National Aeronautics and Space Administration

OPERA

Observational Products for End-Users from Remote Sensing Analysis

Product Description Document

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Observational Products for End-users from Remote sensing Analysis (OPERA) project

Product Description Document

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Document Change Log

Revision	Cover Date	Sections Changed	ECR #	Reason, ECR Title, LRS #*
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V1.0	4 August 2021	All sections	N/A	First version of the document, LRR058655
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V1.2	12 November 2021	Section 3.3	N/A	Incorporate SACR feedback and peer review comments related to disturbance product suite, LRR060878
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Rev D V1.7	2 October 2025	Section 3.4	N/A	Added Section 4 for Level 4 products (TROPO, CAL, and VLM). Also added the following subsections: 2.1.1. CSLC-S1-STATIC, 2.2.1 RTC-S1-STATIC, and 3.1.1 DISP-STATIC. Also push lagging changes to outdated product validation and release schedules.

** Include the JPL Limited Release System (LRS) clearance number for each revision to be shared with foreign partners.*

Table of Contents

1 INTRODUCTION

1.1 Purpose of Description

This document provides an overview of the OPERA (Observational Products for End-Users from Remote Sensing Analysis) data products to be generated by the OPERA Science Data System and provided to the NASA Distributed Active Archive Center(s) (DAAC(s)).

1.2 Scope of Description

This product description document describes the OPERA Level 2 (L2) to Level 3 (L3) products with their notional data layers and posting. This document is not a product specification document. This description document, together with Algorithm Development Team (ADT) L3 requirements, will be used by the OPERA ADT to flow down to a product specification document.

1.3 Applicable and Reference Documents

The applicable documents listed below levy requirements on areas addressed in this document. Reference documents are also cited to provide additional information to readers. In cases of conflict between the applicable documents and this document, the OPERA Project shall review the conflict to find the most effective resolution.

Applicable Documents (ADs):

AD1: SNWG Program-Level Requirements document (Version August 2, 2020)

AD2: OPERA Project requirements document (JPL D-107391)

Reference Documents (RDs):

RD1: NASA EOSDIS Terminology Specification, 423-SPEC-002, Revision A. [link]

RD2: OPERA DIST Product Algorithm Theoretical Basis Document (JPL D-108273)

Bekaert, David, et al. “RAiDER Tropospheric Correction.” Github. [link]

Carroll, Mark, John Townshend, Matthew Hansen, et al. “MODIS Vegetative Cover Conversion and Vegetation Continuous Fields” in *Land Remote Sensing and Global Environmental Change. Remote Sensing and Digital Image Processing* 11 (2010): 725-745. [link]

Claverie, Martin, Junchang Ju, Jeffrey G. Masek, et al. “The Harmonized Landsat and Sentinel-2 surface reflectance data set.” *Remote Sensing of Environment* 219 (2018): 145-161. [link]

Chen, Curtis W., and Howard A. Zebker. “Phase unwrapping for large SAR interferograms: Statistical segmentation and generalized network models.” *IEEE Transactions on Geoscience and Remote Sensing* 40.8 (2002): 1709–1719. [link]

Fattahi, Heresh, Mark Simons, and Piyush Agram. “InSAR time-series estimation of the ionospheric phase delay: An extension of the split range-spectrum technique.” *IEEE Transactions on Geoscience and Remote Sensing* 55.10 (2017): 5984–5996. [link]

Eriksen, Christine. “Why do they burn the ‘bush’? Fire, rural livelihoods, and conservation in Zambia.” *Geographical Journal*, 173.3 (2007): 242-256. [link]

Hansen, Matthew C., et al. “Global percent tree cover at a spatial resolution of 500 meters: First results of the MODIS vegetation continuous fields algorithm.” *Earth Interactions*, 7. 10 (2003):1-15. [link]

Hansen, Matthew C., Peter V. Potapov, Rebecca Moore, Matt Hancher, Svetlana A. Turubanova, Alexandra Tyukavina, David Thau, et al. “High-resolution global maps of 21st-century forest cover change.” *Science* 342. 6160 (2013): 850–853. [link]

Jones, John W. “Improved automated detection of subpixel-scale inundation—Revised dynamic surface water extent (DSWE) partial surface water tests.” *Remote Sensing* 11.4 (2019): 374. [link]

Li, Jian, and David P. Roy . “A Global Analysis of Sentinel-2A, Sentinel-2B and Landsat-8 Data Revisit Intervals and Implications for Terrestrial Monitoring.” *Remote Sensing* 9 (2017) 902. [link]

Liang, Cunren, Piyush Agram, Mark Simons, and Eric J. Fielding, "Ionospheric Correction of InSAR Time Series Analysis of C-band Sentinel-1 TOPS Data," *IEEE Transactions on Geoscience and Remote Sensing* 57.9 (2019): 6755-6773. [link]

NISAR “NASA-ISRO SAR (NISAR) Mission Science Users’ Handbook.” NASA Jet Propulsion Laboratory (2018): 261. [link]

Nobre, Antonio Donato, et al. “Height Above the Nearest Drainage–a hydrologically relevant new terrain model.” *Journal of Hydrology* 404.1–2 (2011): 13–29. [link]

Pekel, Jean-François, Andrew Cottam, Noel Gorelick, and Alan S. Belward. “High-resolution mapping of global surface water and its long-term changes”. *Nature* 540 (2016): 418–422. [link]

Potapov, Peter, Matthew C. Hansen, et al. “Landsat Analysis Ready Data for Global Land Cover and Land Cover Change Mapping.” *Remote Sensing* 12.3 (2020). [link]

Rosen, Paul A., Scott Hensley, and Curtis Chen. “Measurement and mitigation of the ionosphere in L-band interferometric SAR data.” 2010 IEEE Radar Conference. IEEE, (2010): 1459–1463. [link]

Shiroma, Gustavo HX, Marco Lavalle, and Sean M. Buckley. “An Area-Based Projection Algorithm for SAR Radiometric Terrain Correction and Geocoding.” *IEEE Transactions on Geoscience and Remote Sensing* 60 (2022): 1–23. [link]

Small, David. “Flattening gamma: Radiometric terrain correction for SAR imagery.” *IEEE Transactions on Geoscience and Remote Sensing* 49.8 (2011): 3081–3093. [link]

Ying, Qing, Matthew C. Hansen, Peter V. Potapov, et al. “Global bare ground gain from 2000 to 2012 using Landsat imagery.” *Remote Sensing of Environment* 194 (2017): 161-176. [link]

Zhan, Xiwu, Ruth DeFries, Matthew Hansen, John Townshend,Charlene DiMiceli, Robert Sohlberg, Chengqian Huang, MODIS Enhanced Land Cover and Land Cover Change Product Algorithm Theoretical Basis Documents (ATBD), Version 2.0, (1999). [link]

The OPERA Level 1 (L1) requirements are translated into L2 requirements on the various subsystems, including those specifically related to the processing system producing the L2–L3 products. These L2 requirements fall into four general categories: (a) resolution requirements, (b) radiometric and spatial location accuracy requirements, (c) product accuracy requirements, and (d) latency and throughput requirements.

The Committee on Earth Observation Satellites (CEOS) Analysis Ready Data for Land (CARD4L) framework aims to define a community-agreed minimum set of requirements, organized into a form that allows immediate analysis with a minimum of additional user effort and interoperability both through time and with other datasets. CARD4L is the first group to publish formal product specifications for ARD data from synthetic aperture radar (SAR), and the OPERA team has representation on multiple CARD4L advisory groups. While the product specifications by CARD4L are not meant to be exclusive or prescriptive, the OPERA team aims to align with CARD4L guidance where possible.

The NASA Earth Observing System Data and Information System (EOSDIS) nomenclature for classifying mission science products into various processing levels is provided for reference in Table 1.1 [RD1].

Table 1.1: NASA EOSDIS Scientific Data Processing Level Definitions.

Data Level	*Processing Level*
Level 0 (L0)	*Level 0 data products are reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g., synchronization frames, communications headers, duplicate data removed.*
Level 1A (L1A)	*Level 1A data products are reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters, e.g., platform ephemeris, computed and appended but not applied to the Level 0 data.*
Level 1B (L1B)	*Level 1A data that have been processed to sensor units (not all instruments will have a Level 1B equivalent).*
Level 2 (L2)	*Level 2 data products are derived geophysical variables at the same resolution and location as the Level 1 source data.*
Level 3 (L3)	*Level 3 data products are variables mapped on uniform space-time grid scales, usually with some completeness and consistency.*
Level 4 (L4)	*Level 4 data products are model output or results from analyses of lower level data, e.g., variables derived from multiple measurements.*

1.4 Products Overview

The Jet Propulsion Laboratory (JPL) OPERA Project is developing three L3 products that respond to the needs identified by various federal agencies during the 2018 cycle (aka cycle-2) of the Satellite Needs Working Group (SNWG) development activities:

1. A near-global Dynamic Surface Water Extent (DSWx) product suite
2. A near-global Surface Disturbance (DIST) product suite
3. A North America Surface Displacement (DISP) product suite

In addition, OPERA will produce two intermediate L2 data products:

4. A North-America Coregistered Single-look Complex (CSLC) product
5. A near-global Radiometric Terrain-Corrected (RTC) SAR Backscatter product

An overview of the OPERA products and their input datasets are provided in Figure 1.1. The OPERA Project is following a staggered release schedule as shown in Table 1.2. Table 1.3 provides a summary of key product characteristics, including the spatial coverage and resolution of the products, the start of the product record, and the temporal sampling of the sensors used as input for the products.

This document describes the primary data and metadata layers in each L2–L3 product generated by the OPERA Science Data System (SDS). This includes a description of a) the raster layers with resolutions and geographic information; b) metadata layers, including input data information and auxiliary data for further processing; and c) secondary rasters (when applicable) that are shared across imagery in an image stack. Furthermore, each product is labeled using the convention <name>-<sensor>, where <name> and <sensor> are acronyms for the product and the sensor, respectively. For example, the NISAR displacement product is labeled “DISP-NI.” The sensors and input datasets are abbreviated to S1

(Sentinel-1A/B), HLS (Harmonized Landsat 8 and Sentinel-2A/B), SW (SWOT), and NI (NISAR). See the Acronyms section for definitions. Figure 1.1 shows the breakout of the different products in level and sensor.

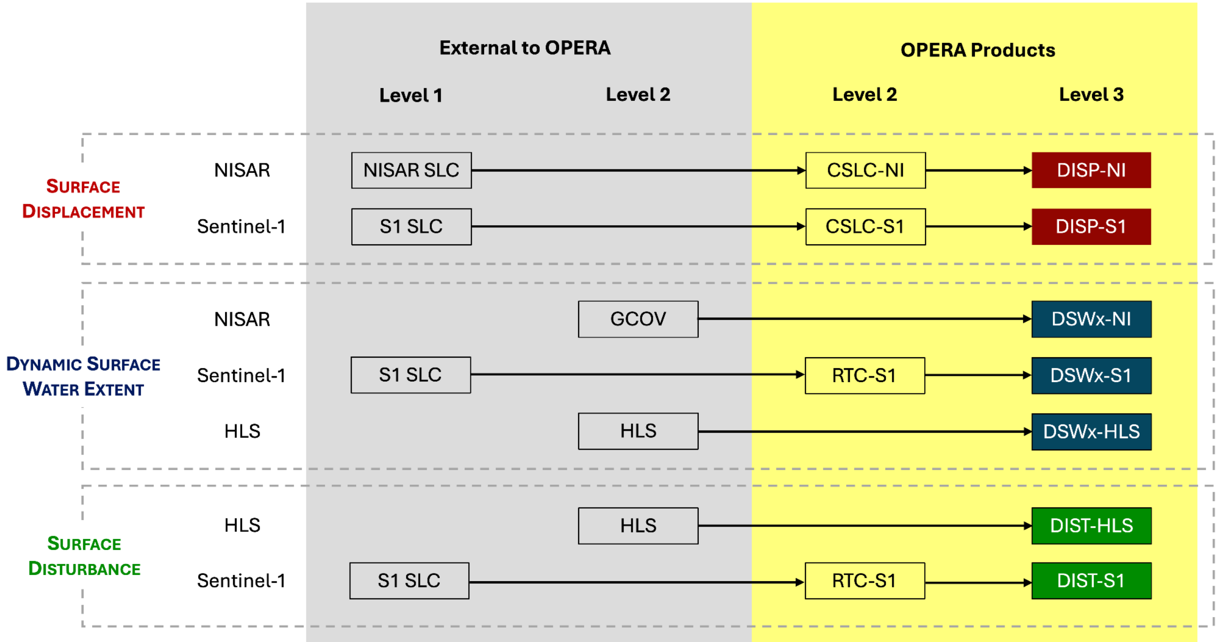


Figure 1.1: OPERA products' dependence and external input datasets to OPERA products that are accessed through the NASA DAACs. Note that the reference to "Sentinel-1A/B" to the DSWx and DIST suites should refer to Sentinel-1A and Sentinel-1A/C respectively after the demise of Sentinel-1B in Aug 2022.

Table 1.2: Overview of the OPERA product release schedule to the public.

Release	Products	Product Release
1	*DSWx-HLS** *DIST-HLS**	*Mid of April 2023 (provisional)* *March 2024 (validated)* *End of February 2023 (provisional)* *March 2024 (validated)*
2	*RTC-S1* *RTC-S1-STATIC* *CSLC-S1* *CSLC-S1-STATIC*	*October 2023* *October 2023* *October 2023* *October 2023*
3	*DSWx-S1* *DISP-S1* *DISP-S1-STATIC* *TROPO*	*September 2024* *May 2025* *May 2025* *September 2025*
4	*DSWx-NI*	*October 2026*
5	*CSLC-NI* *DISP-NI* *DISP-NI-STATIC*	*TBD 2026* *February 2027* *February 2027*
6	*DIST-S1*	*March 2026*

7	*CAL-S1* *CAL-NI*	*February 2028* *February 2028*
8	*VLM-S1* *VLM-NI*	*February 2029* *February 2029*

*Optical includes both Landsat-8 and Sentinel-2A/B sensors for the DSWx-HLS product, and Landsat-8/9 and Sentinel-2A/B sensors for the DIST-HLS product. The optical sensors deliver one product because they use the same HLS as inputs. *All releases are validated products unless otherwise specified.*

1.5 Organization of this Document

This document is organized according to NASA Earth Data product levels (Level 0, 1, 2, 3). The OPERA Project uses validated L1 data products from existing missions (NISAR, Sentinel-1) and projects (HLS) for generation of higher-level products (see Figure 1.1); hence, it does not generate any L0 or L1 products. At higher levels, L2 products are geocoded products measuring a specific geophysical sensor variable, and L3 products are geocoded and uniformly gridded.

Table 1.3: Summary of OPERA product characteristics.

Product Name	Coverage	Sensor	Acronym	Spatial Resolution	Sensor[1] Temporal Sampling***	Beginning of Product Record****
Coregistered Single Look Complex (CSLC)	*North America**	*Sentinel-1A/B/C*	*CSLC-S1*	~15 m × 5 m (azimuth x range)	12 days (single sensor + same geometry) † 6 days (constellation + same geometry) †	May 2016 onwards
		NISAR	*CSLC-NI*	~5 m × 3.1/6.25 m (azimuth x range)	12 days (same geometry) †	Start of NISAR validated record
Radiometric Terrain-Corrected (RTC)	*Near-Global***	*Sentinel-1A/B/C*	*RTC-S1*	30 m	12 days (single sensor + same geometry) † 6 days (constellation + same geometry) †	January 2022 onwards
Displacement Product (DISP)	*North America**	*Sentinel-1A/B/C*	*DISP-S1*	30 m or ~15 m × 5 m (azimuth x range)	12 days (single sensor + same geometry) † 6 days (constellation + same geometry) †	May 2016 onwards
		NISAR	*DISP-NI*	30 m or ~5 m × 3.1/6.25 m (azimuth x range)	12 days (same geometry) †	Start of NISAR validated record
Vertical Land Motion (VLM)	*North America**	*Sentinel-1A/B/C*	*VLM-S1*	120 m	15 or 30 days (TBD)	January 2019 onwards
		NISAR	*VLM-NI*	120 m	15 or 30 days (TBD)	Start of NISAR validated record
Disturbance Product (DIST)	*Near-Global***	*Landsat 8 & Sentinel-2A/B/C (HLS)*	*DIST-ALERT-HLS* *DIST-ANN-HLS*	30 m 30 m	16 days for Landsat 8 (same geometry) 10 days for Sentinel-2 (same geometry) ~5 days for Sentinel-2 (constellation + same geometry) median average 2.9 days for S2A/B+L8 [Li and Roy, 2017]	January 2023 onwards
		Sentinel-1A/B/C	*DIST-ALERT-S1*	30 m	12 days (single sensor + same geometry) † 6 days (constellation + same geometry) †	March 2026 onwards
Dynamic Surface Water Extent (DSWx)	*Near-Global***	*Landsat 8 & Sentinel-2A/B/C (HLS)*	*DSWx-HLS*	30 m	16 days for Landsat 8 (same geometry) † 10 days for Sentinel-2 (single sensor + same geometry) † ~5 days for Sentinel-2 (constellation + same geometry) † median average 2.9 days for S2A/B+L8 [Li and Roy, 2017]	April 2023 onwards
		Sentinel-1A/B/C	*DSWx-S1*	30 m	12 days (single sensor + same geometry) † 6 days (constellation + same geometry) †	September 2024 onwards
		NISAR	*DSWx-NI*	30 m	12 days (same geometry) †	Start of NISAR validated record

[1]Temporal sampling of a pixel on the ground for a given product requires sensor ground simulations (TBD); hence, sensor sampling is provided.

*USA and U.S. Territories, Canada within 200 km of the U.S. border, and all mainland countries from the southern U.S. border to and including Panama. **All landmasses, excluding Antarctica. ***Subject to sensor availability. ****This indicates the beginning of the product record, not the beginning of OPERA processing. † Descending or Ascending.

2. Level 2 Products

2.1 Co-registered Single Look Complex (CSLC) Product

The CSLC product is derived from the range-Doppler radar-coordinate Single Look Complex (SLC) product using the Copernicus GLO-30 Digital Elevation Model (DEM) and orbit information of the relevant sensor, either Sentinel-1A/B or NISAR (Figure 2.1). The Sentinel-1 and NISAR CSLC products are independent products with separate co-registration processes and posting. For each sensor, the CSLC product is resampled to a fixed spatial reference grid and flattened, i.e., topographic phase contributions are removed. The CSLC contains individual raster layers representing complex signal return for each of the input dataset polarizations. The product metadata includes metadata from the input SLC product that allows for subsequent Interferometric Synthetic Aperture Radar (InSAR) processing, metadata related to the SLC co-registration processing algorithm used to generate the product, and metadata capturing the product geolocation grid. The CSLC is a geocoded product. Since the CSLC products are provided as georeferenced products, native SLC resolution is preserved by generating the CSLC product with posting in east and north directions that are comparable to the full-resolution of the original input SLC (i.e., posting of CSLC-NI and CSLC-S1 will not be the same). The products are stored in a cloud-compatible format that allows for subsetting. CSLCs from the same sensor can be combined to derive higher-level products such as displacement maps and surface-change maps. The spatial coverage of the CSLC products is over North America (USA and U.S. Territories, Canada within 200 km of the U.S. border, and all mainland countries from the southern U.S. border to and including Panama).

For Sentinel-1A/B, the CSLC product is burst-based, whereas for CSLC-NI, the product is frame-based using the frame definition established by NISAR.

Tables 2.1 and 2.2 outline key product information as described in the high-level product description above. Note that these tables are *not* meant to be a product specification; see Section 1.2 for details on the scope of this Product Description Document.

Table 2.1: Product raster layers for CSLC.

CSLC Raster Layer	**Posting**	**Description**
Complex backscatter	Full resolution	SLC images for all polarizations resampled to a common grid. All channels are registered.
Secondary Layers Common to CSLC Stack	**Posting or Dimension**	**Description**
Slant range	TBD km scale, with the ability for users to recover it at approximately CSLC posting.	Geometry data layers
Incidence angle		
Line-of-Sight (LOS) vectors		

Table 2.2: Product metadata for CSLC.

CSLC Metadata Layer	Description
Input metadata	Input SLC file names and metadata that allows for subsequent InSAR processing (TBD)
Polarization	Baseline includes VV (vertical transmit and vertical receive) polarization for S1 and HH (horizontal transmit and horizontal receive) polarization for NISAR. TBD on funding/scope if this can be expanded to all polarizations from the input SLC product.
Processed range bandwidth	Signal range bandwidth
TBD: Azimuth Time and slant range information (if in radar coordinates) or geolocation grid information (if in geocoordinates)	The information for georeferencing. If geogrid information (coordinate system, pixel convention, spacing, map projection), Geographic Bounding Box
TBD: if in radar coordinates: look-up on geo-coordinates	
Sensor information	Left/right-looking, sensor name, wavelength, radar frequency
Processing information	Relevant processing parameters of the coregistration approach. References the Algorithm Theoretical Basis Document (ATBD) to allow users to trace and reproduce the process used for the specific product
Auxiliary information	DEM names, orbit files, aux files

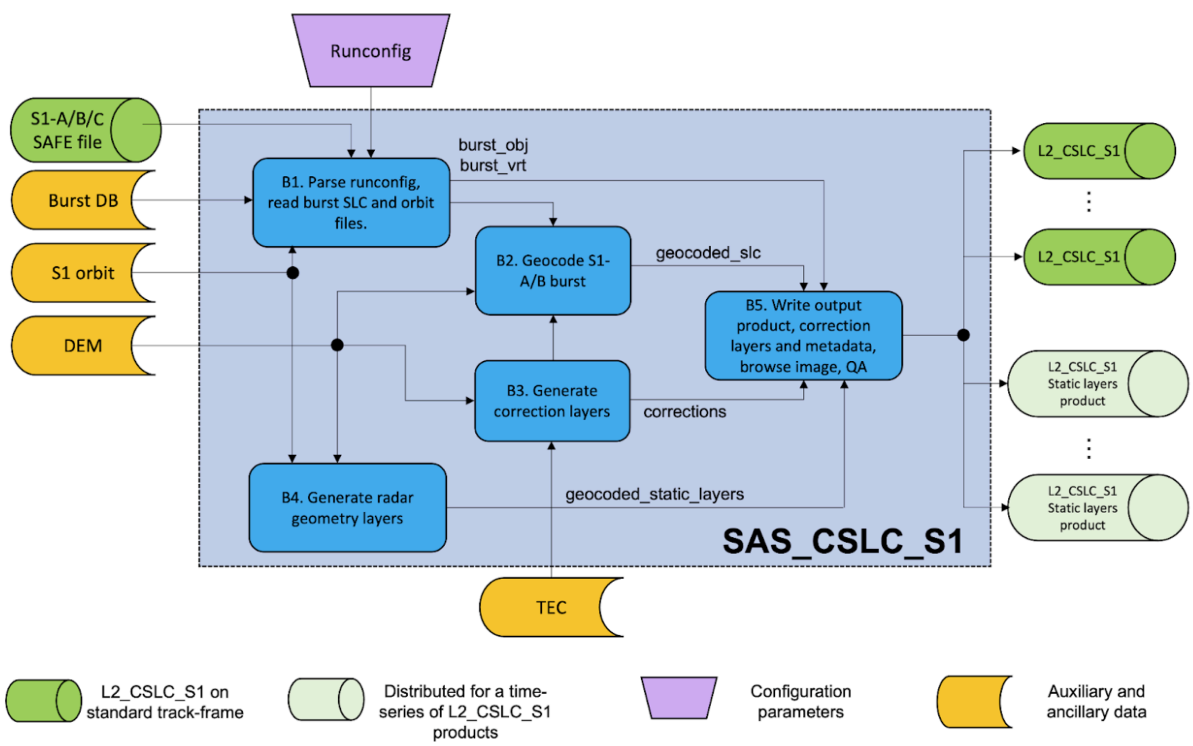


Figure 2.1: OPERA L2 CSLC-S1 and CSLC-S1-STATIC product workflow details.

2.1.1 Co-registered Single Look Complex from Sentinel-1 Static Layers (CSLC-S1-STATIC) Product

The OPERA Level-2 Coregistered Single Look Complex Static Layers from Sentinel-1 (CSLC-S1-STATIC) product provides the geometry and ancillary metadata layers for OPERA CSLC-S1 products. It is distributed separately from the CSLC-S1 products and generated only once or a limited number of times if there are changes in the input parameters or processing algorithms. CSLC-S1-STATIC products are generated for all Sentinel-1 bursts sharing the same burst identification string—that is, for all bursts covering the same spatial footprint.

Each CSLC-S1-STATIC product contains geocoded geometry layers and supporting metadata stored in a Hierarchical Data Format version 5 (HDF5) file compliant with Climate and Forecast (CF) Metadata Conventions CF-1.8 (CF-1.8). The primary raster layers include: (1) east and north components of the radar line-of-sight (LOS) unit vector, (2) local incidence angle, and (3) layover/shadow mask identifying areas affected by radar layover, shadow, or both. These parameters remain constant for a given burst and serve as important reference information for downstream interferometric and displacement analyses.

Products are generated within the same workflow as CSLC-S1 (Figure 2.1). Each granule corresponds to a single Sentinel-1 burst footprint and remains valid for the lifetime of the associated geometry unless the DEM, orbit ephemerides, or processing algorithm are updated.

The CSLC-S1-STATIC file structure includes groups for product identification, processing metadata, data layers, and quality assurance metrics. Metadata describe the burst ID, track, orbit direction, radar band, processing center, and software versions (e.g., COMPASS, ISCE3). Quality metrics summarize pixel classifications and statistical descriptors for each geometry layer.

Products are archived and distributed through the NASA Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC).

2.2 Radiometric Terrain-Corrected (RTC) Product

The RTC product is derived from the original Copernicus Sentinel-1A/B SLC data (Figure 1.1), provided by the European Space Agency, with a temporal product sampling coincident with the availability of Sentinel-1 A/B SLC data. The RTC product is not derived from the OPERA CSLC product as it has a different geographical scope (North America) compared to the RTC product (near-global) (see Table 1.3).

The workflow for generating the RTC product from Sentinel-1A/B consists of three steps (Figure 2.2). Sentinel-1A/B SLCs are first converted to radar brightness β_0 (beta naught) by applying absolute radiometric correction. The radar brightness has a strong dependency with the local topography. The radiometric terrain flattening or radiometric terrain correction (RTC) is then applied to each of the polarization channels at full resolution (single-look) to obtain the corresponding γ^0 (gamma naught) backscatter coefficient that has significantly less dependency with respect to the terrain (e.g., Small, 2011; Shiroma et al., 2022). Finally, the γ^0 backscatter is geocoded from the range-Doppler geometry to map coordinates through an adaptive multi-looking that accounts for the topography and radar geometry

(Shiroma et al., 2022). The Copernicus GLO-30 DEM is used as the reference DEM for the RTC and geocoding.

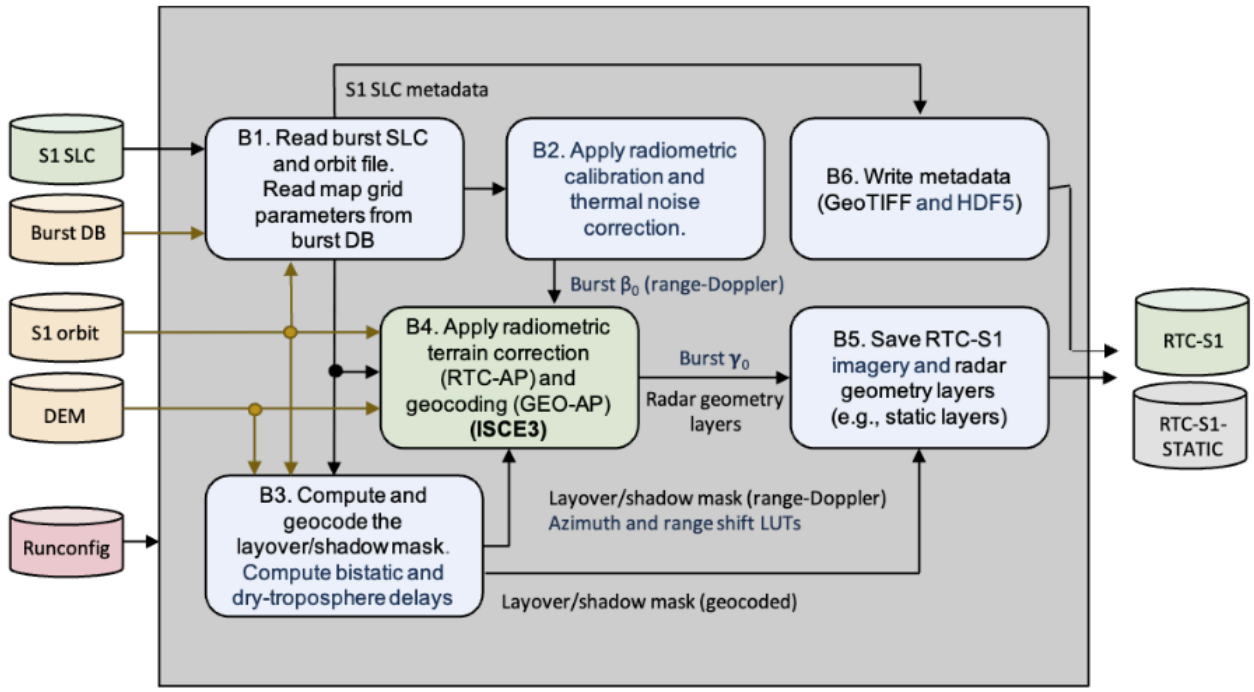


Figure 2.2: OPERA L2 RTC-S1 and RTC-S1-STATIC product workflow details. The steps shown in dark blue color are only enabled in the production of OPERA RTC-S1 products.

In addition to the RTC product imagery, secondary layers including SAR geometric layers, layover/shadow mask, and RTC area normalization factor (or scattering area image TBD) are also provided. All relevant data and lookup tables are converted to map coordinates. The product metadata includes the input SLC metadata (e.g., processing parameters and orbit metadata); sensor information (left/right-looking, sensor name, wavelength, polarization, radar frequency); RTC processing information (algorithms and parameters); and product geolocation grid (including coordinate reference system and map projection).

The products and the metadata are stored in a cloud-compatible format for easy subsetting. As all RTC products are provided at the same reference grid, all the products over a given area can be analyzed in combination to derive higher-level products such as water extents (see Section 3, Level 3 Products). The spatial coverage of these products will be near-global (all landmasses excluding Antarctica). The RTC products are distributed as global tiles aligned with Harmonized Landsat Sentinel-2 (HLS) data.

Tables 2.3 and 2.4 outline key product information as described in the high-level product description above. Note that these tables are *not* meant to be a product specification; see Section 1.2 for details on scope of this Product Description Document.

Table 2.3: Product raster layers for RTC.

RTC Raster Layer	Posting	Description
Backscatter for each polarization	30 m	Linear units of γ^0 backscatter data
Secondary Layers	**Posting or Dimension**	**Description**
SAR geometric information including incidence angle (or TBD local incidence angle) and TBD (LOS unit vectors and ground track unit vectors)	2D rasters or 3D (TBD) metadata cubes with the ability for users to recover it at RTC posting	SAR geometric information
Mask	RTC posting	shadow, layover, water
RTC area normalization factor or scattering area image (TBD based on algorithm)	RTC posting	DEM-based area normalization factor or local contributing area image used for RTC correction

Table 2.4: RTC product metadata.

RTC Metadata Layer	Description
SLC input metadata	Input SLC file names, processing parameters (processed range and azimuth bandwidth, azimuth time information, slant range information), and orbit metadata
Sensor information	Left/right-looking, sensor name, wavelength, polarization, radar frequency
Geolocation grid information	The information for georeferencing (coordinate system, pixel convention, spacing, map projection)
Geographic Bounding Box	The four corners of the product file (bounding box) are identified, expressed in an accepted coordinate reference system
RTC processing information	Relevant processing parameters and algorithm information of the RTC processing approach to produce an RTC γ^0
DEM	DEM file name/link to the DEM used for radiometric terrain flattening
Processing information	RTC algorithm (e.g., bilinear distribution or area projection), RTC algorithm parameters, geocoding algorithm (e.g., nearest, bilinear, bicubic, biquintic, or sinc interpolation or area projection), and DEM interpolation algorithm. References the ATBD to allow users to trace and reproduce the process used for the specific product.

2.2.1 Radiometric Terrain-Corrected from Sentinel-1 Static Layers (RTC-S1-STATIC) Product

The OPERA Level-2 Radiometric Terrain-Corrected SAR Backscatter from Sentinel-1 Static Layers (RTC-S1-STATIC) product provides the fixed radar-geometry and radiometric-normalization layers associated with OPERA RTC-S1 products. It is distributed separately from the RTC-S1 products and generated only once—or a limited number of times—if changes occur in the input data, digital elevation model (DEM), or processing algorithms. RTC-S1-STATIC products are produced for all Sentinel-1 bursts sharing the same burst identification string, ensuring that all RTC-S1 backscatter measurements over a given footprint reference the same geometry.

Each RTC-S1-STATIC product contains geocoded layers describing the acquisition geometry and normalization parameters used in radiometric terrain correction, including local and ellipsoidal incidence angles, the number of looks, a radar-visibility mask identifying shadow and layover regions, and normalization factors that convert between γ^0, β^0, and σ^0 conventions. These layers remain constant for a given burst and provide the geometric and radiometric reference information needed for consistent mosaicking and comparison of RTC-S1 backscatter imagery through time.

Products are generated within the same workflow as RTC-S1 (Figure 2.2), using Sentinel-1 SAFE SLC bursts, precise or restituted orbit ephemerides, and the Copernicus GLO-30 and GLO-90 DEM. The data are projected onto a uniform 30 m × 30 m UTM/Polar Stereographic WGS 84 grid, following a "pixel-is-area" convention. Each granule corresponds to a single Sentinel-1 burst footprint and remains valid for the lifetime of the associated geometry unless updated inputs require reprocessing.

The RTC-S1-STATIC layers are distributed as single-band Cloud-Optimized GeoTIFF (COG) files compressed with the DEFLATE algorithm. Each file includes standardized metadata describing product identification, input datasets, and processing parameters such as algorithm versions, acquisition mode, and orbit direction. Products are archived and distributed through the ASF DAAC.

3. Level 3 Products

3.1 Displacement (DISP) Products

InSAR is a conventional remote sensing technique that exploits the phase difference between two repeat-pass SAR SLCs, acquired from the same sensor (e.g., NISAR or Sentinel-1), to measure anthropogenic and natural changes of Earth's surface (e.g., subsidence, tectonics, landslides). Regions with vegetation, agriculture, snow cover, wetlands, and the like that are prone to surface-scattering changes over time can introduce decorrelation noise in InSAR data (e.g., single SAR interferogram). Unlike conventional InSAR, time-series InSAR methods exploit a stack of co-registered SLC data to decrease the impact of decorrelation noise. These methods can be categorized into three groups: 1) Persistent Scatterer (PS) approaches, which are well-suited for urban areas; 2) Distributed Scatterer (DS) approaches, which are well-suited for rural locations; and 3) hybrid PS/DS approaches, which combine the advantages of both methods.

OPERA utilizes a hybrid PS/DS processing approach that uses the OPERA CSLC products as input data (Figure 1.1) and generates LOS displacement time series data as output (Figure 3.1a). NISAR and Sentinel-1 are processed up to a LOS displacement time series separately. As a new OPERA CSLC product becomes available for NISAR or Sentinel-1, their respective displacement time series is expanded. A DISP product distributed by OPERA corresponds to an individual time slice of the processed displacement time series, i.e., the surface displacements in the radar LOS between two sequential acquisitions. In order to produce DISP at the latest acquisition date (t=N) relative to the previous date (t = N-1), a stack of *k*-CSLCs (e.g., last *k*-CSLCs) are pulled for a time-series analysis from which only the differential estimated displacement between times N and N-1 will be archived. Users can sum consecutive DISP products to reconstruct the cumulative surface displacement time series over a given area, illustrated graphically in Figure 3.1c. Displacements are provided in metric units. Both the DISP-S1 and DISP-NI products – for Sentinel-1 and NISAR, respectively – are frame-based products. The Sentinel-1 and NISAR time series will provide complementing spatial-temporal information on ground displacements. DISP products from different satellite geometries (ascending or descending) and/or from NISAR and Sentinel-1 can be combined by users through application of data fusion or modeling approaches.

The DISP product metadata contains information on CSLC input products and their metadata for reproducibility, time-series processing information, and product geolocation grid. Additional qualitative data layers (e.g., the connected components from phase unwrapping), correction data layers (spatially correlated phase noise from tropospheric and ionospheric path delays, and solid Earth tides), and interferometric baseline data are included within each DISP product (Figure 3.2b). The correction layers are not applied to the data. SAR observation geometry (the incidence, azimuth, and heading angles), auxiliary processing files, and masks (water, shadow and layover) are included in the DISP products.

Tables 3.1 and 3.2 outline key product information as described in the high-level product description above. Note that these tables are *not* meant to be a product specification; see Section 1.2 for details on the scope of this Product Description Document.

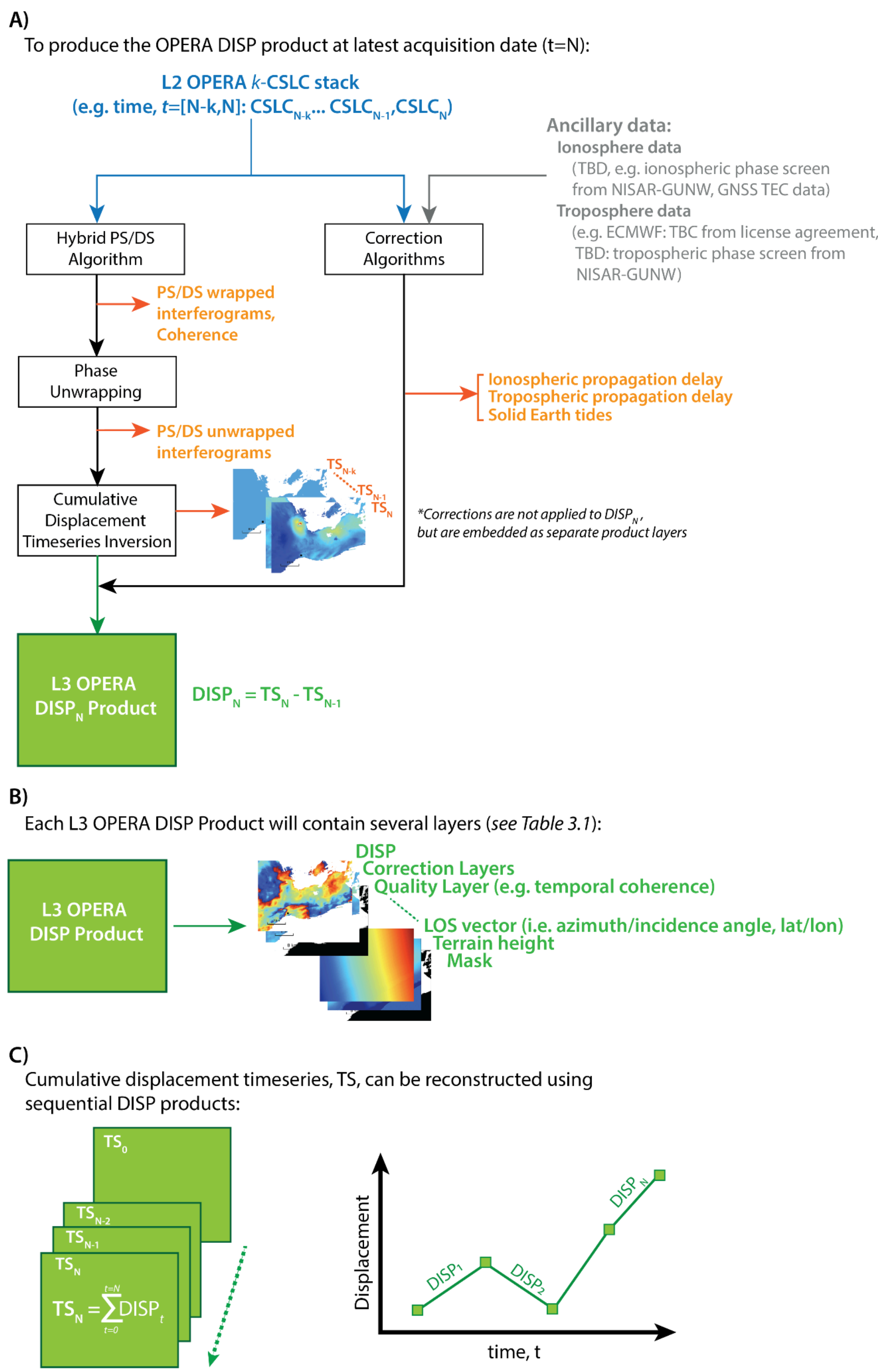


Figure 3.1: OPERA L3 DISP product description details. A) DISP product generated at latest acquisition date (t=N). ***Blue***: input products; ***Gray***: ancillary datasets; ***Orange***: temporary products; ***Green***: output product; ***Black***: processing modules (details to be developed into ATBDs). B) Product raster layer for OPERA DISP as detailed in Table 3.1. C) End users to reconstruct the cumulative displacement time series using OPERA sequential DISP products.

Table 3.1: Product raster layer for OPERA DISP product.

DISP Raster Layer	Posting	Description
Displacement	30 m or approximately native sensor posting (TBD based on volume/cost estimates)	Displacement (metric units) for the HH polarization of the main band for NISAR and VV polarization for Sentinel-1
Connected Components		Connected components as metric for unwrapping quality
Quality		e.g., TBD: Temporal coherence (range 0 – 1) or other metic
(TBD on compute cost) Dense Offsets	TBD	Ground range and azimuth offsets (metric unit) to capture large ground displacements
(TBD on compute cost) Dense Offsets Quality Metrics		Quality metrics indicating the quality of the cross-correlation between the two SLCs
Ionosphere Delay	TBD, driven by resolution of the correction	Ionospheric propagation delay estimated from the data or from auxiliary information (Fattahi et al., 2017; Liang et al., 2019) (metric units)
Tropospheric Delay		Tropospheric propagation delays estimated from weather model data (Bekaert et al., 2021) (metric units)
Solid Earth Tides		Correction related to solid Earth tides (metric units)
Secondary Layer Common to DISP Stack	**Posting**	**Description**
losUnitVectors, (TBD on compute cost) Dense offset unit vectors	TBD, a low-resolution data cube as a function of height. Users can recover values at DISP posting through DEM intersection.	Unit vectors for LOS displacement and dense offset displacements
Incidence and azimuth angle, slantRange		Geometry information
Terrain height (TBD for volume considerations)	Same posting as the Displacement layer	Height layer, TBD if references directly to the source versus embedded in product for volume considerations
Mask		Flags for shadow, layover, water

Table 3.2: OPERA DISP product metadata.

DISP Metadata Layer	Description
SLC input metadata	Input CSLC files, polarization, bandwidth, azimuth time

	information, slant range information
Sensor information	Left/right-looking, sensor name, wavelength, radar frequency
TBD: Azimuth Time and slant range information (if in radar coordinates) or geolocation grid information (if in geocoordinates)	The information for georeferencing
TBD: If in radar coordinates, a lookup on geocoordinates	
Processing information	Algorithm processing parameters (e.g., used for time-series algorithm, ionosphere algorithm, tropospheric algorithm, solid Earth tide algorithm), and references to the ATBD to allow users to trace and reproduce the product using the OPERA open-source algorithm software
Auxiliary information	DEM names, orbit files, aux files, source for water mask, tropospheric model, solid Earth tides

3.1.1 Displacement Static Layers (DISP-STATIC) Products

The OPERA Level-3 Surface Displacement Static Layers (DISP-STATIC) product suite provides the complementary fixed radar geometry and ancillary reference data for the DISP products. Each DISP-STATIC product supplies static layers that remain constant for all displacement granules sharing the same geographic frame—whether derived from Sentinel-1 (DISP-S1-STATIC) or NISAR (DISP-NI-STATIC). These products ensure that all time-variable displacement measurements are referenced to a consistent, geocoded geometry.

Each DISP-STATIC product contains raster layers describing the radar LOS unit vector, the DEM used during CSLC or RTC processing, and the layover/shadow mask that delineates areas of radar visibility loss. The LOS layer provides east, north, and vertical components of the unit vector from ground to satellite; the DEM layer is derived from the OPERA DEM v1.1 (Copernicus GLO-30 DEM resampled to the same UTM grid as the corresponding DISP product); and the layover/shadow mask flags regions affected by shadow (1), layover (2), both (3), or invalid samples (255). All static layers are projected onto a uniform UTM/WGS 84 grid with 30 m × 30 m posting, consistent with the corresponding DISP products.

DISP-STATIC products are distributed as COG files, each file representing one static layer per burst. They include standardized metadata describing product identification (e.g., frame ID, orbit, platform, look direction, processing center, version), input datasets (CSLC-STATIC, RTC-STATIC, DEM sources), and processing information (software and algorithm versions). All products are fully CF-1.8 compliant and interoperable with common GIS and remote-sensing software.

Each granule corresponds to a single DISP frame and is regenerated only if the source DEM, orbit ephemerides, or processing algorithms are updated. The DISP-STATIC suite is produced by the OPERA SDS using a shared processing framework for Sentinel-1 and NISAR inputs. Each product is archived and distributed through the ASF DAAC.

Figure 3.1.1 shows the processing workflow used to generate a DISP-S1-STATIC product which includes the functionality to generate the CSLC-S1-STATIC product.

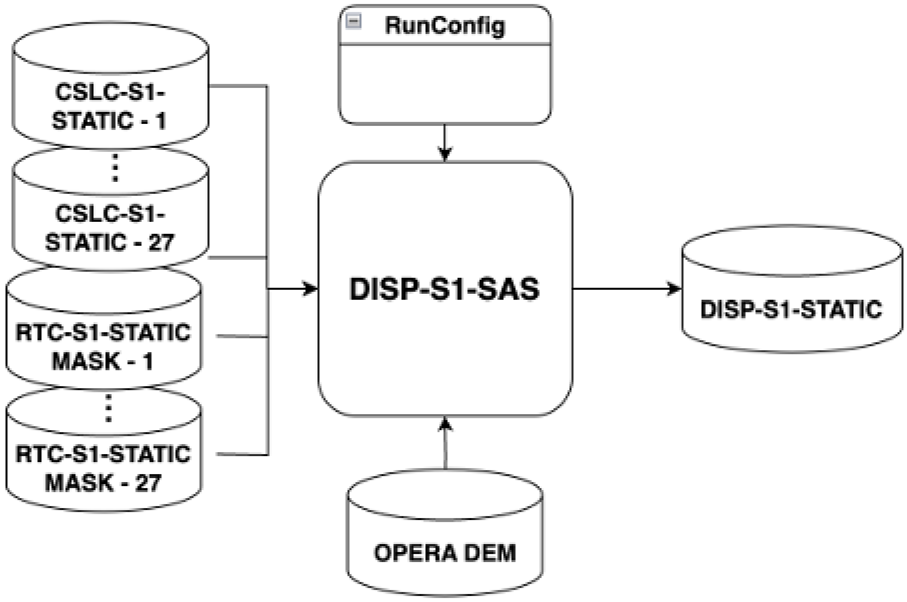


Figure 3.1.1: OPERA L3 DISP-S1-STATIC product workflow detail.

3.2 Dynamic Surface Water Extent (DSWx) Products

The DSWx suite of products maps the surface water extent on a near-global geographical scale (landmasses excluding Antarctica) with a temporal product sampling coincident with the availability of the optical and SAR input datasets (see Table 1.3). The DSWx product suite is not a harmonized product, as the harmonization algorithms were not deemed mature enough at the start of the OPERA DSWx product formulation. However, the DSWx products are structured to promote rapid synchronous analysis across the product suite and promote harmonization activities by the user community. All DSWx products share the same classification labels, grids, confidence layers, etc., allowing the community to rapidly compare sensor sensitivities and develop approaches for harmonization of the sensors for mapping surface water extent. The OPERA team will investigate harmonization as part of the project research activity and report important updates and findings as part of its Stakeholder Engagement Plan (SEP) outreach activities. A harmonized DSWx product may be infused in OPERA activities in a future augmentation of the project.

The DSWx suite is generated from optical (Harmonized Landsat-8 Sentinel-2A/B) and SAR (Sentinel-1A/B, NISAR, and SWOT) data, as summarized in Figure 1.1. Specifically, a separate DSWx product is generated for each input SAR dataset: for Sentinel-1 (DSWX-S1) from the OPERA RTC-S1 product, for NISAR (DSWx-NI) from the NISAR-produced-and-distributed NISAR RTC product, and for SWOT (DSWx-SWOT) using a TBD SWOT product. In the case of optical inputs, OPERA DSWx uses the Landsat Operational Land Imager and Sentinel MultiSpectral Instrument imagery harmonized and made available by NASA as Harmonized Landsat Sentinel-2 (HLS), hence DSWx-HLS. As this optical input data is harmonized prior to processing, the optical DSWx-HLS product has higher temporal sampling than water extent products derived from Landsat-8 or Sentinel-2A/B separately. This is an improvement upon existing available products. For example, while nearly global in extent, the Joint

Research Center Global Surface Water Explorer products are only produced from Landsat, at monthly time steps, with a release frequency currently approaching annual (Pekel et al., 2016). The United States Geological Survey (USGS) Dynamic Surface Water Extent product is generated for each available Landsat scene and has latency nearing that targeted for DSWx but is also only over the United States. Ongoing USGS applications research has demonstrated the need for increased observation frequency, e.g., the development of techniques to estimate large Alaska river streamflow from satellite remote sensing. Such frequency would be facilitated first through DSWx production from the combined Landsat and Sentinel-2 observations provided by DSWx-HLS. DSWx-SAR (i.e., -S1 and -NI) observations are expected to augment the data record significantly, especially in cloud/low-sun incidence locations like Alaska.

DSWx products are distributed as tiles aligned with HLS tiles and are stored in a cloud-compatible format for virtual subsetting and data processing. The consistent gridding permits direct comparison across all DSWx products. Due to the varied nature of each input dataset, each DSWx product captures surface water extent and inundation with different levels of accuracy and uncertainty. For example, NISAR's L-band penetration into vegetation leads to larger estimates of inundated areas than Sentinel-1A/B, whose shorter wavelength leads to its signal's attenuation over such targets. The HLS products are more sensitive to cloud coverage and sun shadow, which are nonissues for SAR; however, SAR can suffer from layover and shadow issues in areas of steep terrain.

Collectively, the DSWx product suite will map the following water-related classes, even though products from one particular sensor may only detect a subset of these classes:

1. *Open water* – An area[2] that is entirely water and unobstructed to the sensor, including obstructions by vegetation, terrain, and buildings.
2. *Partial surface water* – An area that is at least 50% and less than 100% open water. This may be referred to as *subpixel inundation* when referring to a pixel's area. Examples include inundated sinkholes, floating vegetation, and pixels bisected by coastlines.
3. *Inundated vegetation* – An area that contains vegetation and water, either partial surface water or open water.
4. *Obscured* – A mask that identifies an area as obscured by cloud or cloud shadow for the optical-derived products, and terrain or lay-over for the SAR-derived products.
5. *Not water* – An area that is **not** 1, 2, 3, or 4.

Note that *inundated vegetation* and *partial surface water* classes are **not** disjointed. For example, an area with sparse floating vegetation, from the definitions above, should be classified as both *partial surface water* and *inundated vegetation*. There are, however, areas that are distinctly *inundated vegetation* or *partial surface water*. A beach area containing only water and sand is classified strictly as *partial surface water,* while a water body occluded to the sensor entirely by vegetation is strictly *inundated vegetation*. The DSWx suite will not be responsible for differentiating these overlapping classes. Each product may exclude one of these overlapping classes given input dataset sensitivities. Specifically, the DSWx products will indicate the following:

- DSWx-HLS classes:
    - *Open water*
    - *Partial surface water*
    - *Not water*

[2] An *area* may be the area of a pixel in an image.

  - *Obscured (by cloud or cloud shadow)*
- DSWx-NI classes:
  - *Open water*
  - *Inundated vegetation over wetlands:* TBD for inundated vegetation beyond wetlands. The project will perform a trade study to determine the feasibility and performance for retrievals beyond wetlands. The outcome of this study and potential change in scope will be discussed and integrated in a future version of this document (prior to releasing the baseline description for DSWx-NI).
  - *Not water*
  - *Obscured (by terrain shadow)*
- DSWx-S1 classes:
  - *Open water*
  - *Inundated vegetation over wetlands:* The project performed a trade study and decided to provide inundated vegetation mapping over herbaceous wetlands on a best effort basis.
  - *Not water*
  - *Obscured (by terrain shadow)*

While products from SAR and optical sensors may include different subsets of classes, the class labels will be consistent across the entire DSWx suite. Having consistent classification labels across the suite will be invaluable for data fusion and harmonization of the DSWx suite by end users. For example, it will be possible to quantify the overlap of the inundated vegetation from DSWx products from SAR inputs with partial surface water from the DSWx-HLS products to further elucidate the type of inundation present in a particular pixel.

The DSWx suite includes three primary layers that are shared across *all* of the products:

1. Water classification labels (WTR) – This represents pixel-wise classification into one of the four water classes listed above (each product will map to a strict subset of three of the classes). Masks (for the HLS data) are applied indicating where valid data is retrieved. As mentioned previously, the classification labels will be shared across all the datasets for rapid synchronous analysis.
2. Binary water layer (BWTR) – This is a union of water classes (open water, inundated vegetation, partial surface water) in a binary map indicating areas with and without water. This is meant to provide users with a quick view for water/no-water.
3. Confidence layer (CONF) – This assigns a number in the half-open interval (between 0 and 100) to the confidence of the classification label. Each product will assign a confidence value to the WTR label and will be consistently applied throughout each DSWx product. Additional analysis may be required to compare this confidence value across the DSWx suite but could potentially be useful for harmonization activities in the future.

There are additional layers for each product, but the above represent the core of the DSWx product suite, particularly those that are relevant for future harmonization activities. Figure 3.2 shows a sample binary water layer from the USGS Dynamic Surface Water Extent (DSWE). (This product is the predecessor of the DSWx-HLS product, and much of the algorithm is derived from this scientific work.)

Figure 3.2: Side-by-side images over an area northeast of Yuma, AZ, of a Landsat Surface Reflectance Analysis Ready Data (ARD) tile (left) and a Landsat Level-3 DSWE image (right), reclassified to a binary "water/not water" layer (see Table 3.3). Both images are derived from Landsat 7 ARD Tile Horizontal 005, Vertical 013, collected August 16, 2000. The images are in the public domain and taken from the USGS DSWE site.

All the DSWx products from optical (Table 3.3) and SAR (Table 3.4) will share similar metadata layers, as described in Table 3.5. Tables 3.3 through 3.5 outline product information as described in the high-level product description above. These tables are *not* meant to be a product specification; see Section 1.2 for details on the scope of this Product Description Document.

For the optical DSWx-HLS, there are additional intermediate layers, which are summarized in Table 3.4. In addition to the detailed classification labels (WTR), the DSWx-HLS product provides nuanced land cover classification, cloud cover data, and intermediate water extent maps. These additional layers allow users to employ customized cloud and/or shadow masks in place of those distributed with the original input HLS data (Claverie et al., 2018), which are used to create the DSWx-HLS WTR result.

Three relevant masks are utilized to create these intermediate layers. These mask layers are derived from input HLS data and auxiliary datasets: land cover classification (e.g., USGS/Multi-Resolution Land Characteristics Consortium), a shaded relief–based terrain shadow mask (SHAD), and a cloud classification (distributed with the HLS input dataset [Claverie et al., 2018]). The land cover and cloud layers will be called LAND and CLOUD, respectively.

The diagnostic layer (DIAG in Table 3.3), which is the result of five tests applied to each pixel of the HLS input, is initially interpreted into water classes as in Jones (2019) and USGS DSWE without any additional land cover testing or cloud masking applied. The result is named WTR-0. This result is refined through comparison with land cover (LAND) and topographic shadow information (SHAD) to produce a secondary layer (WTR-1). Finally, the primary WTR layer is derived from WTR-1 after masking using CLOUD. The provision of intermediate layers allows advanced users to incorporate more detailed land cover maps and cloud masks to generate related products for their areas of interest.

For the SAR suite, the layers are fewer with only the three core layers (discussed above). More layers may be determined depending on the algorithm flowdown. The classes for BWTR will be open water, inundated vegetation, and not water, as discussed above, although the class labels will be consistent with the entire DSWx suite.

Table 3.3: Product raster layer for DSWx-HLS.

DSWx Raster Layer	**Posting**	**Description**
Water classification (WTR)	30 m	Classification into open water, partial surface water, inundated vegetation, and no-water. Masked layers are applied so that no data areas cover masked inputs and original no-data pixels of the input dataset.
Binary Water (BWTR)		Binary water map with all water classes (open water, partial surface water, and inundated vegetation) combined. Derived from the above interpreted layer.
TBD Confidence (CONF)		Confidence in the prescribed classification. Value in the half-open interval between 0 and 100.
Detailed water classification applied to raw HLS data (WTR-1)		This is the intermediate classification in which the classification is applied directly to the input HLS dataset.
Detailed water classification with additional land cover testing (WTR-2)		Classification into open water, partial surface water, and no-water with additional land cover testing as described in Jones (2019).
Diagnostic (DIAG)		A layer coded to indicate which of the five DSWE tests were positive for water detection on a per-pixel basis. The tests are described in Jones (2019) and are used to derive the Confidence layer. The percentage of positive tests for a particular class determines its confidence value.
Cloud classification (CLOUD)		Cloud, cloud shadow, and snow classifications transferred from HLS input.
Land cover classification (LAND)		Land cover classification used for the intermediate layer WTR-2 and WTR.
Shadow layer (SHAD)		Location and image capture date/time-specific shaded relief used for HLS-based product masking. This is used for optical processing of the HLS inputs.
Secondary Layers Common to DSWx Stack	**Posting**	**Description**
Height above nearest drainage (HAND)	30 m	Height above nearest drainage (Nobre et al., 2011); heuristic layer indicative of likelihood of pixel being a water pixel.
DEM Height		Height of reference DEM.

Table 3.4: Product raster layer for SAR DSWx products (DSWx-S1, DSWx-NI, and DSWx-S1).

DSWx Raster Layer	Posting	Description
Detailed water classification (WTR)	30 m (TBD for SWOT)	Classification into open water, inundated vegetation, and no-water. No data areas match the input datasets and any additionally masked areas. For Sentinel-1 and SWOT, the detection of inundated vegetation is pending a trade study by the project to determine the feasibility and performance baseline.
Binary Water (BWTR)		Binary water map with all water classes (open water, partial surface water, and inundated vegetation) combined. Derived from the above interpreted layer.
Confidence (CONF)		Model confidence for each classification between 0 and 100 .
Secondary Layers Common to DSWx Stack	**Posting**	**Description**
Height above nearest drainage (HAND)	30 m (TBD for SWOT)	Height above nearest drainage (Nobre et al., 2011); heuristic layer indicative of likelihood of pixel being a water pixel, used for DSWx SAR processing.
DEM Height		Height of reference DEM.

Table 3.5: DSWx product metadata across the suite.

DSWx Metadata	Description
Input image metadata	Image (i.e., HLS Sentinel-2A/B or Landsat 8 for DSWx-HLS, Sentinel-1A/B, etc.) input tiles' names, sensor name, time information.
Processing algorithm information	References the ATBD and algorithm-specific parameters to allow users to trace and reproduce the process used for the specific product.
Geolocation grid information	The information for georeferencing (coordinate system, pixel convention, spacing, map projection) aligned with HLS tiles.
Geographic bounding box	Bounding box expressed in an accepted coordinate reference system.
Auxiliary information	Aux files needed for processing.

3.3 Disturbance (DIST) Product

3.3.1 Optical Disturbance Product

Within the DIST product suite, the DIST-HLS products map per-pixel vegetation disturbance (specifically, vegetation-cover loss) from the Harmonized Landsat-8/9 and Sentinel-2A/B (HLS) scenes. Vegetation disturbance is mapped when there is an indicated decrease in vegetation cover within an HLS pixel. The product also provides auxiliary generic disturbance information as determined from the variations of the reflectance through the HLS scenes to provide information about more general disturbance trends. There are two DIST-HLS products according to their temporal scope: 1) the DIST-ALERT-HLS product, which is released at the cadence of HLS imagery, and 2) the DIST-ANN-HLS product, which summarizes the DIST-ALERT-HLS product, specifically confirmed changes, from the previous year. The interannual comparisons used to identify areas of disturbance, the definition of vegetation-cover loss, the types of disturbances that can be detected by the DIST-HLS product, how a disturbance is confirmed, and the relationship between DIST-ALERT-HLS and DIST-ANN-HLS are detailed below.

To define vegetation disturbance, first vegetation cover and its loss must be defined. Cover (as in “vegetation cover”) is defined as “the amount of skylight orthogonal to the surface that is intercepted by the cover trait of interest” (Carrol et al., 2010). In relation to the DIST product, vegetation includes all plant life over land, including woody and herbaceous (i.e., non-woody), as is done for the Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Field (VCF) product (Hansen et al., 2003; Zhan et al., 1999). Vegetation loss within a pixel over a given time frame is defined to be 50% vegetation cover decrease when the scene is compared to the previous calendar years, as in Ying et al. (2017). The number of calendar years for this comparison will depend on HLS availability and be determined during algorithmic calibration, as detailed in the ATBD.

The DIST product suite identifies disturbances in vegetation cover from prior years by comparing each current HLS scene to a composite from previous years representing a lower bound of observed vegetation cover. The composite is derived from a small temporal window around the date of the current HLS scene to account for intra-annual variation. The number of scenes used to generate the composite for interannual comparison will be determined during the algorithm calibration and detailed in the ATBD as well as future versions of this document. Figure 3.3 illustrates a hypothetical time series through an HLS pixel. Specifically, this time series is meant to illustrate how comparisons are made: Each HLS scene compares vegetation cover to previous years, factoring in intra-annual variability to determine a 50% vegetation cover loss.

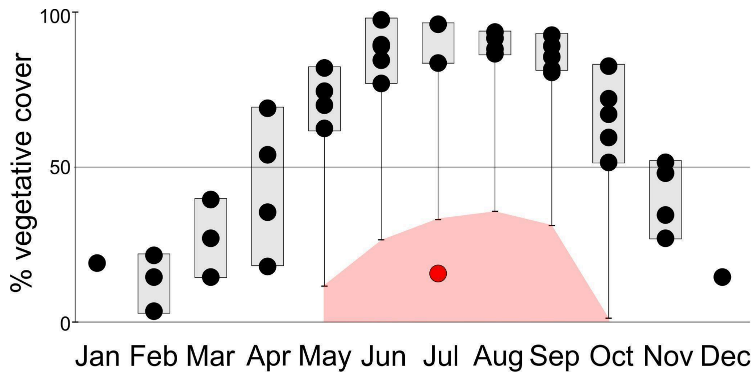


Figure 3.3: Example illustration for an HLS pixel (from RD2). The time series of historical vegetation cover estimates from HLS scenes of previous years are represented by black circles, and the gray boxes represent the range. The pink area represents the range of current-year vegetation-cover estimates that would result in a vegetation disturbance alert with an anomaly of ≥50%. The red circle is an example of a current-year observation from July that would be marked as vegetation disturbance.

The vegetation disturbances detected by the DIST vegetation disturbance product do *not* include *all* land disturbances or all vegetation changes, for that matter – only disturbances that are a result of vegetation cover loss with respect to interannual comparison. Forest loss, fire scars across vegetated landscapes, sick or dying vegetation reducing photosynthetic activity, urban development of vegetated areas, vegetated sandbar erosion, and mining impacts atop vegetated areas *are detected* by the vegetation-disturbance status layer of the DIST product (see examples in Figure 3.4). Landslide extents can also be identified if landslide material (e.g., rock, soil, and sediment) covers a previously vegetated area or if a landslide creates a hillslope scar. Some land disturbances *are not detected* by the vegetation disturbance layer, including vegetation *recovery*; phenological and intra-annual vegetation changes; urban development within urban sprawl (e.g., buildings being replaced or demolished); and more generally, any urban changes of non-vegetated areas (e.g., a highway built over a desert landscape); lava flows over rocky, non-vegetated terrain; crop rotations; and disturbance of non-photosynthetic vegetation. Further, if fire scars are part of *regular* local conservation and management (e.g., annual burns of savanna grasslands in Zambia [Eriksen, 2007]), the vegetation loss and fires scars will not be detected, as such disturbances are within the normal interannual variability.

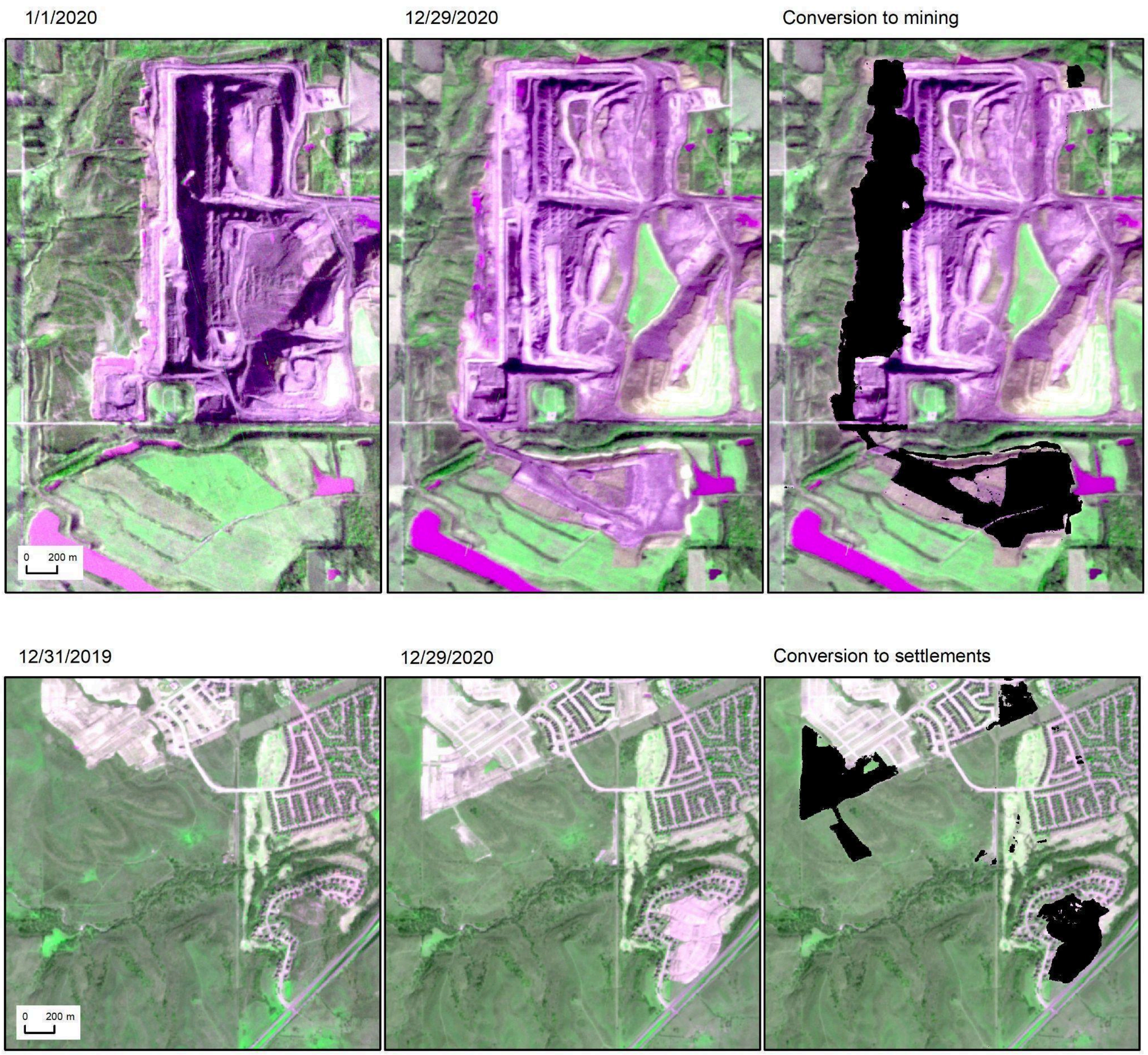


Figure 3.4: Examples of vegetation disturbances that are captured in the DIST product suite (images from PlanetScope, false color composite of Red-NIR [near-infrared]-Green). Here, vegetation is characterized by shades of green and gray, and bare ground by shades of pink. In the final column, black represents areas of conversion. Top row: Vegetation conversion to mining in Indiana. Bottom row: Vegetation conversion to urban development in Dallas, TX. From RD2.

For generic disturbance analysis, the DIST product records the variation of the HLS reflectances from the interannual norm. The variation is measured using the Euclidean distance (or L_2-norm) when viewing the reflectances as a real-valued vector. As in the case for vegetation disturbance, each current HLS scene is compared to a historical composite derived from previous calendar years. Although a single historical composite value cannot be reported given multiple reflectances within an HLS scene, the current HLS scene's distance to the composite's reflectance is recorded within DIST layers. Generic disturbances are meant to provide additional, qualitative outliers with respect to all the HLS reflectance time series.

However, no disturbance category is determined for these generic disturbances, and they only provide an expedient means to identify outliers within the HLS time series.

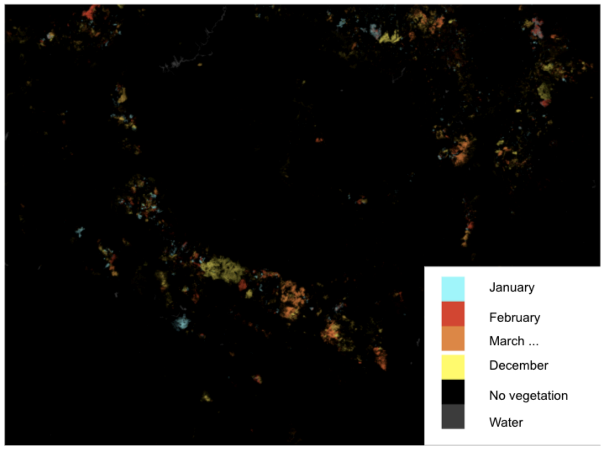


Figure 3.5: A hypothetical DIST product in which vegetation loss and the month of first detection are shown (modified and derived from Hansen et al. [2013]). In the DIST product, the precise Julian date is recorded.

Two DIST products are generated within the DIST product suite with respect to their temporal relevance: 1) the DIST-ALERT-HLS product, capturing vegetation disturbance at the cadence of HLS sampling (median average 2.9 days for S2A/B+L8 [Li and Roy, 2017]); and 2) the DIST-ANN-HLS product, summarizing changes of the DIST-ALERT-HLS products from the previous year. The date of the first disturbance is tracked within both products. Each DIST-ALERT-HLS product is associated with an HLS scene and is used to track vegetation disturbances at the temporal frequency of the input HLS dataset. The DIST-ANN-HLS tracks changes at the annual scale, aggregating changes identified in the DIST-ALERT-HLS product.

This vegetation disturbance is delineated within the *vegetation disturbance status* layer in the DIST product suite (see Tables 3.6 and 3.8). The DIST-ALERT-HLS product tracks two categories of disturbances: *provisional* and *confirmed* (for both ≥50% and <50% estimated vegetation-cover loss). *Provisional disturbances* are when a pixel is first identified to have vegetation-cover loss and *confirmed disturbances* are when this disturbance is identified consistently through some number of subsequent acquisitions in time. The precise number of scenes required for a *confirmed* status will be determined during the algorithmic calibration and detailed in the ATBD. If a pixel marked *provisional disturbance* has no observed loss in subsequent images, then this label will be removed and this pixel's vegetation cover will continue to be analyzed for future vegetation-cover losses. In DIST-ANN-HLS, only *confirmed disturbances* from the associated year are reported together with the date of initial disturbance. *Confirmed disturbances* are determined after subsequent cloud-free observations over the target, which may require *more* HLS scenes depending on the visibility of the target. Due to this, summarizing the DIST-ALERT-HLS in the DIST-ANN-HLS product will have some latency depending on the algorithmic calibration, which will be detailed in subsequent documentation. Additional contextual layers are provided for disturbed pixels, including the date of initial disturbance, vegetation disturbance confidence, number of observed anomalies (defined below), and disturbance duration.

In addition to disturbance status, for every HLS scene an estimate of the current percent vegetation cover and the current anomaly value are provided within the DIST-ALERT-HLS product. The anomaly value is defined as the difference in estimated percent vegetation cover between the seasonally normalized lower bound of historical vegetation cover (historic vegetation cover indicator) and the percent vegetation cover estimate from the current HLS scene. Only anomalies of vegetation loss are reported, but within this, the full range of 1–100% loss is reported. Given potential rapid vegetation recovery, the anomaly value corresponding to the date of maximum anomaly as well as the historical lower bound from that date are reported. As the historical lower bound corresponds to the date of maximum anomaly, it is not reported for pixels without recorded anomalies. The vegetation-cover estimate for the current year at the date of maximum anomaly can be calculated from these two values.

Although disturbances must be reported for ≥50% vegetation-cover loss per the project requirements and validation activities, smaller-scale disturbances are also included. Additional DIST layers (see Tables 3.6 and 3.8) can be leveraged to assess the magnitude and duration of these disturbances. Specifically, within the DIST product, a number of layers capture vegetation indicators (see Tables 3.6 and 3.8) that are correlated with vegetation cover. The statistical relationship of these layers with vegetation cover will be documented through validation activities and released after the DIST validation period. Figure 3.6 shows the MODIS VCF to illustrate how the vegetation indicator layers will be correlated.

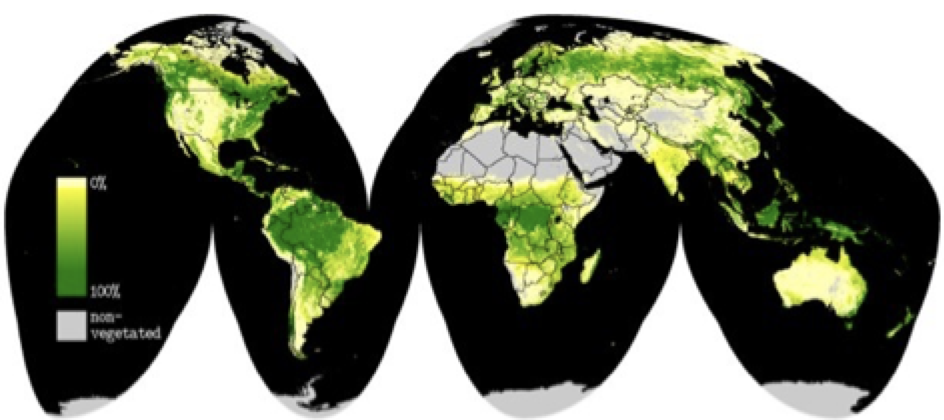


Figure 3.6: The MODIS VCF provides a validated vegetation cover estimate (Hansen et al., 2003). The DIST product will provide a current vegetation indicator layer that will be correlated with vegetation cover.

Although measuring vegetation cover is beyond the scope of the DIST product, these auxiliary vegetation indicator layers that are used by the internal models for identifying areas of disturbance can be used for additional correlative analysis directly. For example, the *maximum vegetation anomaly* can be harnessed to set a threshold for vegetation cover loss at a higher sensitivity (i.e., loss <50%), and the *current vegetation cover indicator* can be tracked over time to evaluate possible recovery trends. Additional layers related to the vegetation indicator are described in Tables 3.6 and 3.8.

In the annual summary of DIST-ANN-HLS, the historic vegetation cover indicator and anomaly value corresponding to the date of maximum anomaly from that year are provided for confirmed disturbance pixels. Additionally, the vegetation cover from that year is summarized by the maximum estimated percent vegetation for all non-disturbance pixels and the estimated percent vegetation cover at the date of maximum anomaly for all confirmed disturbance pixels. In Figure 3.6, the MODIS VCF global vegetation map providing a per-pixel estimate of maximum percent green vegetation cover is shown (for DIST-ANN-HLS, a similar map is created from all HLS scenes of the given year with disturbed pixels, instead having the percent vegetation cover estimate of the date of maximum anomaly). We note that the vegetation cover is a qualitative layer, in that the vegetation covers are not formally validated via requirements (only the *vegetation disturbance status layers* are).

Input metadata, disturbance time-series processing information, product geolocation grid, and data-quality flags such as the employed land mask are included. DIST products are distributed aligned with the HLS input products. The rasters will be stored in a cloud-compatible format for easy subsetting. The DIST products are generated over a near-global scope (all landmasses excluding Antarctica and Greenland). Tables 3.6 and 3.7 outline key product information for DIST-ALERT-HLS, as described in the high-level product description above, and similarly, Tables 3.8 and 3.9 outline the same for DIST-ANN-HLS. These tables are *not* meant to be a product specification; see Section 1.2 for details on scope of this Product Description Document.

Table 3.6: Product raster layer for DIST-ALERT-HLS.

DIST Raster Layer	Posting	Description
Vegetation disturbance status	30 m	Indication of vegetation cover loss (vegetation disturbance). Four possible categories of vegetation disturbance: "provisional ≥50%," "confirmed ≥50%," "provisional <50%," and "confirmed <50%." The label "provisional" is used when disturbance is first detected, and "confirmed" is used when vegetation disturbance is detected for a consecutive number of HLS scenes.[1] These labels are reported for both above and below the 50% disturbance threshold.
Current vegetation cover indicator (TBD)		The percent vegetation cover estimated for the current HLS scene for all land pixels.
Current vegetation anomaly value		Difference between historical and observed vegetation cover at the current date (vegetation loss of 0–100%). The sum of this anomaly value and the current vegetation cover indicator will be the historical vegetation-cover estimate.
Historical vegetation cover indicator		Historical percent vegetation cover proxy from composite of HLS scenes during the same time period of the maximum anomaly for disturbance pixels. A fill value is used for all non-disturbance pixels. Historical vegetation is calculated from a synchronous temporal window from previous calendar years to capture intra-annual/seasonal variation.[2]
Max vegetation anomaly value		Difference between historical and current year observed vegetation cover at the date of maximum decrease (vegetation loss of 0–100%). The sum of the historical percent vegetation and the anomaly value will be the vegetation-cover estimate for the current year. This layer can be used to set a threshold for vegetation disturbance per a given sensitivity (e.g., disturbance of ≥20% vegetation-cover loss).

DIST Raster Layer	Posting	Description
Vegetation Disturbance Confidence Layer		Sum of the differences of vegetation fraction since initial anomaly detection times the number of loss anomalies, until the anniversary date is reached, or a fixed number of consecutive non-anomalies are observed.
Date of initial vegetation disturbance		Julian day of first loss anomaly detection, if applicable.
Number of detected vegetation loss anomalies		Total number of loss anomalies for confirmed disturbances.
Vegetation disturbance duration		Number of days of ongoing loss anomalies since initial anomaly detection.
Generic disturbance anomaly value (TBD)	30 m	Euclidean distance between current HLS scene reflectance and the composite reflectance of previous calendar years.[3]
Generic disturbance maximum anomaly value (TBD)		Maximum Euclidean distance between a current year HLS scene reflectance and the composite reflectance of previous calendar years.[3]
Date of last valid land observation	30 m	Julian day of last quality assessed/passed HLS observation
Land mask		Mask of pixels the vegetation disturbance algorithm is applied to in the current HLS scene. Adapted from methods described in Potapov et al. (2020).

[1] The precise number of scenes required for a "confirmed" status will be detailed in the ATBD.
[2] The precise statistical compositing methodology will be detailed in the ATBD.
[3] The precise statistical compositing methodology will also be determined during calibration and detailed in the future ATBD.

Table 3.7: DIST-ALERT-HLS product metadata.

DIST Metadata Layer	Description
Input image metadata	Image (i.e., HLS Sentinel-2A/B or Landsat 8) input tiles' names, sensor name, time information
Processing algorithm information	References the ATBD to allow users to trace and reproduce the process used for the specific product. Parameters used in heuristical time series modeling.
Geolocation grid information	The information for georeferencing (coordinate system, pixel convention, spacing, map projection), tiling aligned with HLS dataset.
Geographic bounding box	Bounding box expressed in an accepted coordinate reference system.

Table 3.8: Product raster layer for DIST-ANN-HLS.

DIST Raster Layer	Posting	Description
Vegetation disturbance status	30 m	Status of confirmed disturbance, current provisional disturbance, and no disturbance.

DIST Raster Layer	Posting	Description
Historical vegetation cover indicator		Historical percent vegetation from composite of HLS scenes during the same time period of the maximum anomaly for disturbance pixels. A fill value is used for all non-disturbance pixels. Historical vegetation is calculated from a synchronous temporal window from previous calendar years to capture intra-annual/seasonal variation.[1]
Vegetation cover indicator		For non-disturbance pixels, maximum annual vegetation fraction from the HLS time-series data will be reported. For disturbance pixels, the vegetation fraction from the date of maximum anomaly will be reported.
Maximum vegetation anomaly value		Difference between historical vegetation cover and vegetation cover at the date of maximum decrease (vegetation loss of 0–100%). The sum of the global vegetation fraction at the date of maximum anomaly and the anomaly value will provide the previous vegetation-cover estimate at the time of maximum fractional vegetation loss. This layer can be used to set a threshold for vegetation disturbance per a given sensitivity (e.g., disturbance of ≥20% vegetation cover loss).
Vegetation Disturbance Confidence Layer		Sum of the differences of vegetation fraction since initial anomaly detection times the number of loss anomalies, until the anniversary date is reached, or a fixed number of consecutive non-anomalies are observed.[2]
Date of initial vegetation disturbance		Julian day of first loss anomaly detection, if applicable.
Number of detected vegetation anomalies		Total number of loss anomalies for confirmed disturbances.
Vegetation disturbance duration		Number of days of ongoing loss anomalies since initial anomaly detection.
Generic maximum disturbance anomaly value (TBD)	30 m	Max euclidean distance between the reflectance of an HLS scene within the year and the composite reflectance of previous calendar years.[3]
Date of last valid land observation	30 m	Julian day of last quality assessed/passed HLS observation

[1] The precise number of scenes required for "confirmed" status will be detailed in the ATBD.
[2] The precise statistical compositing methodology will be detailed in the ATBD.
[3] The precise statistical compositing methodology will also be determined during calibration and detailed in the future ATBD.

Table 3.9: DIST-ANN-HLS product metadata.

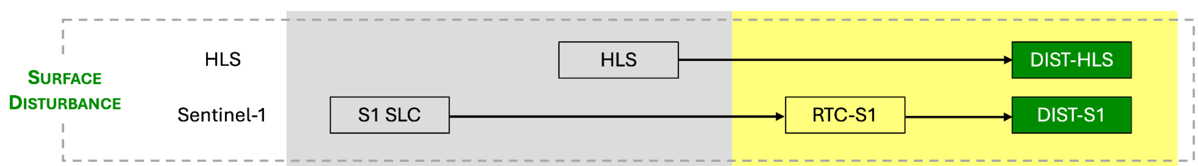
DIST Metadata Layer	Description
Input image metadata	Image (i.e., HLS Sentinel-2A/B or Landsat 8) input tiles' names, sensor name, time information

Processing algorithm information	References the ATBD to allow users to trace and reproduce the process used for the specific product. Parameters used in heuristical time series modeling.
Geolocation grid information	The information for georeferencing (coordinate system, pixel convention, spacing, map projection), tiling aligned with HLS dataset.
Geographic bounding box	Bounding box expressed in an accepted coordinate reference system.

3.3.2 Radar Disturbance Product

Within the DIST product suite, a radar-based surface disturbance product is being formulated and developed. Derived from Sentinel-1A/C (S1A/C) observations, this new product (DIST-S1) will be released in early 2026.

Figure 1.1 in Section 1.4 describes the processing data flow of DIST-ALERT-S1 (with the understanding that the decommissioned Sentinel-1B (S1B) observations be replaced by Sentinel-1C (S1C) slated for launch in late 2024). In essence, S1A/C single-look complex (SLC) observations will go through the RTC-S1 processor to produce radiometric terrain-corrected SAR backscatter data as input to the DIST-S1 algorithm, resulting in product output layers similar to those of the optical DIST-ALERT-HLS product.



While the DIST-ALERT-HLS product uses the per-pixel temporal change in *surface reflectance* to infer surface disturbance events due to wildfires, landslides, and anthropogenic activities such as mining and urban residential growth, the DIST-ALERT-S1 product uses the per-pixel temporal change in *radar backscatter* to infer surface disturbance events due to changes in vegetation structure (e.g. disappearance of vegetation due to natural disasters such as landslides or earthquake), surface geometry (e.g. new buildings due to urban construction), surface scattering properties (e.g., soil moisture before and after precipitation) and volume scattering properties (e.g. change in tree volume/height before and after wildfires/landslides). The product aims to detect *anomalous* surface disturbance events that happened relative to a historical timeline. In other words, surface disturbance events that did not happen several years in a row in the past are to be captured by DIST-ALERT-S1. Under this definition, seasonal recurring events are *not* considered surface disturbance events; they are surface recurrence events instead.

Neither the DIST-ALERT-S1 nor the DIST-ALERT-HLS product attempts to attribute the underlying nature of the detected surface disturbance events. They serve to complement each other in terms of remote sensing physical processes (i.e., radar observations vs. optical observations), spatial coverage (i.e., cloud-penetrating vs. cloud-limited), and temporal coverage (i.e., day/night observations for DIST-ALERT-S1 vs. day observations for DIST-ALERT-HLS).

Table 3.10: High-level DIST-S1 product description

DIST-S1 Description	
Physical Processes	Surface roughness, surface scattering, volume scattering, surface-volume scattering interaction
Potential Applications	Mapping of wildfire, landslide, urbanization, soil moisture, vegetation structure change
Coverage	Near-global
Sensors	Sentinel-1A/C
Spatial Resolution	30 meters
Temporal Sampling	12 days (ascending or descending) or 6 days (ascending plus descending)
Map Projection	UTM
Data Granularity	MGRS tiles
Distribution	ASF DAAC
Forward Production	Mar 2026

The DIST-ALERT-S1 product is an ALERT product only; there is no annual summary product such as DIST-ANN-HLS as in the case of the DIST-HLS suite. Also, ascending and descending observations from S1A/C will be combined to report confirmed disturbances vs. no disturbances with the help of an external disturbance confirmation database that the DIST-S1 SAS keeps updating during forward production.

Table 3.11: DIST-ALERT-S1 product raster layers

DIST-S1 Raster Layer	Description
Disturbance Status	Status of generic SAR disturbance with discrete values indicating status and confidence of detected disturbance events: 0: No Disturbance 1: First Moderate Disturbance 2: Provisional Moderate Disturbance 3: Confirmed Moderate Disturbance 4: First High Disturbance 5: Provisional High Disturbance 6: Confirmed High Disturbance
Disturbance Status Latest	Status of generic SAR disturbance based on the latest (current) pass of S1 data.
Current Metric Anomaly	Distance metric that indicates the confidence on whether a pixel has been disturbed. Smaller values indicate less confidence and higher values indicate higher confidence. This metric allows users to analyze disturbances based on their thresholding.
Date of First Confirmed Occurrence	The date and time of the first confirmed change's first observation. That is when it appeared in the imagery. Expressed in the number of seconds since 00:00:00z on Jan 1, 2020.
Date of Latest Confirmed Occurrence	Date and time of the latest confirmed change's first occurrence. Expressed in the number of seconds since 00:00:00z on Jan 1, 2020.
Number of Confirmed Disturbances	Number of confirmed disturbances since the start of the DIST-ALERT-S1 production.
Number of Observations	Number of Sentinel-1 constellation observations since the start of the DIST-ALERT-S1 production

Table 3.12: DIST-ALERT-S1 product metadata.

DIST-S1 Metadata Layer	Description
Input image metadata	Image (i.e., Sentinel-1A/C) input tiles' names, sensor name, time information
Processing algorithm information	References the ATBD to allow users to trace and reproduce the process used for the specific product. Parameters used in heuristical time series modeling.

Geolocation grid information	The information for georeferencing (coordinate system, pixel convention, spacing, map projection), tiling aligned with HLS dataset.
Geographic bounding box	Bounding box expressed in an accepted coordinate reference system.

4. Level 4 Products

4.1 Troposphere Zenith Radar Delays (TROPO) Products

The OPERA Troposphere Zenith Radar Delays product—referred to by the short name TROPO—provides global, sensor-agnostic estimates of atmospheric path delays used to correct SAR measurements of the Earth's surface (see sample product visualized in Figure 4.1). TROPO is a Level-4 data product derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) High-Resolution Forecast (HRES) model and represents a key ancillary dataset supporting OPERA's radar-based displacement products, including the DISP, CAL, and VLM suites.

Tropospheric delays are the principal source of noise in radar interferometry, and are influenced by variations in temperature, pressure, and water-vapor content along the radar propagation path. The TROPO product quantifies these effects as one-way, zenith-integrated hydrostatic and wet delay components from the surface to 81 km altitude, provided on a global 0.07° (approximately 8 km) latitude/longitude grid (Table 4.1). These layers are derived from HRES model variables—geopotential height, surface pressure, specific humidity, and temperature—which are sampled at 145 vertical levels up to 80 km altitude, four UTC analysis times per day (00, 06, 12, 18 UTC), and cover the globe at a 0.1° × 0.1° latitude/longitude grid.

Each TROPO file is distributed as a Network Common Data Form version 4 (NETCDF4) dataset following CF-1.8 metadata conventions and includes gridded fields for hydrostatic and wet zenith delay (in meters), height, latitude, longitude, and time (Table 4.1). Global attributes capture the model source, spatial and temporal resolution, and software lineage (e.g., RAiDER v0.5.3). Products are generated by the OPERA Science Data System (SDS) using the TROPO Science Algorithm Software (SAS) and Product Generation Executable (PGE) pipelines, implemented within Docker containers for reproducibility and validation (Figure 4.2).

By removing tropospheric noise from radar observations, the TROPO dataset significantly enhances the accuracy of OPERA InSAR measurements of ground deformation and ice surface motion. It is particularly critical for applications requiring millimeter-level precision—such as subsidence monitoring, tectonic strain mapping, and vertical land motion assessment in coastal regions. TROPO products are available globally from July 2016 onward, with updates every six hours, and are distributed through the ASF DAAC.

Table 4.1: High-level TROPO product description

TROPO Description

Potential Applications	Tropospheric correction for SAR/InSAR data
Coverage	Global
Primary Inputs	ECMWF HRES model variables (geopotential height, surface pressure, specific humidity, temperature)
Spatial Resolution	0.07 Decimal Degrees x 0.07 Decimal Degrees
Vertical Levels	Up to 145 height levels (0 – 81 km)
Temporal Sampling	Four times per day (00, 06, 12, 18 UTC)
Data Variables	Hydrostatic delay, Wet delay, Latitude, Longitude, Height, Time
Map Projection	WGS84
Data Granularity	Single global scene per time step
Distribution	ASF DAAC
Beginning of Product Record	July 2016
Beginning of Production	September 2025

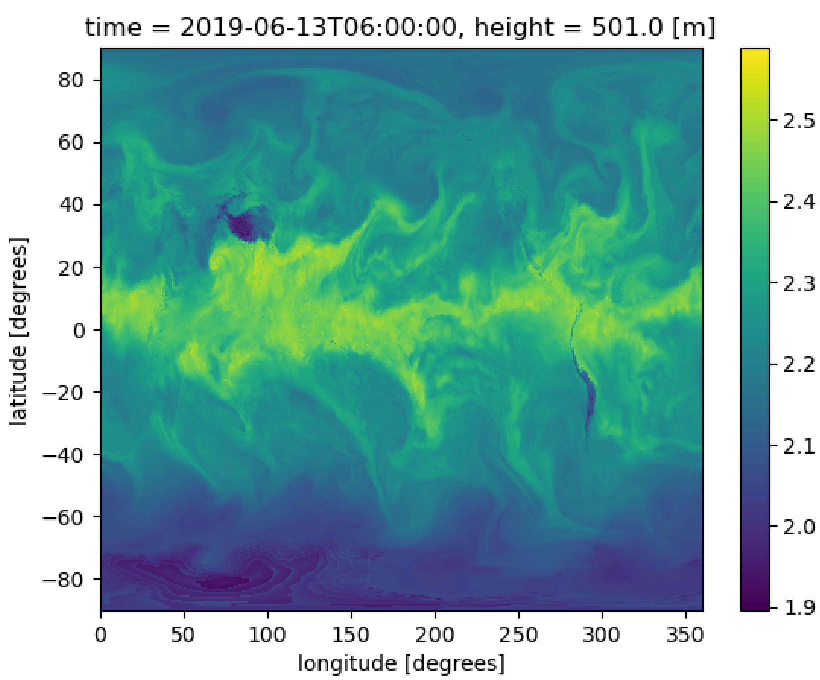


Figure 4.1: TROPO total (hydrostatic plus wet) zenith delay in meters at 501m altitude.

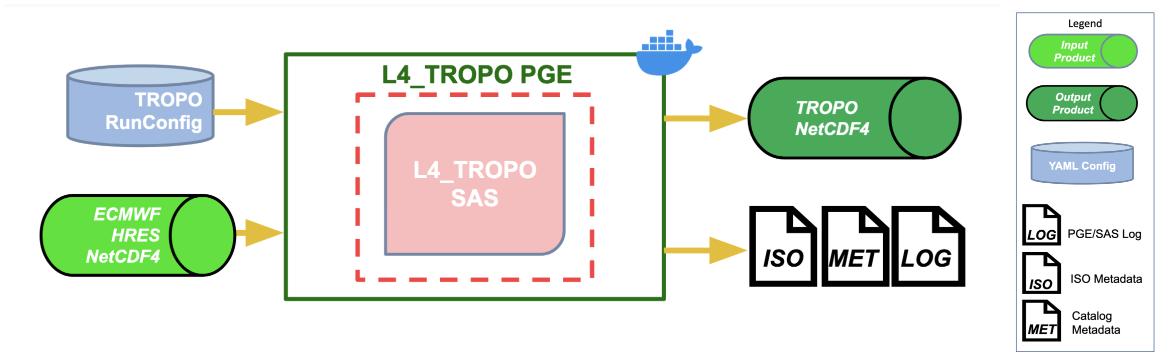


Figure 4.2: OPERA L4 TROPO product workflow details. The TROPO SAS requires input of a global HRES model for a certain date and hour (00/06/12/18), and a run configuration (runconfig) file written in the YAML format to create a TROPO product. Thus, workflow consists of one input one output scheme. The PGE and SAS layers are configured by a single explicit input, the YAML-based RunConfig file.

4.2 Calibration for Displacement (CAL) Products

The OPERA Calibration for Displacement (CAL) product suite provides the intermediate, geodetically-referenced calibration model required to translate relative line-of-sight (LOS) surface displacements from the Level-3 DISP products into absolute LOS motions within a terrestrial reference frame. CAL products represent the foundational, intermediate Level-4 stage for subsequent Vertical Land Motion (VLM) products, ensuring that all OPERA surface deformation products share a consistent geodetic reference across sensors and missions.

Each CAL product is generated by applying long-wavelength corrections to OPERA DISP time-series frames (Figure 4.3), using a calibration model based on Global Navigation Satellite System (GNSS), supplemented with plate-motion (PM) and/or glacial-isostatic-adjustment (GIA) models in regions with spare GNSS. The calibration removes large-scale biases in LOS displacement introduced by arbitrary reference points and unmodeled atmospheric or orbital ramps. The resulting CAL-S1 and CAL-NI products (for Sentinel-1 and NISAR, respectively) express surface displacements in a globally consistent terrestrial reference frame such as ITRF2014 (International Terrestrial Reference Frame, 2014 solution).

CAL products are distributed at 30 m posting on the same frame grid as DISP, preserving the high spatial detail of the interferometric measurements. Each product includes LOS displacement calibration , calibration horizontal and vertical model estimates, residual quality metrics, and ancillary metadata describing the applied GNSS and PM/GIA models. The calibration procedure is implemented in collaboration with the University of Nevada, Reno (Nevada Geodetic Laboratory). Table 4.2 summarizes the key CAL product characteristics.

By providing a geodetic reference frame for OPERA's displacement measurements, the CAL suite enables quantitative integration of InSAR and GNSS observations. This capability supports applications ranging from regional tectonic-strain analysis and interseismic modeling to infrastructure stability assessments and long-term monitoring of subsidence and uplift across North America.

Table 4.2: High-level CAL-S1/CAL-NI product description

CAL-S1/CAL-NI Description	
Physical Processes	Anthropogenic and natural changes of Earth's surface, such as subsidence, tectonics, and landslides
Potential Applications	Maps relative LOS surface displacements to a geodetic reference frame
Coverage	North America*
Sensors	Sentinel-1A/B/C
	NISAR
Spatial Resolution	30 meters
Temporal Sampling	6, 12, or 24 days**
Map Projection	UTM
Data Granularity	Frame-based
Distribution	ASF DAAC
Beginning of Product Record	CAL-S1: May 2016
	CAL-NI: Start of NISAR validated record
Beginning of Production	CAL-S1: February 2028
	CAL-NI: February 2028

*USA and U.S. Territories, Canada within 200 km of the U.S. border, and all mainland countries from the southern U.S. border to and including Panama.

**Based on DISP availability

4.3 Vertical Land Motion (VLM) Products

The OPERA Vertical Land Motion (VLM) product suite represents the OPERA project's Level-4 data Displacement product, as it is derived from the calibrated L3 OPERA DISP products with intermediate CAL products. Whereas DISP products measure relative surface displacement along the radar LOS, and calibrated with CAL products relative LOS displacements within a geodetic reference frame, the VLM products transform these relative measurements into absolute motions in a common geodetic reference frame, decomposed into vertical and East/West horizontal (where applicable) components. This conversion provides users with an analysis-ready representation of ground movement in physical coordinates and facilitates integration with Global Navigation Satellite System (GNSS) observations and other geoinformation datasets (Figure 4.3).

The VLM suite workflow comprises two sequential stages which produce two separate products: (1) a CAL intermediate product and (2) the VLM product. In the first stage, OPERA DISP frames are referenced to a terrestrial reference frame through long-wavelength CAL corrections derived from GNSS-based models of plate motion and GIA to create calibrated DISP measurements. This frame-based CAL product (30 × 30 m posting) is being developed in collaboration with the University of Nevada, Reno (Nevada Geodetic Laboratory), with a planned release in February 2028. In the second stage, the

CAL products are decomposed into vertical and horizontal (East-West, where applicable) motions on a Military Grid Reference System (MGRS) tiling scheme at approximately 120 m posting (TBD). The resulting VLM product combines ascending and descending track geometries (where available) to estimate the vertical and east-west components of land motion (Figure 4.3). Both stages are implemented consistently for Sentinel-1 (VLM-S1) and NISAR (VLM-NI), ensuring interoperability between missions and compatibility with GNSS-based vertical motion estimates. Planned forward production of VLM-S1 and VLM-NI products begins in February 2029 for both Sentinel-1 and NISAR datasets.

The VLM-S1 and VLM-NI products will extend the North America geographical coverage of OPERA, providing continuous temporal records of land motion since January 2019 (Sentinel-1) and through the NISAR validated record onward (up to 5yrs of record), respectively. Temporal sampling will nominally be 15 to 30 days, coarser than the 12-day DISP cadence to accommodate data fusion across multiple imaging geometries. Although the VLM time series do not include derived linear rates by default, users will be able to compute such rates from open-source tools developed by the project. All VLM products will be distributed as cloud-optimized, MGRS tile-based datasets from the ASF DAAC (Table 4.3).

Prototype applications demonstrate the VLM product's utility for critical infrastructure assessment, sea-level rise projections, and solid-Earth process studies. For example, a VLM-S1 prototype over Houston, Texas (Figure 4.4; Buzzanga et al., [2025]) has been used to quantify subsidence rates beneath above-ground storage tanks and evaluate their exposure to flooding hazards. Similarly, a prototype over New York City (Figure 4.5) maps coastal subsidence and its contribution to relative sea-level rise, providing localized estimates previously unavailable in global projection frameworks. On a broader scale, California InSAR-VLM prototypes (Figure 4.6; Govorcin et al., [2025]) illustrate how OPERA VLM can resolve tectonic, hydrologic, and anthropogenic drivers of vertical motion when compared against GNSS networks such as NOAA-Continuously Operating Reference Stations (CORS) and NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs).

The validation strategy for VLM will rely on cross-comparison of time series and long-term rates with GNSS solutions from multiple providers: NOAA CORS, Nevada Geodetic Laboratory, and NASA MEaSUREs Extended Solid Earth ESDR System. Validation sites will coincide with those used for OPERA DISP, ensuring consistent assessment of accuracy and bias correction across the product lineage. Following validation, the VLM products will support a wide range of applications including monitoring of relative sea-level rise, groundwater-related subsidence and rebound, volcanic inflation/deflation, and tectonic deformation mapping throughout North America.

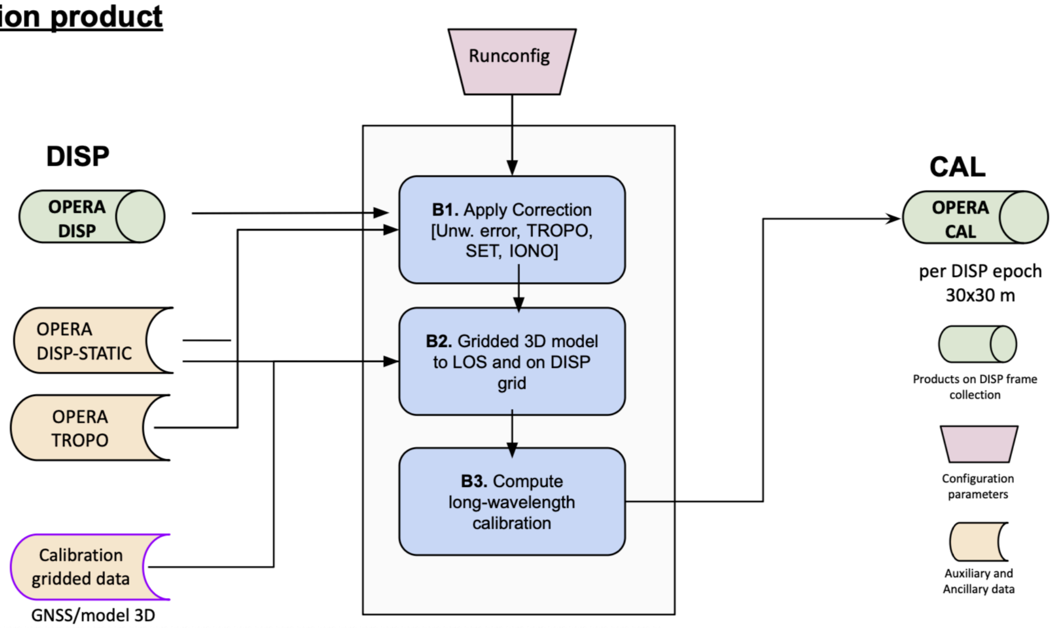
Table 4.3: High-level VLM-S1/VLM-NI product description

VLM-S1/VLM-NI Description	
Physical Processes	Anthropogenic and natural changes of Earth's surface, such as subsidence, tectonics, and landslides
Potential Applications	Maps absolute surface displacements in vertical + horizontal directions
Coverage	North America*
Sensors	Sentinel-1A/B/C
	NISAR

Spatial Resolution	120 meters (TBD)
Temporal Sampling	15 or 30 days (TBD)
Map Projection	UTM
Data Granularity	MGRS tiles
Distribution	ASF DAAC
Beginning of Product Record	VLM-S1: January 2019
	VLM-NI: Start of NISAR validated record
Beginning of Production	VLM-S1: February 2029
	VLM-NI: February 2029

*USA and U.S. Territories, Canada within 200 km of the U.S. border, and all mainland countries from the southern U.S. border to and including Panama.

A) Calibration product



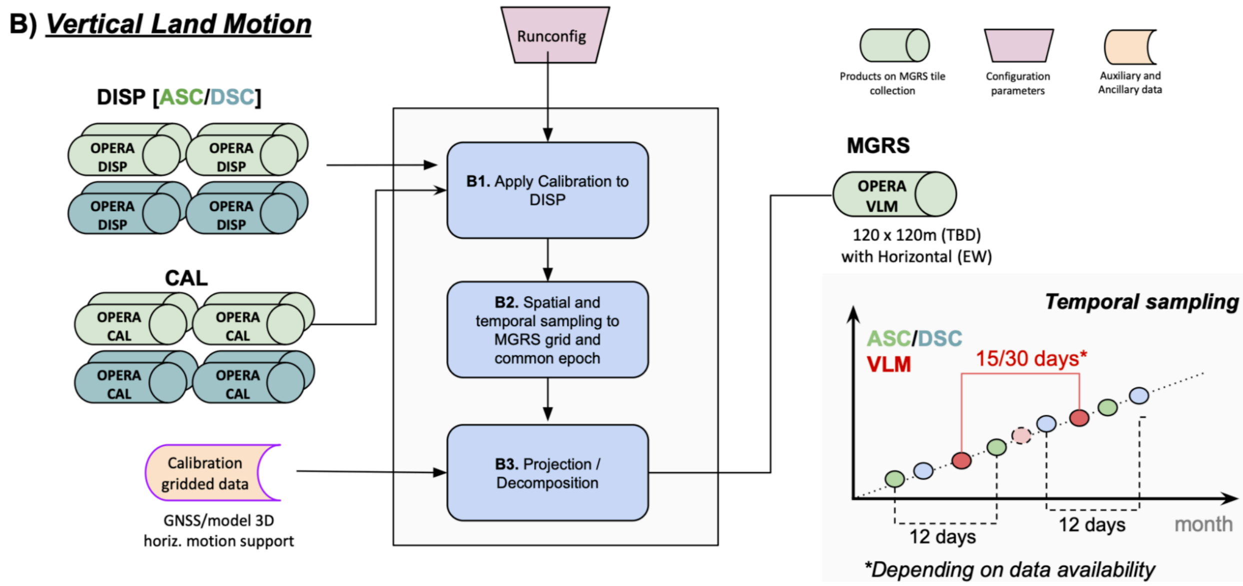


Figure 4.3: OPERA L4 VLM product workflow details. A) Algorithm workflow for the Calibration (CAL) product, which is used as an input to generate the VLM product. ***Blue**:* discrete workflow steps; ***Orange**:* auxiliary and ancillary data; ***Green**:* products on DISP frame collection; ***Red**:* configuration parameters (details to be developed into ATBDs). B) Algorithm workflow for the VLM product. 15/30 day temporal sampling of VLM product with respect to 12 day temporal sampling of constituent ascending/descending track inputs is illustrated on the bottom right. ***Green**:* products on MGRS tile collection, all other colors the same as in A.

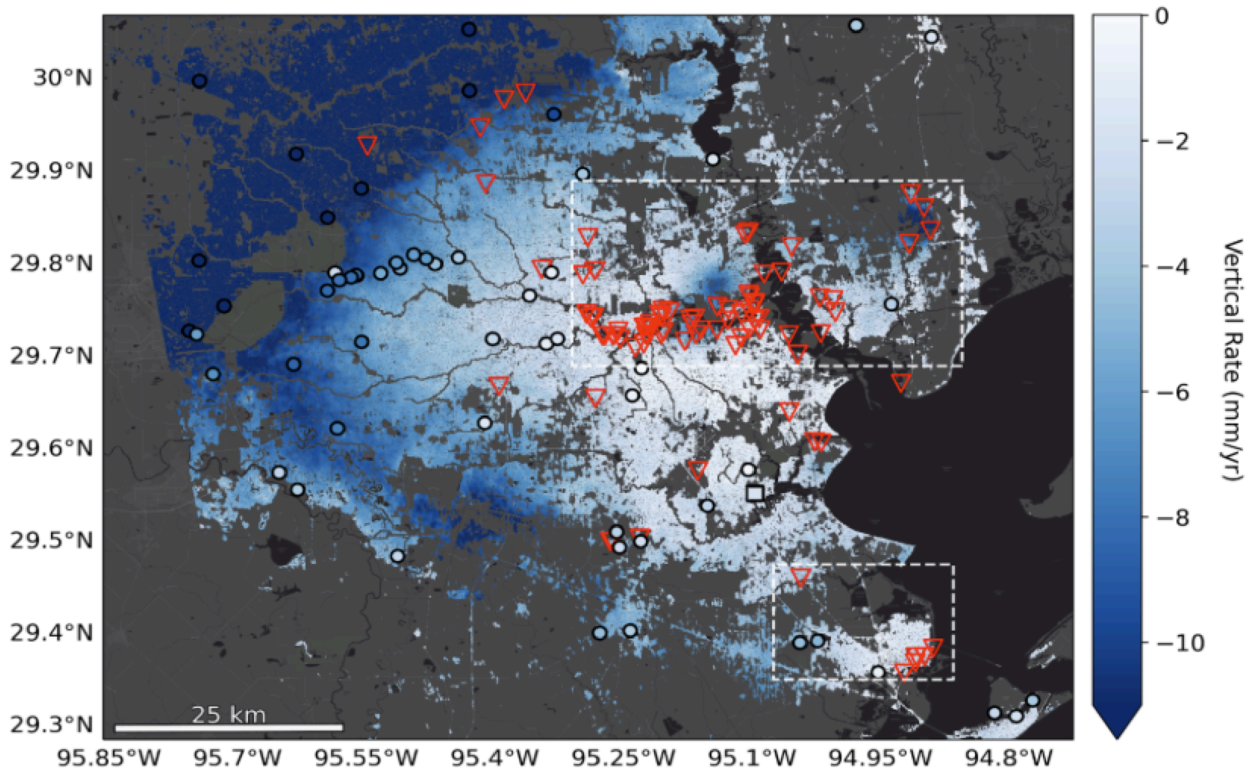


Figure 4.4: VLM (mm/year) over Houston, Texas for the 2016–2024 period estimated from Sentinel-1 InSAR, with GNSS stations (colored dots) and above-ground storage tanks (ASTs) (red triangles) superimposed on the map (modified from Buzzanga et al. [2025]). This analysis serves as a VLM-S1 product prototype to assess critical infrastructure–specifically above ground storage tanks–for exposure to subsidence and flooding hazards.

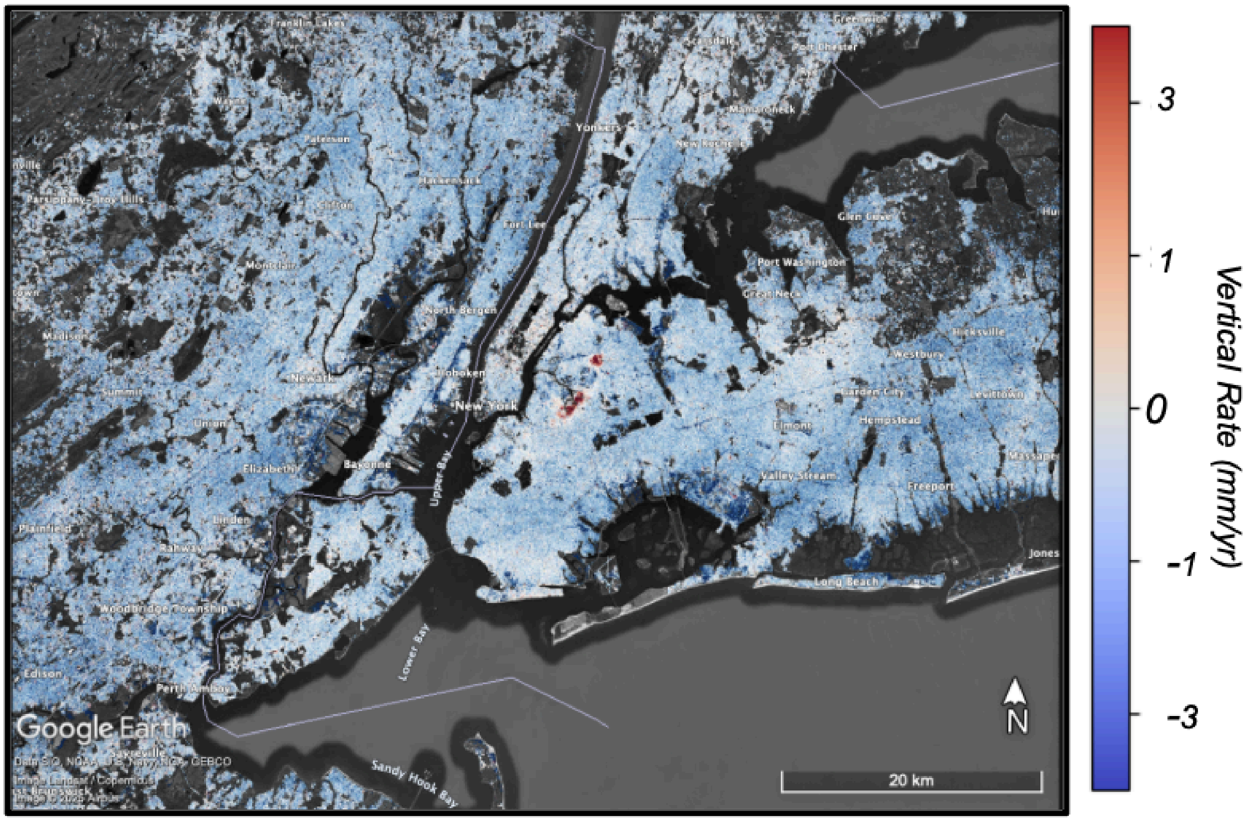


Figure 4.5: VLM (mm/year) over New York City, New York for the 2016–2024 period estimated from Sentinel-1 InSAR. This analysis serves as a VLM-S1 product prototype to capture coastal subsidence and relative sea level rise.

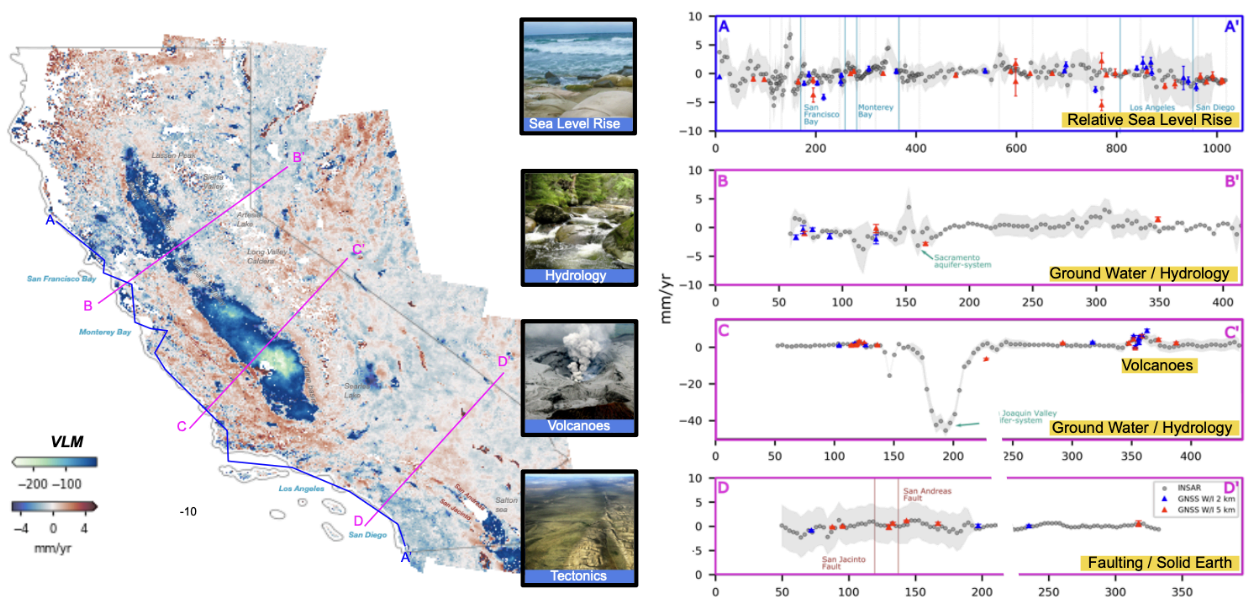


Figure 4.6: [Left panel] VLM (mm/year) over California for the 2015–2023 period estimated from Sentinel-1 InSAR in combination with GNSS data (InSAR-VLM), relative to ITRF2014 (from Govorcin

et al. [2025]). [Right panel] Cross-profiles with superimposed GNSS data across select regions of interest capturing specified land processes. This analysis serves as a VLM-S1 product prototype application.

Acronyms

Acronym	Definition
AD	Applicable Document
ADT	Algorithm Development Team
ARD	Analysis Ready Data
AST	Above-ground Storage Tanks
ATBD	Algorithm Theoretical Basis Document
BWTR	Binary Water (Layer)
CAL	Calibration for Displacement
CARD4L	CEOS Analysis Ready Data for Land
CEOS	Committee on Earth Observation Satellites
CF	Climate and Forecast
CLOUD	Cloud (Classification)
COG	Cloud optimized GeoTIFF
CONF	Confidence (Layer)
CORS	Continuously Operating Reference Stations
CSLC	Co-registered Single Look Complex (Product)
DAAC	Distributed Active Archive Center
DEM	Digital Elevation Model
DIAG	Diagnostic (Layer)
DISP	Displacement (Product)
DIST	Disturbance (Product)
DIST-ALERT-HLS	Disturbance Alert (Product)
DIST-ANN-HLS	Annual Disturbance Summary (Product)
DS	Distributed Scatterer
DSWE	Dynamic Surface Water Extent (USGS Product)
DSWx	Dynamic Surface Water Extent (Product)
ECMWF	European Centre for Medium-Range Weather Forecasts

EOSDIS	Earth Observing System Data and Information System
EPSG	European Petroleum Standards Group
GIA	Glacial Isostatic Adjustment
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
HAND	Height above Nearest Drainage
HDF5	Hierarchical Data Format version 5
HH	Horizontal Transmit and Horizontal Receive
HLS	Harmonized Landsat Sentinel-2 (Input Product)
HRES	High-Resolution Forecast (HRES) model
InSAR	Interferometric Synthetic Aperture Radar
ITRF	International Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
L1, L2, L3, etc.	Level 1, Level 2, Level 3, etc.
LAND	Land Cover (Classification)
LOS	Line-of-Sight
LULC	Land Use and Land Classification
LUT	Lookup Table
MEaSUREs	Making Earth System Data Records for Use in Research Environments
MGRS	Military Grid Reference System
MODIS	Moderate Resolution Imaging Spectroradiometer
NIR	Near-Infrared
NISAR or NI	NASA-ISRO SAR (Mission)
OPERA	Observational Products for End-Users from Remote Sensing Analysis
PGE	Product Generation Executable
PM	Plate-Motion
PS	Persistent Scatterer
PST	Project Science Team
RD	Reference Document
RTC	Radiometric Terrain-Corrected (Product), or Radiometric Terrain Correction
SAR	Synthetic Aperture Radar
SAS	Science Algorithm Software

SDS	Science Data System
Sentinel-1 or S1	Sentinel-1A/B (Mission)
Sentinel-2 or S2	Sentinel-1A/B (Mission)
SEP	Stakeholder Engagement Plan
SHAD	Shadow (Layer)
SLC	Single Look Complex
SNWG	Satellite Needs Working Group
SWOT or SW	Surface Water and Ocean Topography (Mission)
TBD	To Be Determined
TROPO	Troposphere Zenith Radar Delays (Product)
U.S. or USA	United States of America
USGS	United States Geological Survey
VCF	Vegetation Continuous Field
VLM	Vertical Land Motion (Product)
VV	Vertical Transmit and Vertical Receive
WTR	Water (Classification)