MASTER: A FULL AUTOMATIC MULTI-SATELLITE INSAR MASS PROCESSING TOOL FOR RAPID INCREMENTAL 2D GROUND DEFORMATION TIME SERIES

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ABSTRACT

Taking advantage of the ever-increasing amount of available SAR data requires adapted processing infrastructures. We present here the InSAR Mass processing Toolbox for Multidimensional time series (MasTer), which can combine any type of SAR data to produce unsupervised vertical and horizontal ground deformation time series. MasTer is optimized to automatically download SAR data, select the appropriate interferometric pairs, perform the interferometric mass processing, compute the geocoded deformation maps, invert and display the velocity maps and the 2D time series on a web page updated incrementally as soon as a new image is made available. MasTer also allows the production of time series of coherences or SAR amplitude images, which can be used e.g. for land use monitoring or geomorphological changes detection. The capabilities and performances of MasTer are illustrated with several examples. Software and manual are available on request to authors. *To MasTer the art of InSAR mass processing.*

Index Terms — InSAR time series, MSBAS, Displacement monitoring, Automatic mass processing, SAR Amplitude time series

1. INTRODUCTION

The increasing amount of Synthetic Aperture Radar (SAR) satellites orbiting the Earth, their increasing time and space resolution, the variety of wavelengths, polarizations and looking geometries, the shortening of data availability latency and the lengthening of archive databases offer unprecedented opportunities for Earth observation and hazard monitoring. The downside is that it brings new challenges for processing that huge amount of data and for making the results quickly analyzable.

To fully benefit from these advances in SAR, it requires efficient data processing infrastructure (optimized for processing speed, storage usage and security), efficient data visualization, and standardization of the final products for easy ingestion by conventional analysis tools.

We present here the InSAR Mass processing Toolbox for Multidimensional time series (MasTer) [1], which can combine any type of SAR data to produce unsupervised 2D ground deformation time series. MasTer can run with cron jobs and perform fully automatic processing from data download up to displaying 2D time series results on a web page updated incrementally as soon as a new image is available. The incremental architecture allows updating the time series within the shortest time possible (typically a few hours) as soon as a new SAR image is provided. Several steps are self-evaluating to ensure robust and reliable processing.

Moreover, recent methodological improvement consists in the computation of a coherence proxy to guide the pair selection optimization balancing the use of each image as *primary* and *secondary* image during the differential interferometric (DInSAR) processing. Such a pair selection increases both the processing efficiency and the signal-to-noise ratio of the time series [Smittarello et al., in prep].

MasTer's capabilities will be illustrated with several examples from DR Congo (volcano monitoring combining > 1700 images acquired by several satellites to produce a 18 years long time series; monitoring of lava lake level changes), Réunion Island (time series combining Wide Swath and Strip Map Sentinel-1 (S1) images and comparison with GNSS time series; volcano and landslides monitoring) as well as Argentina-Chile border region (remote volcanoes and mass movement monitoring).

2. THE MASTER TOOLBOX

MasTer is composed of three main elements:

1. The *CIS MasTer Engine,* a command line InSAR processor and tools written in C derived from the *CSL InSAR Suite software* (CIS) [2] and tuned to the specific needs of the automated mass processing,
2. The *Multidimensional Small Baseline Subset processor* (MSBAS) [3,4,5], an extension of the Small BAseline Subset method (SBAS) [6] written in C++, allowing the simultaneous inversion of several time series of SAR interferograms acquired in different geometries, including different sensors, SAR wave-lengths, incidence angles, polarization etc., to solve for the horizontal and vertical components of the ground displacement.
3. A set of mostly shell scripts aiming at downloading and processing automatically a large number of interferometric pairs and feeding and running the MSBAS processor to obtain the desired deformation maps and time series [7]. The final products are output in standard Geographic Information System (GIS) format. Maps and times series can be displayed on dedicated web pages.

MasTer can process most type of SAR data: ERS, ENVISAT, ALOS, RADARSAT, COSMO-SkyMed, TerraSAR-X, TanDEM-X (incl. bistatic and pursuit mode), Sentinel-1, Kompsat5, PAZ, SAOCOM...

To ensure standardization and fast processing, images are cropped (optional) and converted (once) in a common internal format, whatever the sensor. For S1 wide swath images, as many frames, bursts and swaths – and/or only those of interest to the user as defined in an optional kml file - can be stitched to form a new image in that internal format. Each image from a series acquired by a given sensor in a given geometry is then coregistered on an optimum reference *global-primary* image (selected by a dedicated tool). DEM and mask (optional) are computed (once) in the slant range geometry of that reference image. Masks can be built with a dedicated tool to keep only the pixels that are expected to remain coherent for the whole database given the maximum temporal and spatial baselines considered.

Mass processing can be split into several parallel processing and performed directly in the geometry of the reference image. Unwrapping is performed using classical SNAPHU [8] or homemade branch cut algorithm [9]. SNAPHU unwrapping can be speeded up by masking the zones that are known to be decorrelated. An option exists to make adaptive masking, that is keeping the pixels identified by the mask, but also those which remain coherent above a selected threshold for the considered pair. Finally, amplitude, coherence, interferogram (optionally filtered) and deformation maps (optionally detrended and/or interpolated to fill small gaps) are geocoded in an (optional) grid common to all the SAR geometries to be further ingested by MSBAS.

MasTer offers specific tools e.g. to track possible unwrapping errors (by checking the phase closure between triplets of DInSAR [10]), to select the best MSBAS inversion order and regularization factor ([4]), to visualize the deformation maps in QGIS ([11]), to extract and plot the time series of clicked pixels, to export maps in kmz format for visualization in Google Earth, to check the integrity of the mass processed results etc.

For data safety reasons, processing architecture is planned to easily split the storage of raw data, images in internal format, intermediate interferometric results and final deformation time series on separate hard drives. All the parameters required for the processing are stored in a single text file that is archived along with the results and the processing log files. This allows to check at any time what was really performed, with which parameters and which version of the software.

Images that are affected by unwanted characteristics (missing lines, artifacts etc.) can be quarantined and will be ignored throughout the process. Note that MSBAS software can also produce enhanced SBAS time series, that is merging all the time series acquired in a given Line of Sight (LOS) by different sensors with similar incidence angles.

More details about MasTer can be found in [1], which is published in open access. Software and tools, which are Linux and Mac compliant, are available on request to the authors.

3. ILLUSTRATIVE EXAMPLES

Products obtained with MasTer are of several types:

1) For displacement studies: linear velocity maps and cumulated displacement maps at the date of each SAR image used for the inversion (in vertical and horizontal and/or LOS directions), time series of displacement (in m) at pixels that remain coherent along the whole timespan, differential displacement time series between two pixels (useful to eliminate possible common source of noise or have an accurate location of reference point for estimating the displacement), geocoded wrapped interferograms…
2) For land use monitoring or geomorphological changes detection: amplitude images, sigma nought calibrated images (for S1), coherence maps… Those products can be issued in slant range geometry or in geographic coordinates, both as independent images or as animated gifs.

Illustrative examples are provided below.

3.1. Pre-eruptive signals detected through 18 years of multi-satellite time series in the Virunga Volcanic Province (RDC)

The Virunga Volcanic Province (VVP) hosts among the most active volcanoes in Africa. A 18 year long time series (2003-2021) merging ENVISAT, CSK, RADARSAT and S1 (1.709 images; 13.984 interferograms) reveals pre-, co- and post-eruptive ground deformation. Fig. 1 shows an example of differential displacement measured between two pixels located on the flanks of Nyamulagira volcano.

Such a time series of displacement revealed deformation starting 3 weeks before the Nyamulagira 2006 eruption. Similar time series at pixels located closer to other eruptive sites confirmed e.g. a 3 weeks pre-eruptive signal observed prior the 2010 eruption [12] and 3 months before the 2011 eruption [13].

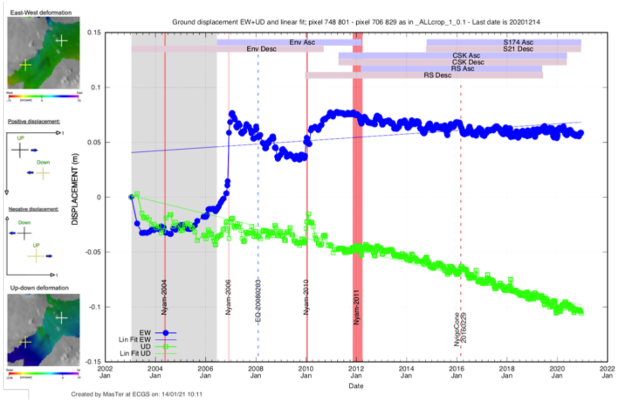

Fig. 1: Double difference of Vertical (green) and EW (blue) ground deformation (in m) between 2 pixels located on the flank of Nyamulagira volcano (see crosses on the velocity maps wrapped on the DEM in insets). Direction of displacement of one pixel with respect to the other is explained with the two graphs on the left. Orange and Grey vertical rectangles illustrate respectively eruptions duration and period of asymmetric SAR geometry (Ascending vs Descending). Blue and Red horizontal rectangles highlight the epoch covered with each satellite along Ascending and Descending orbits respectively.

Several types of vertical and horizontal colored rectangles and bars can automatically be added to the plot to illustrate the various types of events (e.g. eruption durations, satellite coverage, earthquakes, seismic swarms, periods of asymmetric SAR geometry (Ascending or Descending), SAR polarization changes, unusual events etc). Dates and labels of each event are listed in text files (one file per type of event).

3.2. Lava lake level measurement through amplitudes time series at Nyiragongo volcano (DR Congo)

Using a simple geometrical formula (see Fig. 2), one can measure the height of sub-vertical structures by measuring the length of its SAR shadow. This method is applied to measure the lava lake level variations in the crater of Nyiragongo volcano [14, 15]. MasTer is routinely used to perform automatic time series of sigma nought calibrated S1 amplitude images. These images are then used to compute time series of lava lake level and crater floor level changes using SAsha software [Barrière et al. in prep.] with a (relative) resolution of 1.5 m.

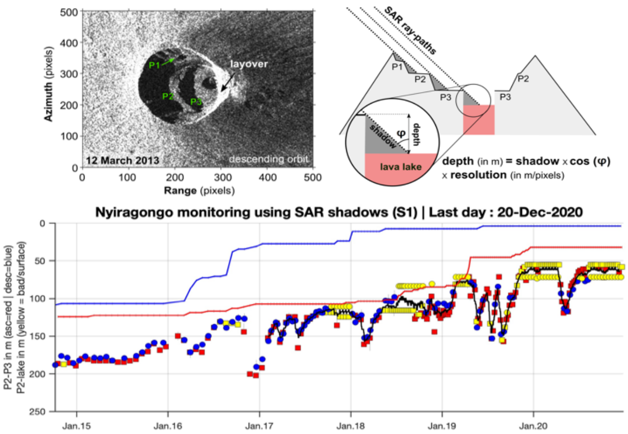

Fig. 2: Upper left: CSK SAR amplitude image acquired along the descending orbit showing the 3 platforms visible in the crater of Nyiragongo: P1 (~3270 m a.s.l) and P2 (~3190 m a.s.l) are batches of remaining crater floor level reached prior 1977 and 2002 eruptions respectively. P3 is the crater floor hosting the lava lake. Upper right: geometrical formula used to measure the height based on SAR shadow length. Below: Time series of lava lake (dots) and P3 (line) depth (in m) measured with S1 SAR images with respect to P2.

3.3. Multi-mode Sentinel-1 time series for volcano and landslides monitoring at La Réunion Island.

Comparing GNSS and automatic MasTer EW and Vertical ground deformation allows checking the consistency of the results. Fig 3 illustrates deformation measured at Piton de la Fournaise by combining Wide Swath and Stripmap S1 data. Due to the InSAR insensitivity to displacements occurring in the NS direction, results are valid as long as the NS displacements are not significantly larger than EW displacements [3]. See for instance the small offset in Fig 3 at the time of the April 2018 eruption.

3.4. Coherence restriction for time series of ground deformation at Laguna del Maule

MasTer offers to further restrict the MSBAS inversion to only the interferograms satisfying a mean coherence threshold computed over a dedicated region

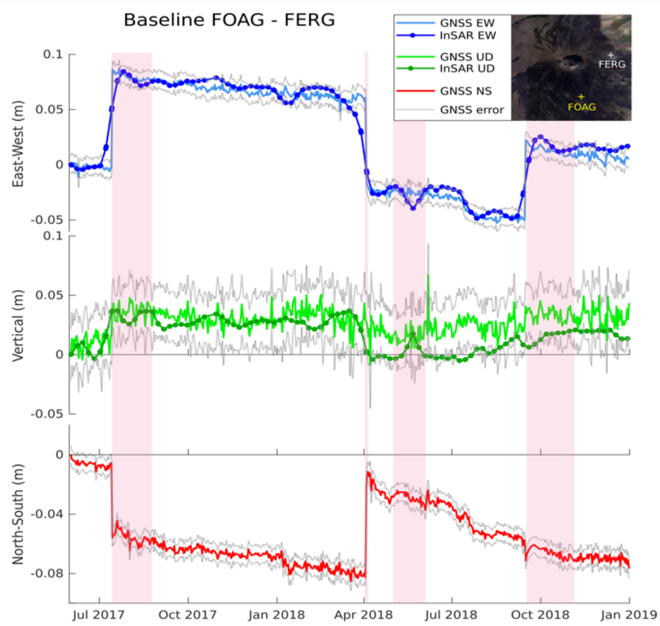

Fig. 3: Differential time series for 2 pixels where GNSS stations are installed (FOAG and FERG) at Piton de la Fournaise volcano. MSBAS time series combine Wide Swath and Stripmap S1 data. MasTer automatic processing accurately measures co-eruptive displacements associated with several eruptions (Orange). MSBAS results remain within the GNSS uncertainty (Grey lines).

defined by a kml. This can be useful for regions affected by strong seasonal decorrelation (e.g. snow cover). Neglecting that may result in strongly underestimating the deformation as illustrated by the ground deformation at the Laguna del Maule volcanic complex, Argentina (Fig 4) [1].

Another tool allows computing a coherence proxy to guide a pair selection optimization balancing the use of each image as *primary* and *secondary*. This improves the signal-to-noise ratio by reducing the influence of DEM errors and atmospheric noise. It also reduces the total number of computed interferograms by up to 75% (Fig 4), which as a consequence also reduces the computation time and raw-memory and storage requirements [Smittarello et al., in prep.].

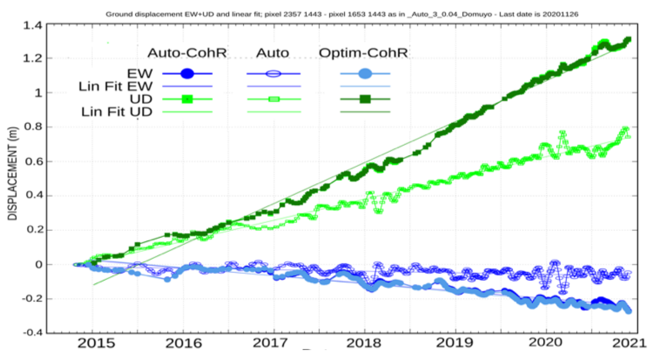

Fig. 4: Differential deformation at Laguna del Maule between the center of deforming zone and a pixel located 50 km to the West (Auto-CohR, filled symbols). Neglecting decorrelation during austral winter underestimates the displacement by several tens of % (Auto; open symbols). Pair selection optimization reduces the noise and speed up the computation by up to 75% (Optim-CohR; filled symbols).

3.5. Monitoring landslide with 3D time series in Bukavu (DR Congo)

When ground deformation is expected to occur along the steepest slope (e.g. for landslides or glaciers), MSBAS can perform a 3D decomposition of the ground deformation.

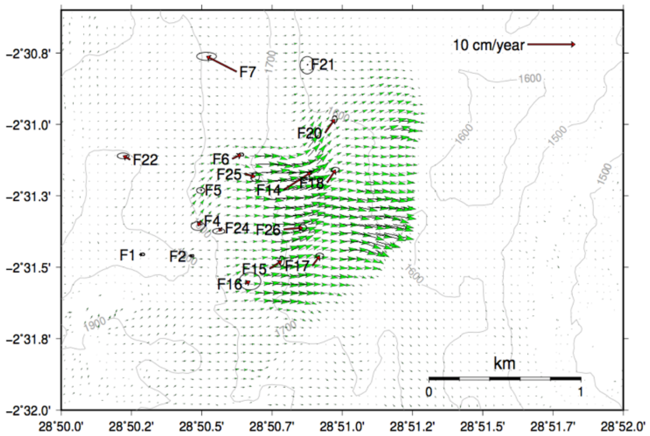

Fig. 5: Horizontal deformation vectors computed at Funu landslide from CSK data (green) with MSBAS-3D. Red vectors F1-F26 are deformation from D-GPS campaigns. Ellipses are 95% confidence interval (after [12]).

Although this functionality is not (yet) implemented in the full-automatic incremental processing and web display, MasTer is perfectly suited to perform the required InSAR mass processing and MSBAS inversion, as illustrated in Fig. 5 for a 1.5 km2, slow-moving deep-seated slope instability at Funu, Bukavu city (South Kivu, DRC) measured from 2015 to 2019 [12].

4. CONCLUSION

MasTer was designed and developed by users for the users i.e. it aims at answering as much as possible the new requirements to benefit from the ever-increasing amount and quality of available SAR data. It was designed to be fast, incremental, flexible and easily adapted to new requirements. It is routinely applied for several type of monitoring. More examples and specificities will be shown during the presentation. It remains under constant improvement and is available upon request to the authors.

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