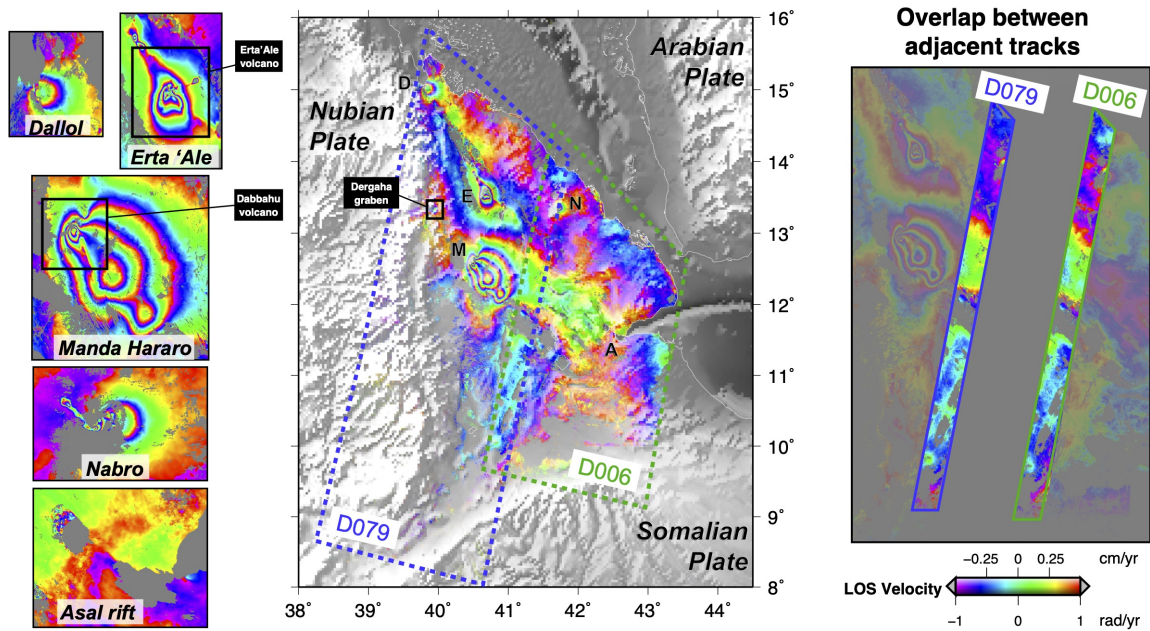


Figure 17. Mean velocity map for track D079 and D006 showing a number of geophysical signals.

665 The time-series quality is highlighted by extracting the displacement history for a number of
 666 selected pixels (Figure 18). Three geophysical phenomena, with contrasting temporal signatures, are
 667 shown here :

- 668 • Following a major rifting episode that took place between 2005 and 2011 [55], the Dabbahu
 669 volcano (located North West of Manda Hararo in Figure 18) has experienced a steady re-inflation,
 670 inducing uplift at a rate of ≈ 3.5 cm/yr. The inflation is remarkably constant between 2014 and
 671 2021, confirming the findings of [56].
- 672 • In contrast, the volcano Erta 'Ale has shown a transient deflation that started in January 2017
 673 following a lava lake overflow event, that produced long-lived lava flows [57].
- 674 • Finally, a very small signal is detected in the Dergaha graben, coinciding with a cluster of
 675 seismicity detected in 2008 [58]. The time-series shows a clear step around March 2018, which
 676 corresponds well with the time of occurrence of the largest event of the seismic sequence.

677 Note that no low-pass filtering nor model adjustment have been applied on the time series presented
 678 here. They can therefore be safely interpreted, and uncertainties on the geophysical interpretation can
 679 be assessed using the dispersion of the time series.

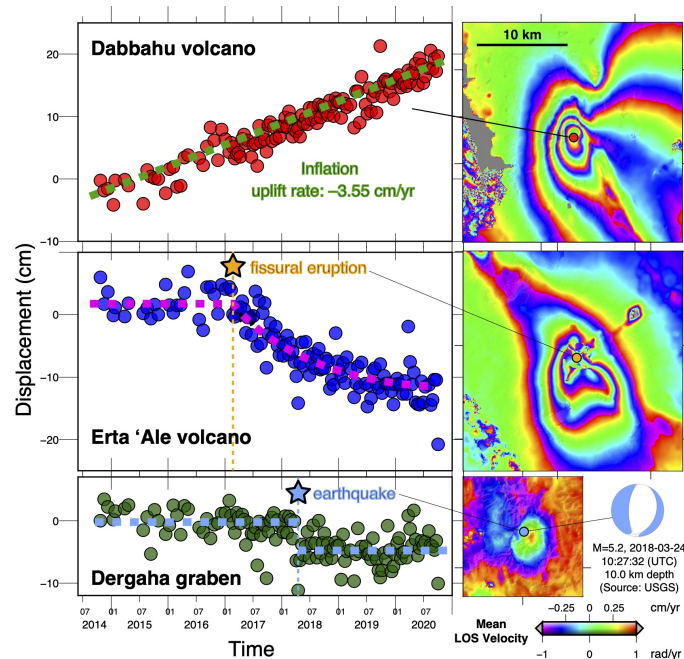


Figure 18. Zoom on three geophysical signals. Location of areas of interest is indicated by the black rectangles in Figure 17.

680 6. Conclusion and future work

681 The FLATSIM service is dedicated to the monitoring of surface deformation of broad areas (*i.e.*
 682 larger than 250,000 km²). It aims at providing accurate measurements of ground displacements for
 683 a large range of geophysical applications as pointed out in sections 5.2 and 5.3, mostly in natural
 684 environments. The service is a collaborative effort between InSAR experts, researchers in geophysics,
 685 and CNES engineers. Scientists provide their expertise on Multi-Temporal InSAR processing with a
 686 state of the art processing chain (NSBAS v2.0) and on geophysical processes, while CNES supports the
 687 implementation and deployment of this service in an operational mode. Taking advantage of the CNES
 688 mirroring of the Sentinel-1 data, as part of the PEPS infrastructure, this service benefits from rapid
 689 access to large volumes of imagery, a prerequisite for the efficient execution of the processing chain.
 690 The success of the implementation relies (1) on the algorithm of the NSBAS stack processing, with a
 691 single reference image for the whole image stack, avoiding redundant copies of input data, together
 692 with optimizations for a large number of steps, but more importantly, (2) on the specific, parallel
 693 NSBAS chain implementation on the CNES HPC infrastructure, with local transfer of input-output
 694 data on cluster nodes, allowing very fast I/O between disk and processors.

695 Since the goal of the service is to serve scientific purposes, the processed regions are selected
 696 according to scientific criteria. FLATSIM thus provides a set of products (like *e.g.* the DTs product)
 697 that allows the end-users that do not have large computational capabilities to take advantage of the
 698 MTInSAR methodology, making an optimal use of the wealth of data provided by the Sentinel-1
 699 mission. Moreover, a set of auxiliary data is also provided, which allows for assessing the quality
 700 of the delivered products. The product versatility makes possible their direct use by the end-users:
 701 for example by using the velocity maps as provided, ingesting the time-series in signal detection
 702 algorithms (*e.g.* principal component analysis, independent component analysis, geophysical
 703 modeling, ...), or even by reprocessing individual interferograms or reinverting the time-series. Since
 704 the products are given a DOI, they can be cited.

705

706 In the future, the NSBAS processing chain will continue to evolve to integrate the most recent
 707 advances in InSAR processing. As the FLATSIM service has entered its operational phase, the core
 708 processing chain is anticipated to be updated at most twice a year. Another step will consist in

709 providing the user with visualisation capabilities, either online or with standalone tools, that will allow
710 to explore more deeply into the delivered products.

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726 7. References

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