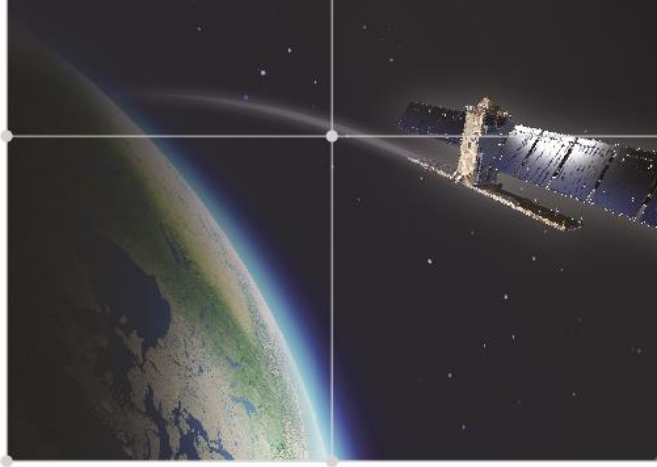
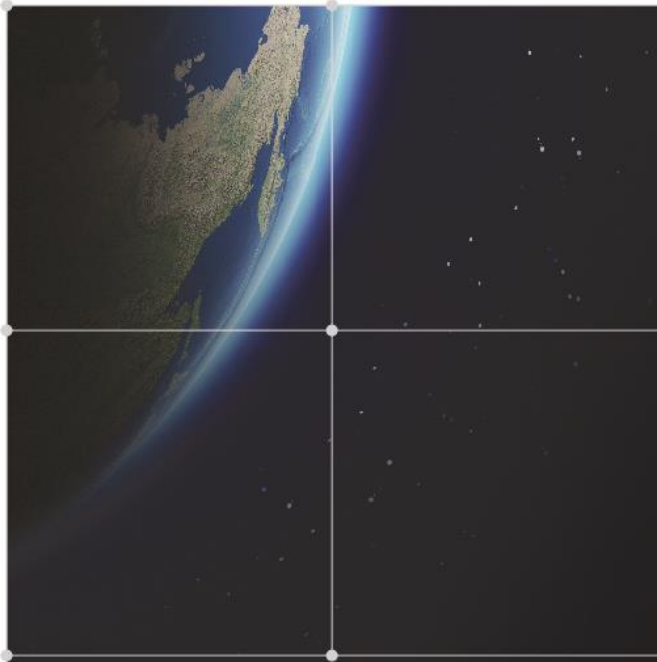




InSAR land surveying and mapping services in support of the DWR SGMA program

Technical Report - March 2020



TRE
ALTAMIRA
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16 March 2020

Executive Summary

TRE Altamira Inc. (TRE) has been contracted by Towill, Inc (Towill) to provide InSAR ground deformation measurements over groundwater basins in California (Task Order No. 37 – Contract No. 4600011239, *supporting the Sustainable Groundwater Management Act (SGMA) of the California Department of Water Resources*).

The objective of the work is to update the 2018 ground deformation measurements (Task Order No. 26 – Contract No. 4600011239) up to September 2019. The output consists of continuous uninterrupted vertical deformation time series from 01 January 2015 to Sept 2019, obtained by stitching the 2019 results to the 2018 historical data.

TRE's SqueeSAR algorithm is used to generate the ground deformation measurements and the results are calibrated and validated using ground-based, continuously operating Global Positioning System (GPS) stations located throughout the state of California.

This **Milestone 4 Report** represents the final deliverable and provides a description of all tasks and milestones.

- **Task 1 - Study Area:** The study area defined by DWR covers 101,210 km² (39,000 mi²) in California. It has increased by 6,737 km² (2,600 mi²) compared to the 2018 study as it now includes additional basins located in the north and in the south of California.
- **Task 2.1 - Imagery procurement:** All available (2,235) Sentinel images were downloaded. The new imagery covers the period 01 June 2018 - 30 September 2019 for the areas in common with the 2018 analysis and the full 01 January 2015 – 30 September 2019 period for the new areas.
- **Task 2.2 - Processing polygons definition:** The downloaded imagery was analyzed and 35 polygons defined for the data processing. To maintain maximum consistency with the 2018 results, the 27 processing polygons over the 2018 areas have remained unchanged while 8 new processing polygons were defined for the new basins.
- **Task 2.3 – SqueeSAR Processing:** The SqueeSAR data processing for the 27 previous processing polygons produced LOS measurements that cover 01 January 2018 - 30 September 2019, which includes an overlap of 15-20 images with the previous analysis. These results were then integrated with the 01 January 2015 – 01 June 2018 measurements to generate uninterrupted deformation time series from January 2015 to September 2019. Over the new areas, the SqueeSAR processing was carried out from scratch, using the entire image archive available from January 2015 to September 2019.

- **Task 2.4 – Data calibration:** 231 GPS station were selected from the UNAVCO network to calibrate the LOS measurements. The calibration was performed using the methodology defined in the 2018 analysis.
- **Task 2.5 – Vertical measurements:** The vertical measurements were derived from the LOS calibrated time series using the same methodology of the 2018 analysis. To maintain the maximum consistency with the previous results, the same spatial grid and temporal sampling were used.
- **Task 2.6 – Draft deliverables:** The draft deliverables were generated for both the common period and the variable start date results, using the same format defined in the 2018 analysis and made available on the TREmaps web platform and a dedicated SFTP.
- **Task 2.7 – Final deliverables:** TRE received and addressed the modification requests from DWR and Towill to produce the final deliverables, including the high-resolution LOS data. All deliverables were provided to Towill and DWR through TREmaps and SFTP.

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Acronyms and Abbreviations

AOI	Area of Interest (study area)
ASC/A	Ascending orbit
DESC/D	Descending orbit
GNSS	Global Navigation Satellite System
InSAR	Interferometric Synthetic Aperture Radar
LOS	Line of Sight
MP	Measurement Point
SNT	Sentinel Satellite
TS	Time series
SqueeSAR®	Advanced InSAR algorithm patented by TRE Altamira

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This document contains confidential proprietary information and is intended solely for the recipient. The contents of this document, including information related to TRE ALTAMIRA methodology and know-how, may not be disclosed in whole or in part to any third party by any means or used for any other purpose without the express written permission of TRE ALTAMIRA

1. Introduction

TRE has been contracted by Towill under Task Order No. 37 - Contract No. 4600011239 to provide InSAR ground deformation monitoring data over groundwater basins in California, in support of land surveying and mapping services for the Department of Water Resources (DWR) and its mission to enact the Sustainable Groundwater Management Act (SGMA).

The project consists of four Tasks (Table 1), with TRE responsible for Task 2 - *InSAR data Acquisition and Analysis*, whose objective is to update the ground deformation measurements provided in 2018 (Task Order No. 26 – Contract No. 4600011239) to September 2019. Task 2 comprised seven sub-tasks and four milestones (Table 2) and this Milestone 4 report constitutes the final document.

Project Task	Description	Appointed
1	Study Area definition	DWR
2	InSAR data Acquisition and Analysis	TRE
3	CGPS Data Acquisition and Analysis	Towill
4	InSAR-CGPS Comparative Analysis	Towill

Table 1: Project Tasks

Task 2	Description	Milestone (report)	Expected Delivery	Delivery date
2.1	Imagery procurement	M1	25 Oct 2019	28 Oct 2019
2.2	Processing polygons definition	M2	16 Dec 2019	23 Dec 2019
2.3	SqueeSAR processing (LOS data)			
2.4	Data calibration (LOS data)	M3	14 Feb 2020	20 Feb 2020
2.5	Vertical measurements generation			
2.6	Draft deliverables			
2.7	Final deliverable	M4	16 Mar 2020	16 Mar 2020

Table 2: Task 2 subtasks and schedule.

2. Task 1: Study Area

The study area covers 101,210 km² (39,000 mi²) and includes the groundwater basins of interest to DWR. The area has increased by 6,737 km² (2,600 mi²) compared to the 2018 study as it now includes additional basins located in the north and in the south of California (Figure 1).

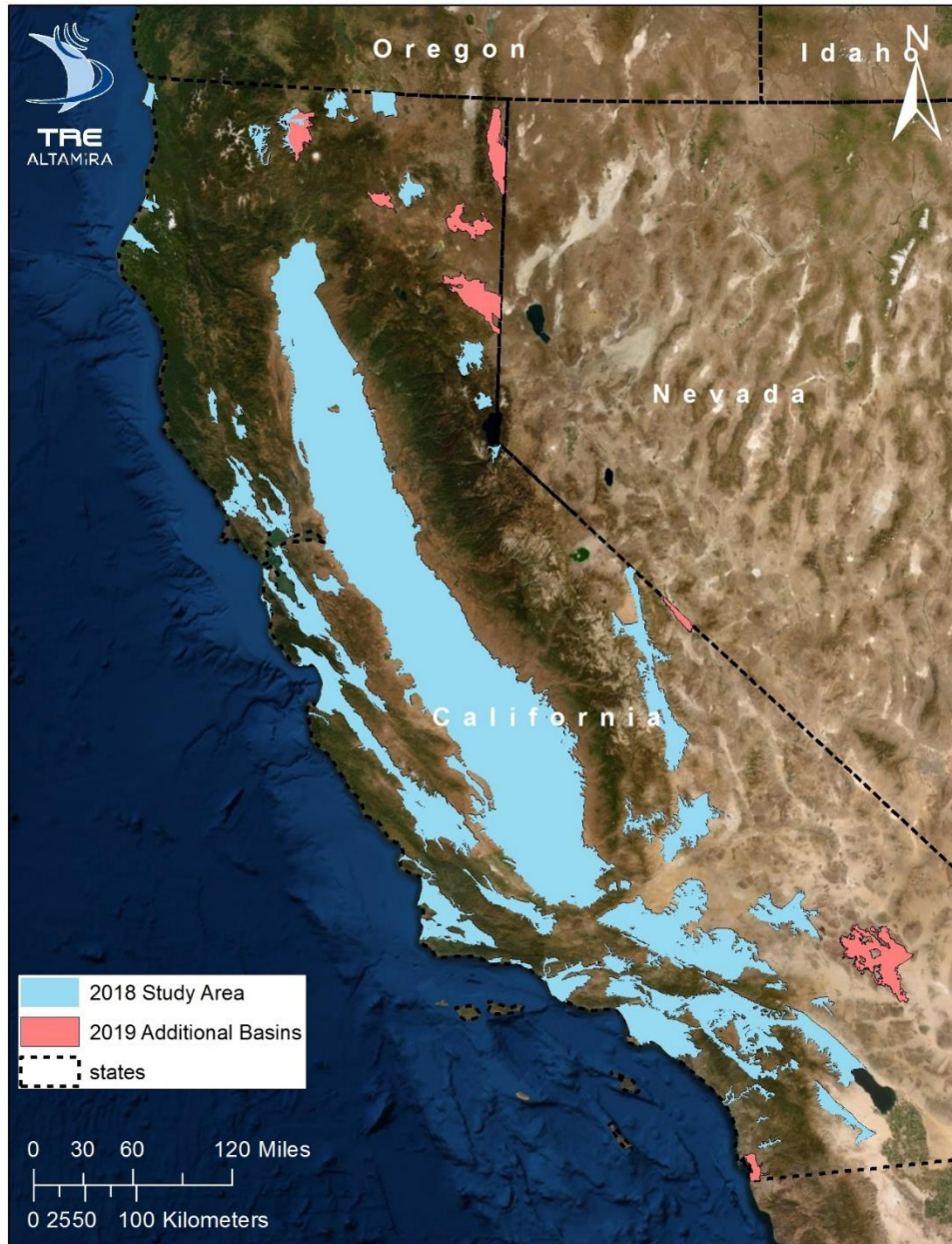


Figure 1: The 2019 study area covers the groundwater basins of the 2018 analysis (light blue) and also includes new basins (light red).

3. Task 2.1: Imagery procurement

The 2019 update included new satellite radar imagery acquired over the study area by the Sentinel-1 (SNT) mission since the end of the 2018 analysis (01 June 2018).

The SNT mission is part of the European Radar Observatory for the Copernicus joint initiative of the European Commission and the European Space Agency and comprises two satellites that share the same orbit, with each satellite acquiring data in the C-band wavelength (5.9 cm), with a 5x20 meter ground resolution. SNT has been collecting radar imagery over California since late 2014 from both ascending and descending orbits (Figure 2), initially with a 24-day revisit frequency and, since early 2017, with a nominal 12-day revisit frequency. The acquisition orbits are denominated ascending (south to north) or descending (north to south) according to the flight direction of the sensor.

The ascending and descending imagery acquired between 1 June 2018 and 30 September 2019 over the previous study area, and from 1 January 2015 and 01 June 2018 over the new basins (Figure 1) consisted of 2,235 images.

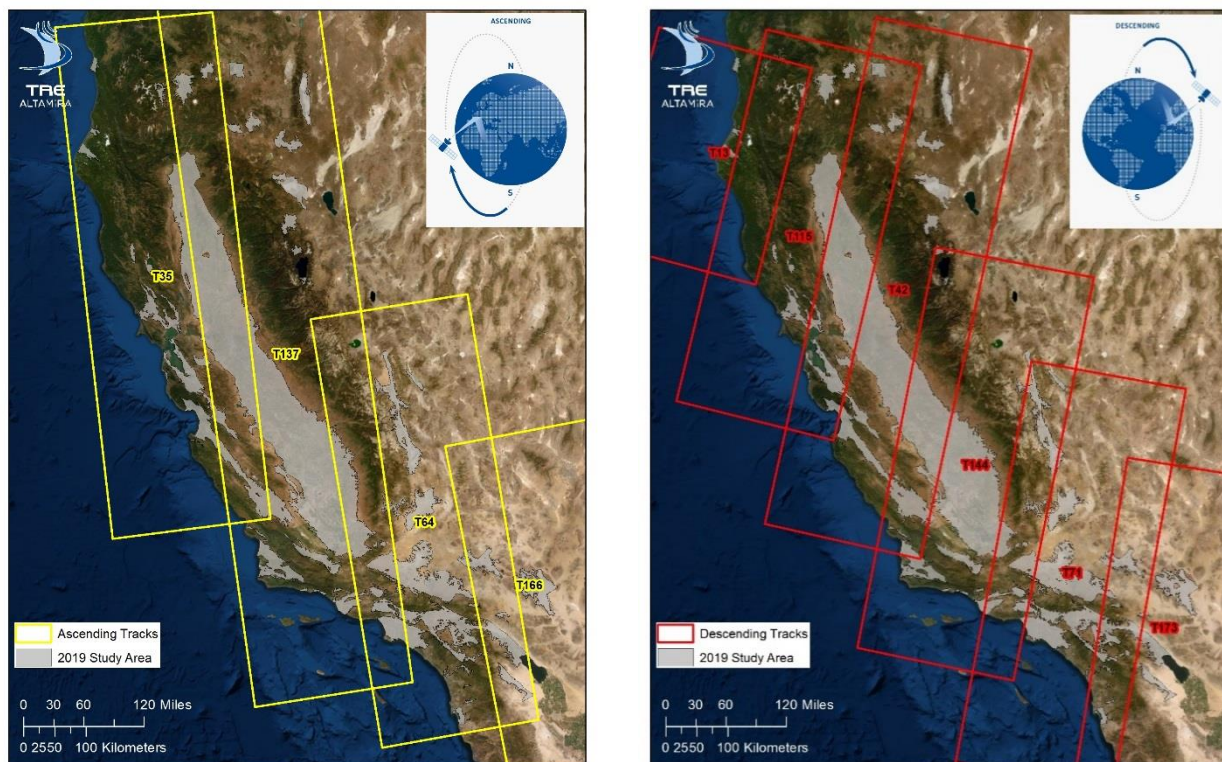


Figure 2: Ascending and Descending SNT acquisition tracks over California.

4. Task 2.2: Processing polygons definition

The downloaded imagery was analyzed to define the number of processing polygons. To maintain maximum consistency with the 2018 results, the 27 processing polygons over the 2018 areas have remained unchanged while 8 new processing polygons were defined for the new 2019 basins, based on their extent, the maximization of the temporal coverage and the optimization of GPS station coverage.

The final data processing includes 18 descending and 17 ascending polygons (Figure 2).

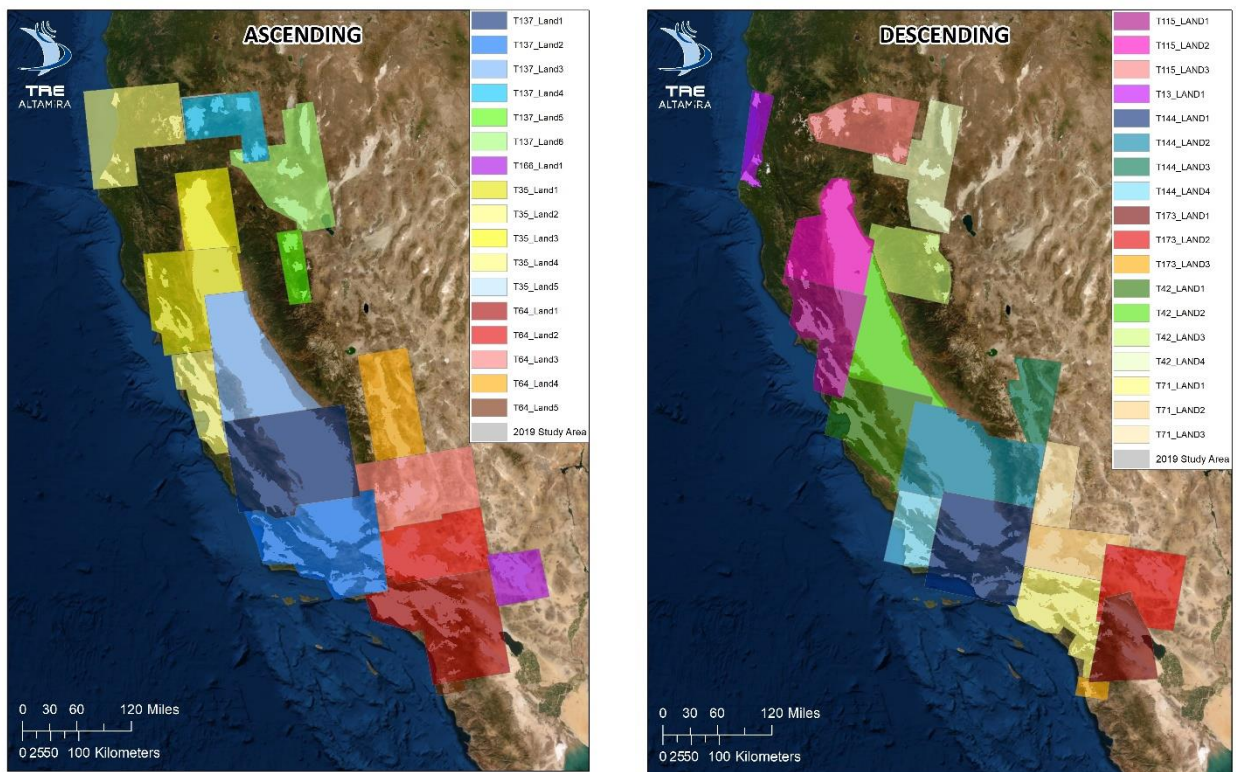


Figure 3: Ascending and Descending processing polygons.

5. Task 2.3: SqueeSAR processing

The SqueeSAR processing for the 27 previous processing polygons produced LOS measurements that cover 01 January 2018 - 30 September 2019, which includes an overlap of 15-20 images with the previous analysis (Figure 4). The overlap was applied in order to maximize the robustness of the integration with the 2018 measurements and minimize the impact of isolated noisy measurements in the time series.

The integration of the new LOS measurements with the 2018 measurements generated uninterrupted deformation time series spanning the period January 2015 – September 2019. Over the new 2019 areas, the SqueeSAR processing was carried out ex novo, using the entire image archive available from January 2015.

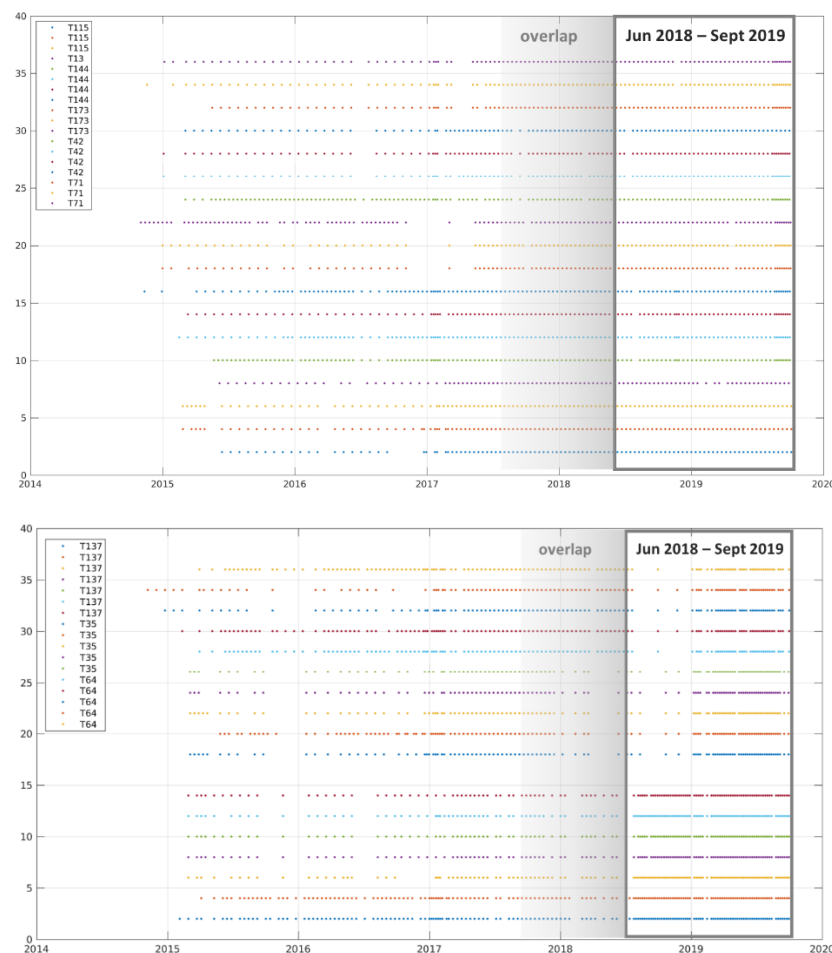


Figure 4: Temporal distribution of the imagery for all ascending and descending processing polygons. The current 2019 analysis used the imagery collected between June 2018 and September 2019 plus an overlap of approximately 15-20 images with the historical imagery.

6. Task 2.4: Data Calibration

A total of 231 GPS stations was selected from the UNAVCO network to perform the calibration of the 2019 measurements. This network included the 200 stations used in the 2018 analysis as well as 31 additional stations to cover the new 2019 areas (Figure 5). The selection criteria for the calibration stations were the same as for the 2018 project: at least 10 stations (when available) with a homogeneous spatial distribution within each processing polygon and absence of long temporal gaps in the time series.

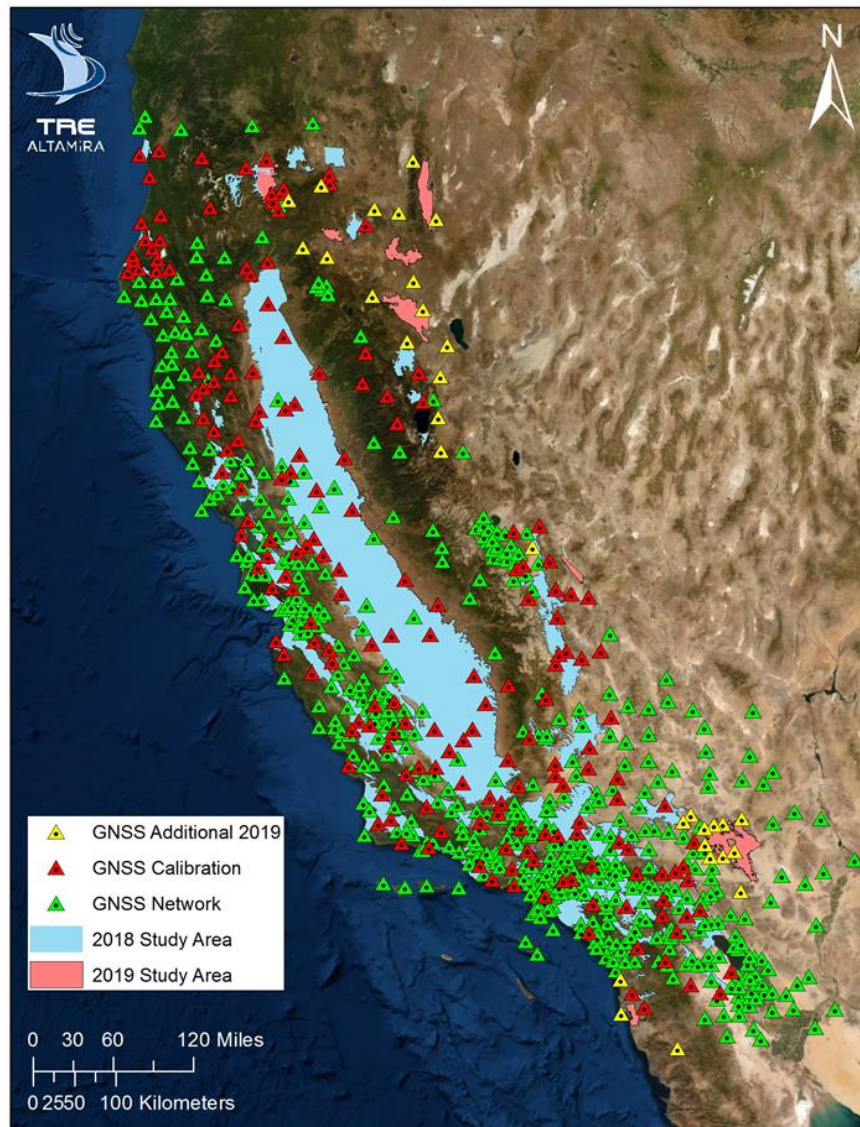


Figure 5: GNSS network over California. The same stations (red) used for the 2018 calibration will be used for the 2019 update, with the addition of 31 stations (yellow) to cover the new areas

The GPS time series have minor differences with the data used for the 2018 analysis within the overlap period (1/1/2015 to 6/30/2018), due to the use of a different file format starting from September 2018 and the removal of NULL values through linear interpolation prior to applying the 31-day moving average (Towill communication).

An analysis of the updated GPS time series by TRE confirmed slight differences with an overall improvement of the quality of the time series (Figure 6). The average differences in rate are within $\pm 2\text{mm}$ for all three motion components (N, E and Vertical) and had a minimal impact on the consistency of the calibration results with the historical data.

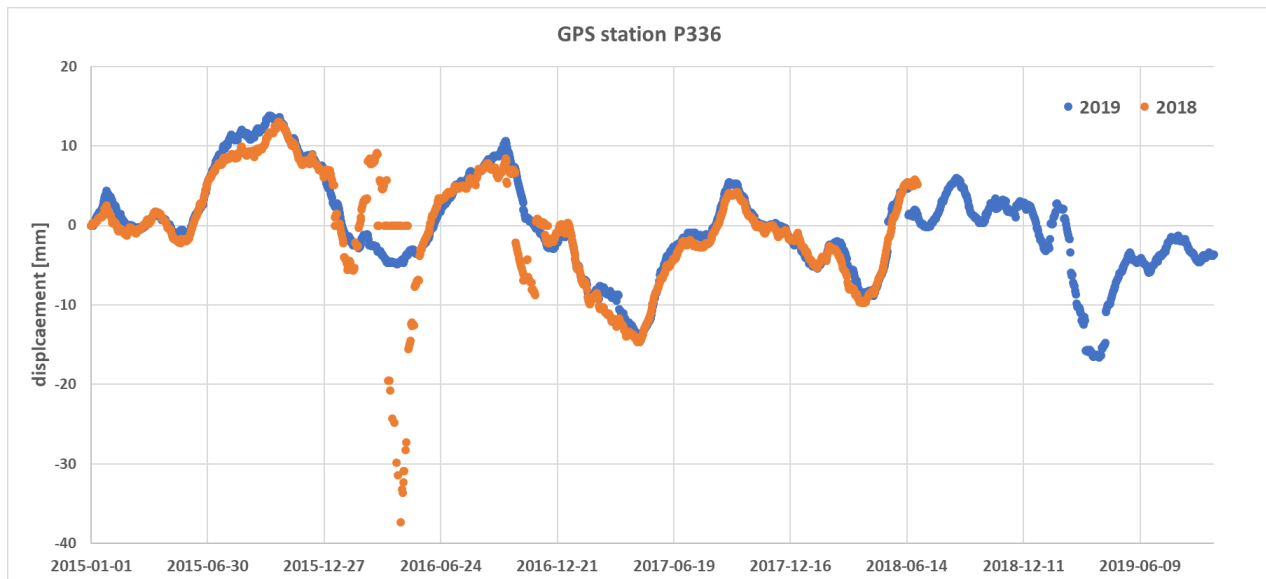


Figure 6: Comparison between the time series of the GPS P336 used for the 2018 analysis (in orange) and the 2019 analysis (in blue).

6.1. Methodology

The calibration of the LOS data was performed using the methodology defined in 2018, which is reiterated below (Figure 7):

- Time series filtering and projection to the satellite LOS:
 - The GNSS 3-D measurements provided by Towill were projected to the satellite 1-D LOS to create a GNSS LOS time series (LTS). This step allows a direct comparison of the two independent measurements (InSAR and GPS).
 - All InSAR measurement points (MP) within a 100-meter radius of each GNSS were selected and used to calculate an average time series (ATS) for the overlapping period with the GNSS

time series (one InSAR ATS for each GNSS). This step allows the comparison of data collected at a same location over a corresponding period of time.

- Plane removal: to remove possible linear errors related to potential satellite orbital inaccuracies, a difference in average velocity (linear trend) was calculated for each ATS and corresponding LTS. The average velocity differences calculated for each ATS and LTS pair were then used to estimate and remove a first order surface (plane) from all InSAR MP. The plane is statistically estimated at regional scale by minimizing the residuals of the differences between the ATS and corresponding LTS.
- Absolute calibration: to tie the two measurement techniques together and convert the relative InSAR measurements to the absolute reference system of the GNSS network, it was necessary to calibrate the local InSAR reference points to the same absolute reference. The procedure involved the generation of an average time series of residuals by comparing the ATS to the corresponding LTS for each GNSS location. All the time series of residuals obtained were then averaged to define a unique common time series of residuals (cRTS) at regional scale. This cRTS represents the movement of the local InSAR reference points with respect to the absolute GNSS reference frame. The cRTS was then removed from every InSAR MP time series.

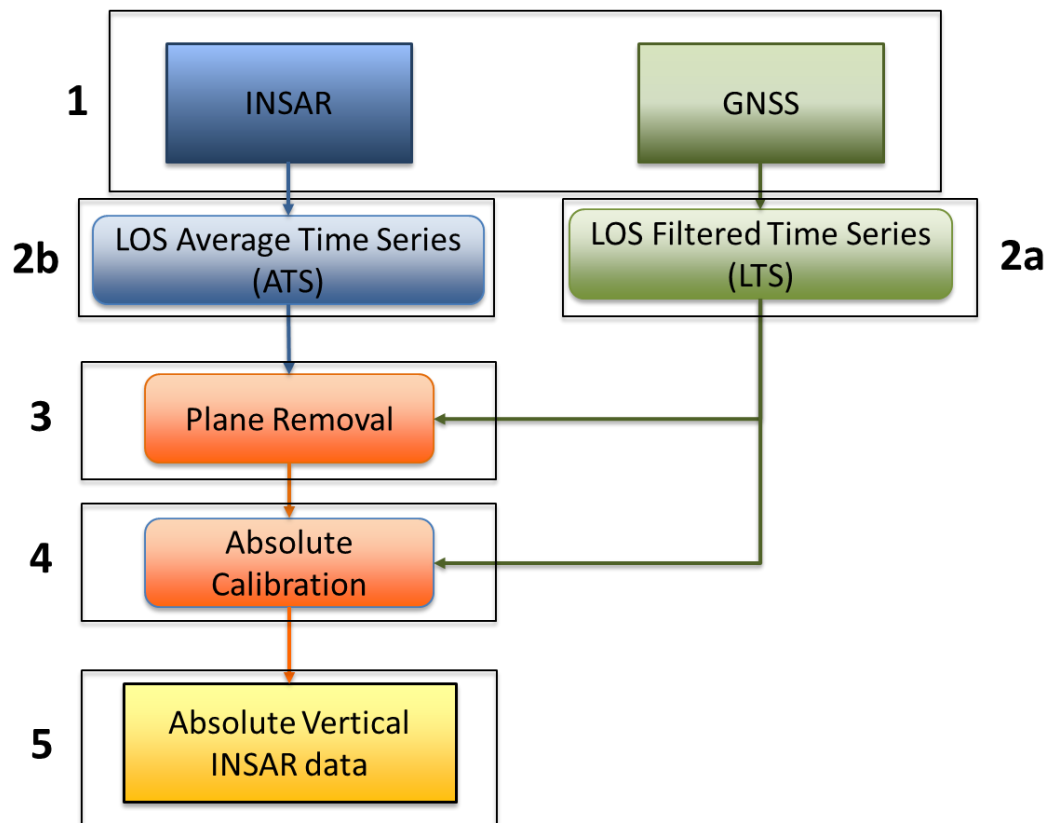


Figure 7: Diagram of the calibration methodology.

7. Task 2.5: Vertical measurements

The ascending and descending calibrated LOS InSAR time series covering the period January 2015 – September 2019, constitute the input for the absolute vertical time series estimation. The vertical measurements are produced using the same assumptions and methodology of the 2018 analysis:

- Satellites from different orbits and tracks identify different objects on the ground. For this reason, the data combination procedure requires the use of a common spatial grid to subsample the full resolution LOS results. The entire area was divided into a lattice of cells, using the same grid of the 2018 analysis (100x100 m square cells with the same code of the 2018 analysis), with the assumption that MPs belonging to the same cell are affected by the same motion.
- The average of all measurements within a same cell are referred to as synthetic measurement points (SMP). Both ascending and descending SMP are calculated for each cell. The resolution of the SMP, and thus of the resulting vertical data, as consequence of the use of the previously mentioned grid, is 100 m. SMP do not correspond to specific radar targets on the ground but instead represent synthetic points positioned at the centre of the cells.
- Since acquisition dates differ for each processing polygon, the LOS displacement time series of each SMP must be interpolated and re-sampled on a common temporal grid. The temporal grid was defined with the same criteria used for the 2018 analysis: one sample at the 1st day of each month and a frequency of approximately 7 days within the same month.
- The vertical time series of deformation for each SMP was calculated by combining all available ascending and descending LOS time series for the period in common to all LOS data (13 June 2015 – 19 September 2019). The data combination is only performed for cells that contain SMP from both ascending and descending orbits.
- Following the same procedure as in 2018, for those areas where either the ascending or descending orbit data were unavailable, the vertical time series were calculated by projecting the available LOS results to the vertical direction. Descending results were selected by default as they are generally less affected by atmospheric noise compared to the ascending data.

This methodology maintains the maximum consistency with the 2018 vertical results. Minimal differences in the point coverage were observed with respect to the 2015-2018 analysis (due to the loss of a few cells stemming from changes to the ground surface) as well as in the time series (due to the changes in the input GNSS time series), with an overall further improvement of the results.

8. Task 2.6: Draft deliverables

The draft deliverables were generated for both the common period and the variable start date results, as for the 2018 results, and made available on the TREmaps web platform and the dedicated SFTP.

Following the delivery of the draft data sets (Milestone 3), TRE received and addressed the following requests from DWR and Towill:

- Include within the final vertical measurements the points that have lost coherence in the 2018-2019 period by padding them with Null values in the database.
- Include an additional cumulative displacement raster map for the last image of the vertical dataset, 19 September 2019, even if it covers a period shorter than 1 month.

9. Task 2.7: Final Deliverables

The following are the final deliverables:

- Common start date measurements
- Cumulative deformation raster maps
- Variable start date measurements
- Annual deformation raster maps
- LOS (ascending and descending) measurements

9.1. Common start date:

- Start date: 13 June 2015
- Period covered: 13 June 2015 - 19 September 2019
- Vertical measurement point database is provided in shapefile format, subdivided into 9 shapefiles to not exceed the file size limitations of current GIS software. Database contents are reported in Figure 8.
- The temporal sampling consists of one measurement every ~7 days with a sample fixed at the first day of each month.
- The reference system is WGS84 and the measurements are in metric units (mm).

Field	Description
CODE	Synthetic Measurement Point (sMP) identification code
VEL_V	sMP average vertical displacement rate in the common period 13 June 2015 - June 2018. Positive values correspond to uplift; negative values correspond to subsidence. Values are expressed in [mm/year]
V_STDEV	Vertical displacement rate standard deviation [mm/year]
ACC	Acceleration [mm/year ²]
SEASON_AMP	Average seasonal amplitude [mm]
Dyyyymmdd	Each field contains the cumulative displacement with respect to the first acquisition. Displacement values are expressed in [mm]

Figure 8: Database contents of the common start date shapefiles.

9.2. Cumulative raster maps

- Cumulative raster maps are generated using the common start date database
- Each map covers an increasing window with monthly increments, starting from 13 June 2015, using the measurement value at the 1st of each month. As required, a final raster map covering the period 13 June 2015-19 September 2019 was added.
- Raster maps are generated using an interpolation radius of 500m, have a geotiff format, are 32-bit and have 100-meter resolution.
- The maps are in WGS84 reference system and measurement unit is U.S. Survey feet.

9.3. Variable start date:

- Variable start date for each point. The temporal coverage of each measurement point depends on the available satellite imagery in that area.
- Period covered: 01 January 2015 - 19 September 2019.
- Vertical measurement point database is provided in
 - shapefile format, subdivided into 10 shapefiles to not exceed the file size limitations of GIS software. Database contents are reported in Figure 9.
 - table format (.csv), subdivided into 10 files to not exceed file size limitations. *Null* values assigned for dates where there is no satellite data or loss of interferometric coherence (i.e. for points that are no longer radar reflectors because of the surface changes occurred with respect to the 2018 analysis). Zero value corresponds to the start date. Database contents are reported in Figure 10.
- The temporal sampling consists of one measurement every ~7 days with a sample mandated to the first day of each month.
- The reference system is WGS84 and the measurements are in metric units (mm).

Field	Description
CODE	Synthetic Measurement Point (sMP) identification code
VEL_V	sMP average vertical displacement rate in the specific period. Positive values correspond to uplift; negative values correspond to subsidence. Values are expressed in [mm/year]
V_STDEV	Vertical displacement rate standard deviation [mm/year]
ACC	Acceleration [mm/year ²]
SEASON_AMP	Average seasonal amplitude [mm]
Dyyyymmdd	Each field contains the cumulative displacement with respect to a variable start date. Zero value assigned for dates where there is no satellite data. Displacement values are expressed in [mm]

Figure 9: Database contents of the variable start date shapefiles.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	CODE	X	Y	D20150101	D20150107	D20150113	D20150120	D20150126	D20150201	D20150207	D20150212	D20150218	D20150223	D20150301	D20150307	D20150314
2	ERSSIS9	-121.97	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-1.9	-2.8	-3.7
3	ERSSIS5A	-121.969	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-3.2	-5.4	-7.6
4	ERSSIS5C	-121.966	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	1	1.6	2.1
5	ERSSIS5D	-121.965	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	2.1	4.2	6.3
6	ERSSIS5E	-121.964	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-0.1	-0.3	-0.5
7	ERSSIS5F	-121.963	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	0.3	0.7	1.1
8	ERSSIS5G	-121.962	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-0.6	-0.9	-1.2
9	ERSSIS5H	-121.961	42.00544	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	0.2	0.6	1.0
10	ERRK2JM	-121.964	42.00454	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-0.6	-1.3	-2.0
11	ERRK2JN	-121.963	42.00454	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-0.2	-0.2	-0.2
12	ERRK2JO	-121.962	42.00454	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	2.2	3.5	4.8
13	ERRK2JP	-121.961	42.00454	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	2	4.2	6.4
14	ERRK2JQ	-121.96	42.00454	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	2	3.8	5.0
15	ERQYMXV	-121.963	42.00364	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	-2	-4.2	-6.4
16	ERQYMXW	-121.962	42.00364	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	NULL	0	1.4	2.5	3.6

Figure 10: Example of the table contents.

9.4. Annual raster maps

- Annual raster maps are generated using the variable start date database
- Each raster map covers a moving one-year period, produced at monthly intervals starting from 01 Jan 2015, using the measurement value at the 1st of each month. The maps contain values for those areas where measurements exist for the full annual interval (other cells have No Data values). As requested, a final raster map covering the period 01 Oct 2018 - 19 September 2019 was added.
- Raster maps are generated using an interpolation radius of 500m, have a geotiff format, are 32-bit and have 100-meter resolution.
- The maps are in WGS84 reference system and measurement unit is U.S. Survey feet.

9.5. LOS measurements

- The full resolution LOS data consist of 40 shapefiles, 20 ascending (Figure 11) and 20 descending (Figure 12), divided into two main groups:
 - OLD AREAS: 30 shapefiles including the 2018-2019 LOS measurements obtained by the 2019 processing of the areas covered in the 2018 analysis.
 - NEW AREAS: 10 shapefiles including the 2015- 2019 LOS measurements over the new basins covered by the 2019 analysis.
- Table 3 describes the parameters included in the database of each LOS shapefile.
- The reference system is WGS84 and the measurements are in metric units (mm).

9.5.1. LOS measurements characteristics

Every measurement point (MP) identified by SqueeSAR corresponds to a radar target on the ground that displays stable reflectivity and coherent phase throughout every image of the processed imagery. The MPs belong to two different families (indicated by the parameter EFF_AREA in Table 3):

- Permanent Scatterers (PS): point-wise radar targets characterized by high stable radar signal return (e.g. buildings, rocky outcrops, linear structures, etc.), with EFF_AREA = 0 in the attribute table.
- Distributed Scatterers (DS): patches of ground exhibiting a lower but homogenous radar signal return (e.g. uncultivated land, debris, deserted areas, etc.), with EFF_AREA > 0 in the attribute table.

The density and distribution of the MPs depends on the land cover. In general, MP density increases with the presence of man-made structures and decreases with the presence of vegetation. The highest density is reached over urban areas and arid ground, while it is lower over vegetated or agricultural areas, which are affected by reflectivity changes over time.

For each MP identified, SqueeSAR provides the ground target's position and the displacement time series (Dyyyymmdd fields in Table 3), representing the evolution of the MP's displacement for each acquisition date measured along the LOS direction.

SqueeSAR displacement measurements are provided with two precision indices:

- Displacement rate standard deviation (V_STDEV in Table 3), which provides an indication of the error bar associated with the annual displacement rate measurements.
- Time series standard deviation (STD_DEF in Table 3), which provides an indication of the error bar associated with the displacement time series.

The displacement rate standard deviation characterizes the error associated with rate measurements. Given the standard deviation (σ), and assuming that the errors are normally distributed (or Gaussian), 95% of the values tend to be included in a $\pm 2\sigma$ range

The standard deviation of the deformation time series indicates how well an analytical model fits the deformation time series. The model is selected individually for each measurement point with an advanced Model Order Selection technique that also considers the quality of the image archive (number of processed images, time span covered by the archive and possible gaps in the acquisitions). The lower the standard deviation, the lower the average residual with respect to the analytical model. (i.e. the smaller the error bar of the time series).

In order to facilitate the analysis of non-linear movements, acceleration (ACC in Table 3) and seasonal amplitude (SEASON_AMP in Table 3) parameters are provided within the database of each shapefile.

The acceleration [mm/year^2] is calculated by fitting a displacement polynomial model to the time series:

$$d(t) = a + bt + ct^2$$

The seasonal amplitude [mm] is calculated by fitting a displacement polynomial model with a seasonal component to the time series:

$$d(t) = a + bt + ct^2 + A \cos\left(\frac{2\pi T}{365} + \varphi\right)$$

Where A = semi-amplitude, T = time [day] and φ = phase (seasonal amplitude maximum value with respect to the first image acquisition)

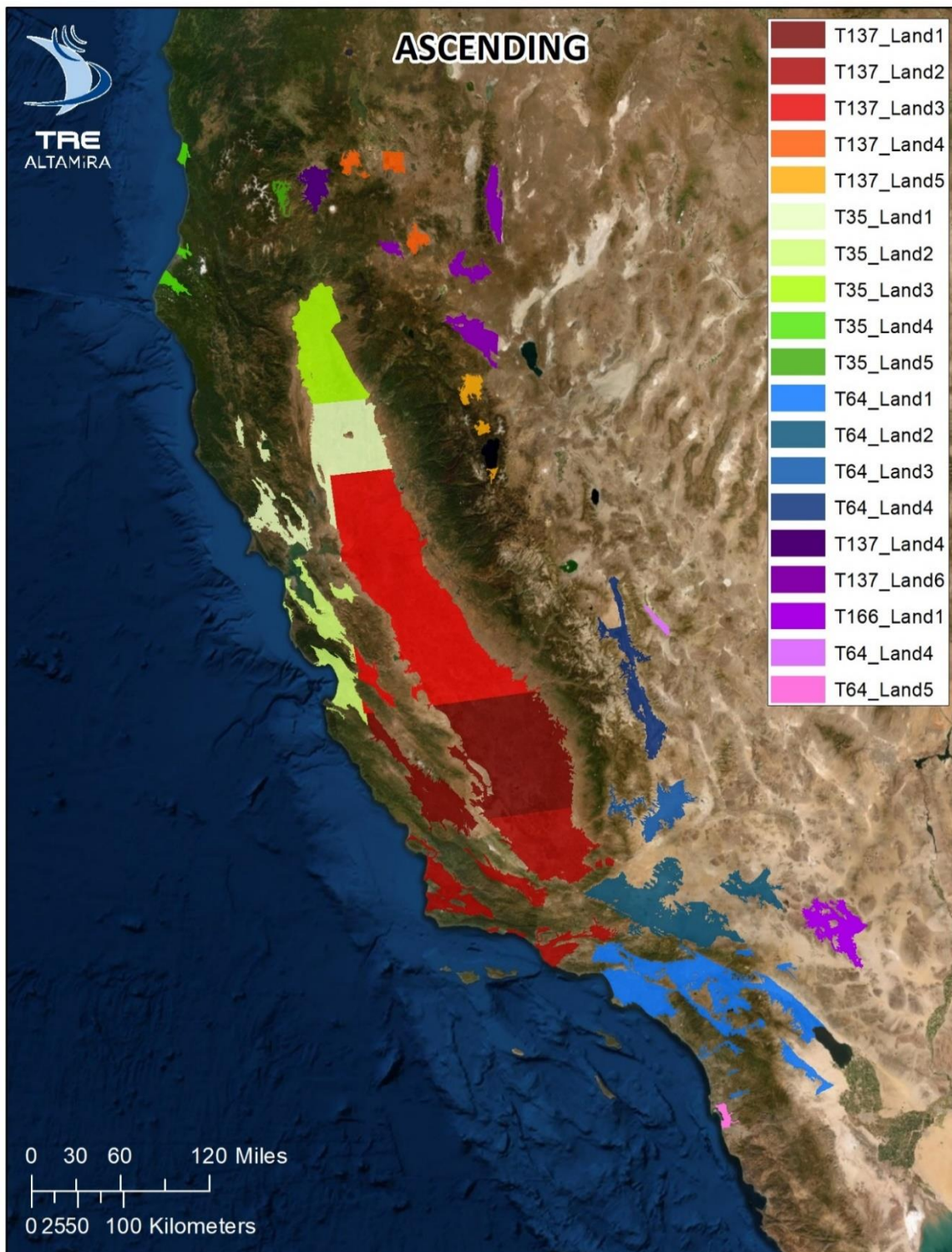


Figure 11: Coverage of the 20 LOS ascending shapefiles.

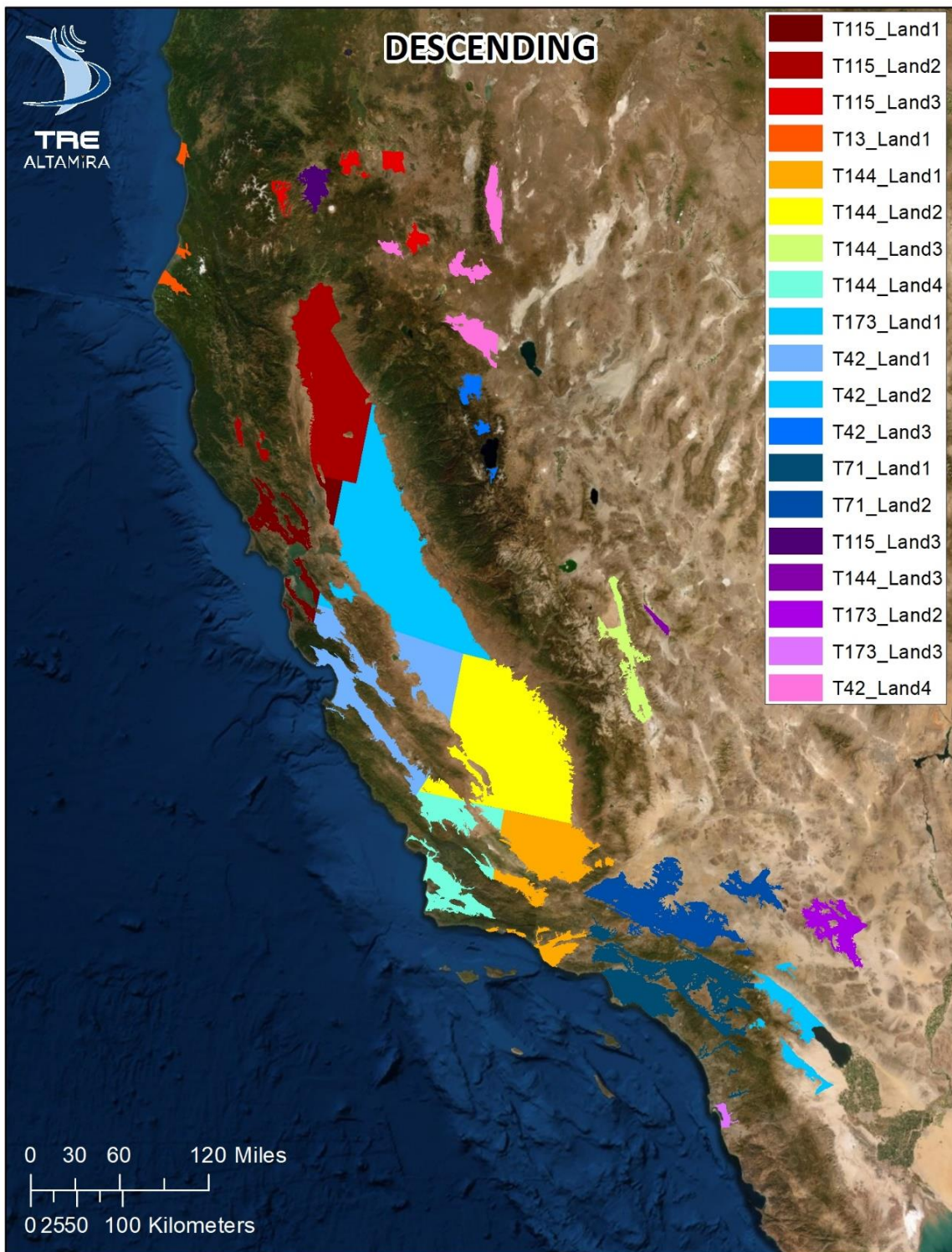


Figure 12: Coverage of the 20 LOS descending shapefiles.

Field	Description
CODE	Measurement Point (MP) identification code
HEIGHT	Topographic Elevation [m] referred to WGS84 ellipsoid
H_STDEV	Height standard deviation [m]
VEL	MP displacement rate. Positive values correspond to motion <i>toward the satellite</i> ; negative values correspond to motion <i>away from the satellite</i> [mm/year]
V_STDEV	Displacement rate standard deviation [mm/year]
ACC	Acceleration [mm/year ²]
SEASON_AMP	Average seasonal amplitude [mm]
COHERENCE	Index varying between 0 and 1, related to the MP phase noise and to the capability of the motion model adopted to cope with the actual MP behaviour
STD_DEF	Average standard deviation of the displacement time series
EFF_AREA	This parameter represents the effective extension of the area [m ²] covered by Distributed Scatterers (DS). For Permanent Scatterers (PS), its value is set to 0
Dyyyymmdd	Fields containing the displacement values of successive acquisitions relative to the first acquisition available. Displacement values are expressed in [mm]

Table 3: Description of the fields contained in the database of a LOS shapefile

9.5.2. Notes for the comparison of LOS data with other 3-D data

InSAR measurements are originally 1-D, corresponding to the projection of real movement onto the satellite Line of Sight (LOS). The schematic of ascending and descending acquisition geometries is reported in Figure 13. θ is the angle between the LOS and the vertical direction. δ is the angle between the LOS and the NS direction.

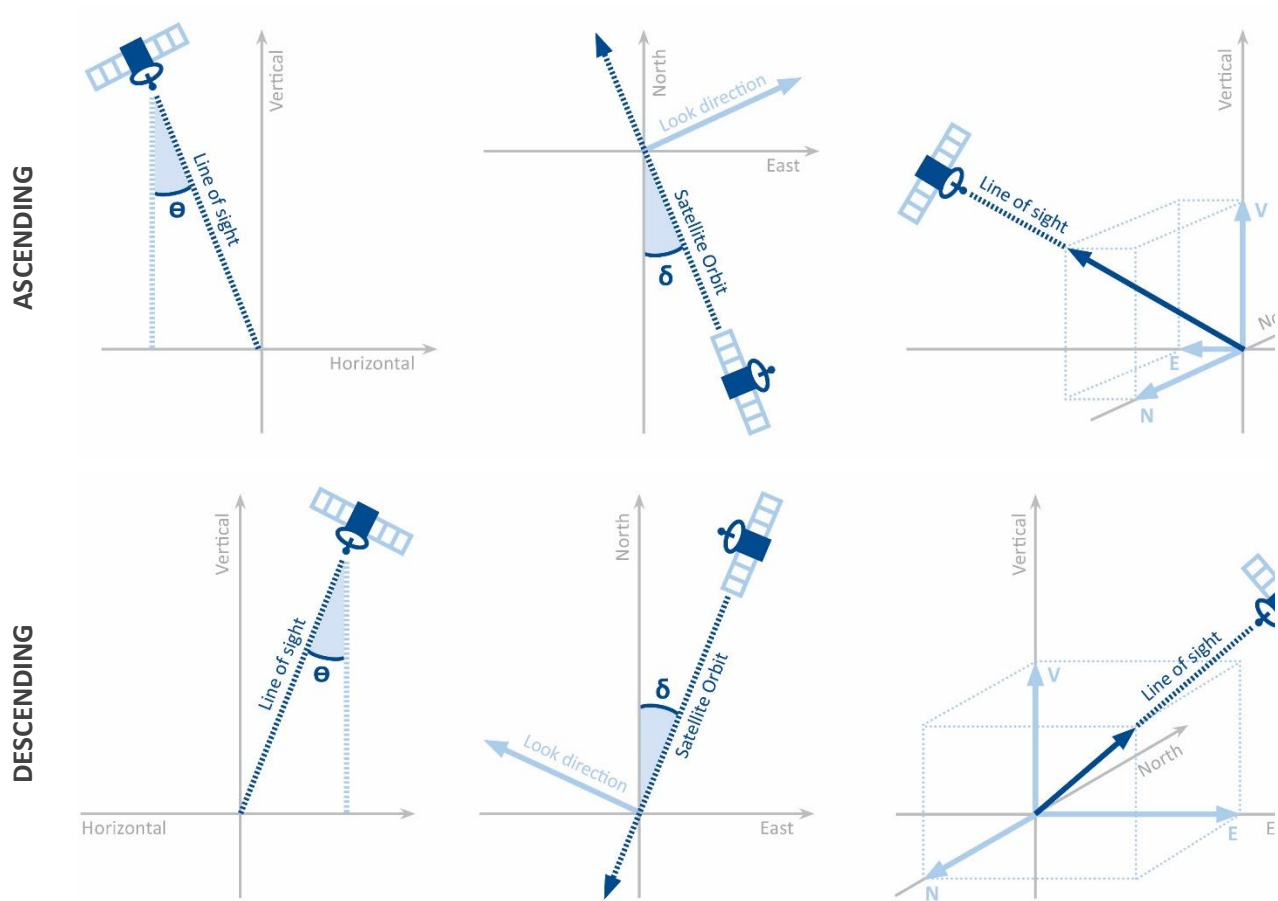


Figure 13: Schematic of the LOS orientation for ascending and descending orbits.

To compare 3-D measurements obtained by other technique such a GNSS network with InSAR LOS data, it is necessary to project the 3-D measurement to the specific LOS according to:

$$D_{LOS} = D_{VERT} * H_{LOS} + D_{EW} * E_{LOS} + D_{NS} * N_{LOS}$$

D_{VERT} , D_{EW} e D_{NS} are the measurements provided by the GNSS along the three directions. H_{LOS} , E_{LOS} e N_{LOS} are the cosine versors of the LOS along the three directions, which are specific for each LOS processing

polygon and are reported in the metadata files (xml) attached to the shapefile. D_{LOS} is the GNSS measurement projected to the LOS direction. The cosine versors of each LOS shapefiles are summarized in Table 4.

Orbit	Processing polygon	N_{LOS}	E_{LOS}	H_{LOS}	new/old
ASCENDING	CALIFORNIA_SNT_A_T35_LAND1	-0.117	-0.646	0.753	old
	CALIFORNIA_SNT_A_T35_LAND2	-0.121	-0.649	0.750	old
	CALIFORNIA_SNT_A_T35_LAND3	-0.119	-0.671	0.731	old
	CALIFORNIA_SNT_A_T35_LAND4	-0.102	-0.589	0.801	old
	CALIFORNIA_SNT_A_T35_LAND5	-0.116	-0.669	0.733	old
	CALIFORNIA_SNT_A_T64_LAND1	-0.111	-0.632	0.766	old
	CALIFORNIA_SNT_A_T64_LAND2	-0.109	-0.631	0.767	old
	CALIFORNIA_SNT_A_T64_LAND3	-0.101	-0.593	0.798	old
	CALIFORNIA_SNT_A_T64_LAND4	-0.102	-0.617	0.780	old and new
	CALIFORNIA_SNT_A_T64_LAND5	-0.113	-0.631	0.767	new
	CALIFORNIA_SNT_A_T166_LAND1	-0.118	-0.603	0.788	new
	CALIFORNIA_SNT_A_T137_LAND1	-0.129	-0.611	0.780	old
	CALIFORNIA_SNT_A_T137_LAND2	-0.096	-0.634	0.766	old
	CALIFORNIA_SNT_A_T137_LAND3	-0.125	-0.603	0.787	old
	CALIFORNIA_SNT_A_T137_LAND4	-0.114	-0.577	0.808	old and new
	CALIFORNIA_SNT_A_T137_LAND5	-0.132	-0.647	0.750	old
	CALIFORNIA_SNT_A_T137_LAND6	-0.129	-0.645	0.753	new
	CALIFORNIA_SNT_A_T166_LAND1	-0.604	-0.118	0.789	new

Table 4: Cosine versors of the LOS ascending data.

Orbit	Processing polygon	N _{LOS}	E _{LOS}	H _{LOS}	new/old
DESCENDING	CALIFORNIA_SNT_D_T13_LAND1	-0.115	0.594	0.795	old
	CALIFORNIA_SNT_D_T42_LAND1	-0.100	0.625	0.774	old
	CALIFORNIA_SNT_D_T42_LAND2	-0.095	0.615	0.782	old
	CALIFORNIA_SNT_D_T42_LAND3	-0.095	0.627	0.772	old
	CALIFORNIA_SNT_D_T42_LAND4	-0.094	0.646	0.757	new
	CALIFORNIA_SNT_D_T71_LAND1	-0.115	0.613	0.781	old
	CALIFORNIA_SNT_D_T71_LAND2	-0.115	0.622	0.773	old
	CALIFORNIA_SNT_D_T71_LAND3	-0.121	0.661	0.740	old
	CALIFORNIA_SNT_D_T115_LAND1	-0.105	0.593	0.798	old
	CALIFORNIA_SNT_D_T115_LAND2	-0.103	0.597	0.795	old
	CALIFORNIA_SNT_D_T115_LAND3	-0.101	0.602	0.792	old and new
	CALIFORNIA_SNT_D_T144_LAND1	-0.121	0.587	0.799	old
	CALIFORNIA_SNT_D_T144_LAND2	-0.127	0.624	0.770	old
	CALIFORNIA_SNT_D_T144_LAND3	-0.112	0.558	0.821	old and new
	CALIFORNIA_SNT_D_T144_LAND4	-0.096	0.670	0.735	old
	CALIFORNIA_SNT_D_T173_LAND1	-0.110	0.653	0.748	old
	CALIFORNIA_SNT_D_T173_LAND2	-0.108	0.652	0.750	new
	CALIFORNIA_SNT_D_T173_LAND3	-0.117	0.687	0.717	new

Table 5: Cosine versors of the LOS descending data

10. Data delivery

All deliverables are provided to Towill and DWR through the [TREmaps](#) web platform and a dedicated SFTP site (login credentials provided by email).

For ease of use, the deliverables are organized into four different groups: 1) Common start date; 2) Cumulative raster maps; 3) Variable start date; 4) Annual raster maps; 5) LOS data

Cumulative and annual maps are visualized on TREmaps starting from the last map of the 2018 analysis but all the raster files for the entire period 01 January 2015-01 September 2019 can be downloaded.

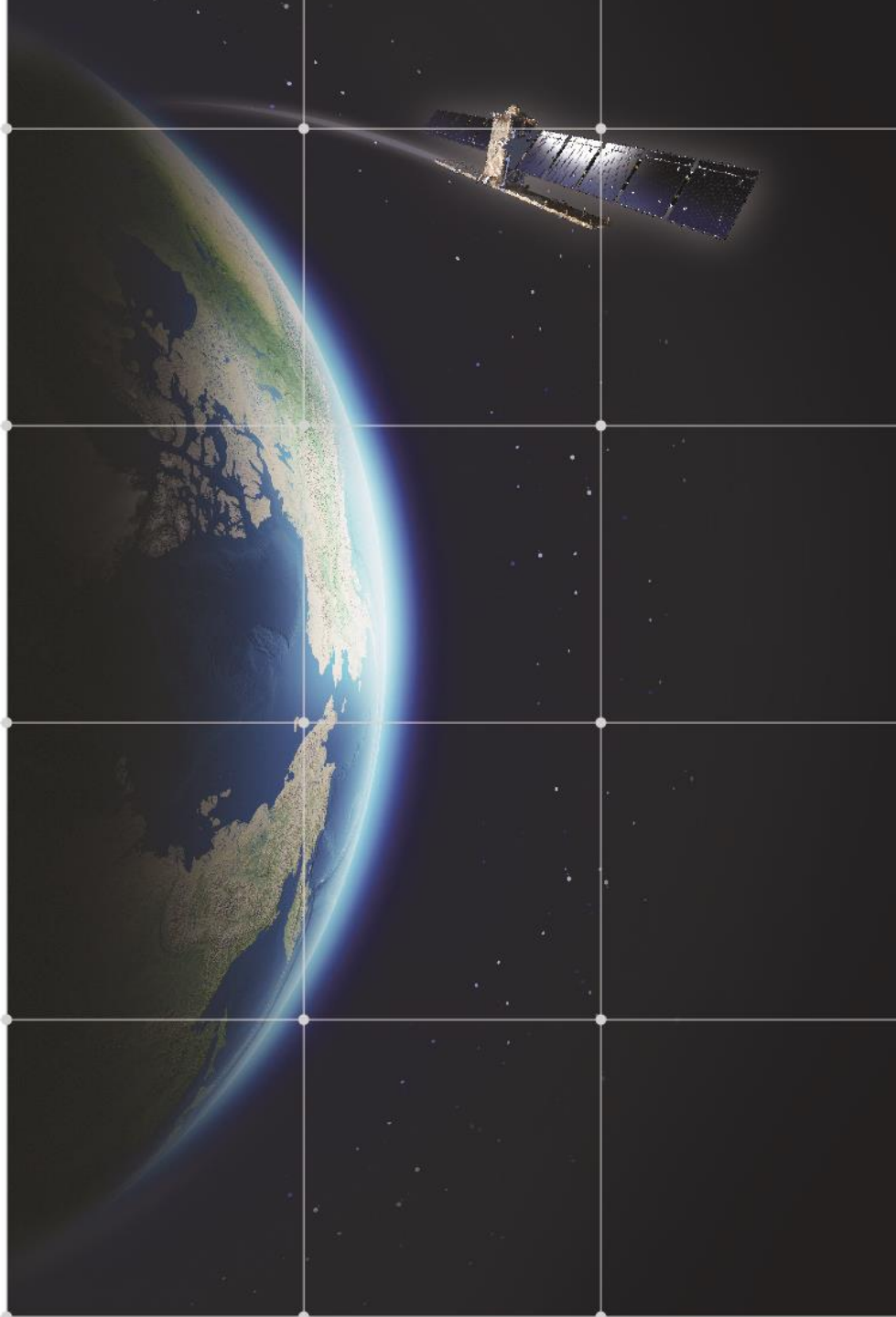
LOS results are provided only through the SFTP site because of the big size of the files.

11. Summary

Ground deformation measurements over the basins indicated by DWR were updated using the SqueeSAR data processing algorithm for the period June 2018 - September 2019. The results were integrated with the previous 2018 study results to generate uninterrupted vertical deformation time series for the period January 2015 - September 2019. New basins indicated by DWR were processed separately and then included in the final database.

The processing strategy had the aim of providing the most accurate measurements over the entire extent of the area of interest while maintaining the maximum consistency with the results obtained in 2018. This was achieved in several steps that included the minimization of possible sources of noise (e.g. atmospheric variations, satellite orbital errors) and calibrating the InSAR data to the regional GNSS network.

The calibration phase followed the regional scale methodology defined in the 2018 study, using 231 GNSS stations out of 782 available from the UNAVCO network, to remove orbital inaccuracies and to fix the local InSAR reference points to the absolute GNSS network reference system. The results will be validated by Towill in the project Task 4.



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