Guide to Sentinel-1 Geocoding

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Authors: David Small & Adrian Schubert

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<th>Name</th>
<th>Affiliation</th>
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<tbody>
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<td>ESA-ESRIN</td>
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<td>UZH-RSL</td>
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1 INTRODUCTION

The ability to geolocate Sentinel-1 (S-1) image products and transform them into a map projection is a critical step required to enable overlays with other sources of information (e.g. DEM, GIS layers) or images from other SAR sensors acquired with a different track, beam, or incident angle. Sentinel-1 time series analyses are of increasing importance, making it important that one be able to geocode and co-register many S-1 images acquired over the same (including partially overlapping) area.

This document describes methodologies to geocode S-1 images that present themselves in a single 2-D raster radar geometry (slant or ground range). It has been written for ESA to provide a reference for users wishing to know the details of Range-Doppler geocoding, and potentially also developers working on software to geocode S-1 SAR products.

1.1 Sentinel-1 Product Types for Geocoding

The S-1 products that can be geocoded with the methodology described here are listed in Table 1. Corrections of fine perturbations are presently only possible in a subset of these products – the differences are clarified in Table 11. The abbreviations listed are used in all subsequent sections of this document. Note that Wave mode (WV) SLC products are not listed explicitly here, as they were not analysed by the University of Zurich (UZH). However, the WV SLC product format shares the most important characteristics with the tested products, making the methods described in this document applicable to these products as well.

Table 1: Sentinel-1 Product types that may be geocoded using the methods described in this report

<table>
<thead>
<tr>
<th>Acquisition Mode</th>
<th>Product Type Abbreviations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slant Range Complex</td>
</tr>
<tr>
<td>SM</td>
<td>SM SLC</td>
</tr>
<tr>
<td>IW</td>
<td>IW SLC</td>
</tr>
<tr>
<td>EW</td>
<td>EW SLC</td>
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</table>

This document describes how to geocode an S-1 product in the general “Geocoded-Terrain-Corrected” (GTC) sense, whereby a DEM is used to make use of knowledge of the local height during geocoding. If no DEM is available, a single mean value may be used during geolocation of each point, and a “Geocoded-Ellipsoid-Corrected” (GEC) product is produced rather than the more accurate “GTC” output image. Radiometric normalisation of local terrain effects, i.e. “Radiometrically-Terrain-Corrected” (RTC) products [20], are beyond the scope of this document, and not considered here.
1.2 Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AGP</td>
<td>Antenna Gain Pattern</td>
</tr>
<tr>
<td>ALE</td>
<td>Absolute Location Error</td>
</tr>
<tr>
<td>APD</td>
<td>Atmospheric Path Delay</td>
</tr>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>CHOM</td>
<td>Swiss Oblique Mercator map projection type</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DN</td>
<td>Digital Number</td>
</tr>
<tr>
<td>EO CFI</td>
<td>Earth Observation Customer Furnished Interface</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EW</td>
<td>Extra Wide swath (S-1 acquisition mode)</td>
</tr>
<tr>
<td>GEC</td>
<td>Geocoded Ellipsoid Corrected (single ellipsoid height for whole scene considered for geolocation)</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GRD</td>
<td>Ground Range Detected (S-1 product type category)</td>
</tr>
<tr>
<td>GTC</td>
<td>Geocoded Terrain Corrected (2D raster of local height values considered for geolocation)</td>
</tr>
<tr>
<td>GTS</td>
<td>Ground-To-Slant (polynomials governing conversion between ground and slant range)</td>
</tr>
<tr>
<td>IPF</td>
<td>Instrument Processing Facility (Sentinel-1 processor)</td>
</tr>
<tr>
<td>ITRF</td>
<td>International Terrestrial Reference Frame</td>
</tr>
<tr>
<td>IW</td>
<td>Interferometric Wide swath (S-1 acquisition mode)</td>
</tr>
<tr>
<td>LCC</td>
<td>Lambert Conformal Conic map projection type</td>
</tr>
<tr>
<td>LUT</td>
<td>Look-Up Table</td>
</tr>
<tr>
<td>MPC</td>
<td>Mission Performance Centre</td>
</tr>
<tr>
<td>PD</td>
<td>Path Delay</td>
</tr>
<tr>
<td>RD</td>
<td>Range Doppler</td>
</tr>
<tr>
<td>RSL</td>
<td>Remote Sensing Laboratories - University of Zürich, Switzerland</td>
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<tr>
<td>RTC</td>
<td>Radiometrically Terrain Corrected (2D raster of height values considered for geolocation and radiometric normalisation for local terrain variations)</td>
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<tr>
<td>S-1, S-1A/B</td>
<td>Sentinel-1, Sentinel-1A/B</td>
</tr>
<tr>
<td>S-1 IPF</td>
<td>Sentinel-1 Instrument Processing Facility</td>
</tr>
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<td>SET</td>
<td>Solid Earth Tide</td>
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<tr>
<td>SLC</td>
<td>Single-Look Complex data set</td>
</tr>
<tr>
<td>SM</td>
<td>Strip Map swath (S-1 acquisition mode)</td>
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<tr>
<td>SWST</td>
<td>Sampling Window Start Time</td>
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<td>TOPS</td>
<td>Terrain Observation with Progressive Scans</td>
</tr>
<tr>
<td>UPS</td>
<td>Universal Polar Stereographic map projection type</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator map projection type</td>
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<tr>
<td>WGS84</td>
<td>World Geodetic System 1984</td>
</tr>
<tr>
<td>WV</td>
<td>WaVe (S-1 acquisition mode)</td>
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<tr>
<td>UZH</td>
<td>University of Zurich, Switzerland</td>
</tr>
<tr>
<td>ZDT</td>
<td>Zero Doppler Time</td>
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</table>
1.3 Sentinel-1 Product Data Types

A set of data type primitives used within the S-1 product annotations is listed in Table 3. The data type names listed there are used in later references to the S-1 annotation format.

Table 3: Sentinel-1 data type primitives

<table>
<thead>
<tr>
<th>Data type code</th>
<th>Description</th>
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<tbody>
<tr>
<td>uint32</td>
<td>32 bit unsigned integer. Value range: 0 .. 4294967295</td>
</tr>
<tr>
<td>uint64</td>
<td>64 bit unsigned integer. Value range: 0 .. 18446744073709551616</td>
</tr>
<tr>
<td>int64</td>
<td>64 bit signed integer. Value range: -9223372036854775808 .. 9223372036854775807</td>
</tr>
<tr>
<td>uint64</td>
<td>32 bit signed integer. Value range: 0 .. 18446744073709551616</td>
</tr>
<tr>
<td>Array of LONG</td>
<td>Array of 64 bit signed integers (unspecified array length)</td>
</tr>
<tr>
<td>float</td>
<td>32 bit (7 decimal digits) single precision floating point number with an optional &quot;units&quot; attribute. Range is machine dependent.</td>
</tr>
<tr>
<td>double</td>
<td>64 bit (16 decimal digits) double precision floating point number with an optional &quot;units&quot; attribute. Range is machine dependent.</td>
</tr>
<tr>
<td>doubleCoefficientArray</td>
<td>String containing an array of double values separated by spaces. The mandatory count attribute defines the number of elements in the array. 0 .. 22 double values permitted.</td>
</tr>
<tr>
<td>intArray</td>
<td>String containing an array of int values separated by spaces. The mandatory count attribute defines the number of elements in the array. 0 .. 25100 integer values permitted.</td>
</tr>
<tr>
<td>floatArray</td>
<td>String containing an array of float values separated by spaces. The mandatory count attribute defines the number of elements in the array. 0 .. 25100 float values permitted.</td>
</tr>
<tr>
<td>doubleArray</td>
<td>String containing an array of double values separated by spaces. The mandatory count attribute defines the number of elements in the array. 0 .. 25100 double values permitted.</td>
</tr>
<tr>
<td>complexArray</td>
<td>String containing an array of complex values separated by spaces. The mandatory count attribute defines the number of complex elements in the array. 0 .. 25100 complex values permitted.</td>
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<tr>
<td>timeType</td>
<td>Time within a specified reference time system, given as UTC string with 1 microsecond precision</td>
</tr>
<tr>
<td>unsignedInt</td>
<td>32 bit unsigned integer. Value range: 0 .. 4294967295</td>
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2 REQUIRED SAR GEOMETRY PARAMETERS

Level-1 S-1 products are provided in the form of one or more binary TIFF files containing the raster (image) information, in addition to a number of XML-formatted annotation files that describe, among other things, the image characteristics, SAR acquisition and processing parameters, platform positions and radiometric calibration parameters.

The parameters potentially used during the geocoding of an S-1 product are listed in Table 4 to Table 6. Descriptions of the corresponding data types are listed in Table 3. Product data format field name and table numbers refer to [3]. When several values are defined (e.g. an array of values), a subscripted index denotes the particular value, beginning at 1. For example, StripOffsets, refers to the first element of StripOffsets. The directly read product input parameters are expressed in boldface to highlight dependencies. Parameters derived using those values (e.g. during a multi-looking process) are expressed in italics.

<table>
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<th>Source file(s)</th>
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<th>Field Contents (see [3])</th>
<th>Data type</th>
<th>Description</th>
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<tr>
<td>AzSpacing</td>
<td>Annotation XML</td>
<td>6-65</td>
<td>azimuthPixelSpacing</td>
<td>float</td>
<td>Nominal pixel spacing between range lines [metres]</td>
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<tr>
<td>AzTimeFirst, AzTimeLast</td>
<td>Annotation XML</td>
<td>6-65</td>
<td>productFirstLineUtcTime, productLastLineUtcTime</td>
<td>timeType</td>
<td>Zero Doppler azimuth time to the mid-slant range of the (first, last) line of the image [UTC]. When bistatic correction is performed (bistaticDelayCorrectionApplied set to true) during processing, the time annotated is the time of the imaging of the ground. When bistatic correction is not performed the time annotated is the time of the reception of the echo.</td>
</tr>
<tr>
<td>DataOffset</td>
<td>TIFF</td>
<td>6-13</td>
<td>StripOffsets tag (first element only)</td>
<td>Array of LONG</td>
<td>Array of LONG integer offsets for each strip within the image. For S-1, each &quot;strip&quot; represents a range line, and the offset to the start of the image is the first value in the StripOffsets array. The offset to the first range line is the first element of StripOffsets.</td>
</tr>
<tr>
<td>FastTime</td>
<td>Annotation XML</td>
<td>6-65</td>
<td>slantRangeTime</td>
<td>double</td>
<td>Two-way slant range time to first sample [s].</td>
</tr>
<tr>
<td>LineTimeInterval</td>
<td>Annotation XML</td>
<td>6-65</td>
<td>azimuthTimeInterval</td>
<td>double</td>
<td>Time spacing between azimuth lines of the output image [s].</td>
</tr>
<tr>
<td>RadarFreq</td>
<td>Annotation XML</td>
<td>6-31</td>
<td>radarFrequency</td>
<td>double</td>
<td>Radar (carrier) frequency [Hz]</td>
</tr>
<tr>
<td>RgSampleRate</td>
<td>Annotation XML</td>
<td>6-31</td>
<td>rangeSamplingRate</td>
<td>double</td>
<td>Range sample rate [Hz]</td>
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<tr>
<td>SwathHeight</td>
<td>Annotation XML</td>
<td>6-65</td>
<td>numberOfLines</td>
<td>uint32</td>
<td>Total number of lines in the output image (image length) [samples]; for IW/EW mosaic “height” derivation, see [16]</td>
</tr>
<tr>
<td>SwathWidth</td>
<td>Annotation XML</td>
<td>6-65</td>
<td>numberOfSamples</td>
<td>uint32</td>
<td>Total number of samples in the output image (image width) [samples]; for IW/EW mosaic “width” derivation, see [16]</td>
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Table 5: Sentinel-1 State Vector Parameters required for range-Doppler geocoding

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<th>Data Type</th>
<th>Description</th>
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<tr>
<td>N_{SV}</td>
<td>Annotation XML</td>
<td>6-44</td>
<td>orbitList / count</td>
<td>unsignedInt</td>
<td>Number of state vectors</td>
</tr>
<tr>
<td>S_{ij}</td>
<td>Annotation XML</td>
<td>6-45</td>
<td>time</td>
<td>timeType</td>
<td>Time of state vector (converted to seconds elapsed since azimuth start time)</td>
</tr>
<tr>
<td>S_{ij}</td>
<td>Annotation XML</td>
<td>6-46</td>
<td>x</td>
<td>double</td>
<td>X position in Earth fixed reference frame [m]</td>
</tr>
<tr>
<td>S_{ij}</td>
<td>Annotation XML</td>
<td>6-46</td>
<td>y</td>
<td>double</td>
<td>Y position in Earth fixed reference frame [m]</td>
</tr>
<tr>
<td>S_{ij}</td>
<td>Annotation XML</td>
<td>6-46</td>
<td>z</td>
<td>double</td>
<td>Z position in Earth fixed reference frame [m]</td>
</tr>
<tr>
<td>V_{ij}</td>
<td>Annotation XML</td>
<td>6-47</td>
<td>x</td>
<td>double</td>
<td>X velocity in Earth fixed reference frame [m/s]</td>
</tr>
<tr>
<td>V_{ij}</td>
<td>Annotation XML</td>
<td>6-47</td>
<td>y</td>
<td>double</td>
<td>Y velocity in Earth fixed reference frame [m/s]</td>
</tr>
<tr>
<td>V_{ij}</td>
<td>Annotation XML</td>
<td>6-47</td>
<td>z</td>
<td>double</td>
<td>Z velocity in Earth fixed reference frame [m/s]</td>
</tr>
</tbody>
</table>

Table 6: Sentinel-1 Slant/Ground Range Parameters additionally required for range-Doppler geocoding of GRD products

<table>
<thead>
<tr>
<th>Name used in this document</th>
<th>Source file(s)</th>
<th>Table # (see [3][3])</th>
<th>Field Contents (see [3][3])</th>
<th>Data Type</th>
<th>Description</th>
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<tbody>
<tr>
<td>N_{SRGR}</td>
<td>Annotation XML</td>
<td>6-90</td>
<td>coordinateConversion-List / count</td>
<td>unsignedInt</td>
<td>Number of coordinateConversion records (i.e. polynomial updates)</td>
</tr>
<tr>
<td>ZDT_{SRGR,j}</td>
<td>Annotation XML</td>
<td>6-91</td>
<td>azimuthTime</td>
<td>timeType</td>
<td>Azimuth ZDT for this update. j varies from 1…N_{SRGR}</td>
</tr>
<tr>
<td>FastTime_{SRGR,j}</td>
<td>Annotation XML</td>
<td>6-91</td>
<td>slantRangeTime</td>
<td>double</td>
<td>2-way slant range time [m]</td>
</tr>
<tr>
<td>GR_{ij}</td>
<td>Annotation XML</td>
<td>6-91</td>
<td>gr0</td>
<td>double</td>
<td>Ground range origin [m]</td>
</tr>
<tr>
<td>GTS_{ij}</td>
<td>Annotation XML</td>
<td>6-91</td>
<td>grsrCoefficients</td>
<td>doubleCoeffi- cientArray</td>
<td>Slant range = S_0 + S_1(GR-GR_0) + … + S_{count}(GR-GR_0)^{count-1} where GR is the ground range distance from the first pixel of the range line, and “count” is the parameter attribute indicating the number of coefficients</td>
</tr>
</tbody>
</table>
3 SYSTEM DESIGN

The processing steps inherent in any geocoding system for S-1 products may be broadly arranged as consisting of the following steps:

- Sentinel-1 Product Ingestion
  - Detection
  - Debursting (for IW and EW SLC)
  - Multi-looking
- DEM Input & Map Geometry Initialisation
- Radar Geometry Initialisation
  - Product or External State Vector Format Input
  - Timing Annotations Initialisation
- DEM Traversal
  - Point Geolocation
    - Coordinate Transformation
- Annotation Output

The major system design features of an S-1 geocoding software system are shown in Figure 1. A brief summary is provided below; further details are presented in later sections.

The relevant product annotations are first read and a contiguous 2-D radar image (or images in the case of IW/EW SLC products) is loaded from the input S-1 product. If the product measurements are complex (SLC), the values are “detected” to first generate radar intensity values; IW/EW SLC products are also “debursted” and “mosaicked” into a single contiguous slant range image [16]. Within the input stage, the product may also be multi-looked if necessary to a resolution compatible with the output geocoded image resolution that is desired.

Once the product has been ingested, the raster geocoding algorithm can begin. The multi-looked radar geometry image is read into memory, and the geographic area of interest is traversed progressively. Either a DEM or a simpler ellipsoid model presented in map geometry is used to describe the position of each point within the area: the 2D cartographic (northing, easting) or geographic (latitude, longitude) positions are transformed into Cartesian (x,y,z) coordinates. For each point, the S-1 satellite modelled state vectors (available also in Cartesian coordinates) are used to determine the image’s azimuth row corresponding to Zero-Doppler time, the azimuth convention used by the standard S-1 Instrument Processing Facility (IPF), i.e. the S-1 processor. A small azimuth “bistatic” residual timing correction can next be applied (see section 4.7.3) to better model satellite movement between pulse transmission and reception. Finally, the local slant range is calculated, and converted to ground range if necessary. Now that both the azimuth and range coordinates corresponding to the current map position are known, the image content is resampled from the known location in radar geometry into the current map geometry position. One traverses the 2D map geometry grid, geolocating in the manner described, until all DEM grid points have been visited and the geocoding is complete.
Figure 1: SAR Geocoding System Components
4 SAR GEOCODING IN DETAIL

The components of the S-1 geocoding algorithm (see Figure 1) are described in the following sections.

4.1 Ingestion to Annotated RADAR Geometry Raster

The tasks accomplished during the initialisation phase are described in the following subsections.

4.1.1 Product Input

**StripMap SLC/GRDF/GRDH/GRDM Product Input**

In the case of S-1 images acquired in StripMap Mode (SM), there is a single focussed contiguous image that is input to the geocoding software. Depending on product type, that image is presented either in slant range, “single-look complex” (SLC) or a sliding ground range geometry with multiple slant/ground range conversion updates provided along the azimuth dimension (GRDF/H/M).

While GRDF/H/M products present themselves as scalar images with nominally “square” pixels on the ground, an SLC product provides complex (real & imaginary) components of the radar backscatter with the (spatial ground-equivalent) azimuth sampling interval shorter than the equivalent ground range sampling interval, a consequence of the natural slant range sampling. One therefore typically first carries out a detection operation, retrieving radar backscatter amplitude from the SLC complex image content followed by averaging over a defined window to generate an image with nominally “square” pixel sizes that is then input to the geocoder. The detection and multi-looking step is described in section 4.1.2.

**IW/EW GRD Product Input**

In the case of S-1 images acquired in Interferometric Wide Swath (IW) or Extended Wide Swath (EW) mode processed into GRD products, the subswaths (three for IW, five for EW) are stitched together into a single detected focussed contiguous image that can be input to the geocoder.

The images are presented in sliding ground range geometry with multiple slant/ground range conversion updates provided along the azimuth dimension. The parameters necessary to describe this kind of geometry are listed in Table 6.

**IW/EW SLC Product Input: Debursting and Mosaicking**

The S-1 IW/EW SLC core products are a special case among S-1 product family: the images from the individual subswaths (three for IW, five for EW) are provided as separate TIFF files with non-continuous azimuth zero Doppler time reflecting the retention of all burst data in each subswath. Debursting and mosaicking [16] these TIFFs results in a single image with contiguous azimuth and range timelines, comparable to the case of SM SLC products. The debursting and mosaicking are recommended as pre-processing steps for IW/EW SLC products before geocoding is performed. The mosaicked intermediate product may then be processed during geocoding as a simple slant range image, without any slant/ground range considerations.

**Ingested Parameters for Geocoding**

Note that although knowledge of the spatial range and azimuth pixel spacings is useful, it is important to emphasise that imaging radars actually measure time differences between transmission and reception of echoes. Also in the azimuth direction, it is time-tagging of the radar echoes that is the primary reference. Orbital state vector positions are attached to those same times later as secondary (nonetheless important) items of information. Yet it cannot be overstated that geolocation of radar images is tied to timing information in a way that optical imagery is not: for radar images, the primacy of timing annotations extends also into the
cross-track dimension. Radar ranging measurements are primarily quantifications of time separation, and only secondarily measurements of distance.

Table 7: Geometry parameters required for geocoding different Sentinel-1 product types; names of parameters referring to multi-looked images are in italics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SM SLC</th>
<th>IW SLC</th>
<th>EW SLC</th>
<th>SM GRD</th>
<th>IW GRD</th>
<th>EW GRD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radar Timing Annotations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth Start Time</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AzTimeFirst / AzTimeFirst&lt;sub&gt;roll&lt;/sub&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth Stop Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AzTimeLast / AzTimeLast&lt;sub&gt;roll&lt;/sub&gt;</td>
<td>❌ Redundant: can be derived as AzTimeFirst + (SwathHeight – 1) · LineTimeInterval</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slant range (near)</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FastTime&lt;sub&gt;1&lt;/sub&gt; / FastTimeNear&lt;sub&gt;roll&lt;/sub&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slant range (far)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FastTime&lt;sub&gt;11&lt;/sub&gt; / FastTimeFar&lt;sub&gt;roll&lt;/sub&gt;</td>
<td>❌ Redundant: can be derived as FastTime&lt;sub&gt;11&lt;/sub&gt; = FastTime&lt;sub&gt;1&lt;/sub&gt; + (SwathWidth – 1) · FastTime&lt;sub&gt;1&lt;/sub&gt; / 2 · RgSampleRate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth sample interval</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LineTimeInterval / LineTimeInterval&lt;sub&gt;roll&lt;/sub&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range sample interval</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RgSampleRate / RgSpacing&lt;sub&gt;roll&lt;/sub&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Image Size</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image raster width</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SwathWidth / Width</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image raster height</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SwathHeight / Height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>State Vectors</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One of product header state vectors or same from external source (AUX_POEORB, AUX_RESORB, AUX_ORBPREF)</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nsv, S&lt;sub&gt;i&lt;/sub&gt;[1...Nsv], S&lt;sub&gt;j&lt;/sub&gt;[1...Nsv], S&lt;sub&gt;i&lt;/sub&gt;[1...Nsv], S&lt;sub&gt;j&lt;/sub&gt;[1...Nsv]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Slant/ground range conversion parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of slant/ground range polynomials</td>
<td>N&lt;sub&gt;SRGR&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground range origin</td>
<td>GR&lt;sub&gt;ri&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slant/ground range polynomial coefficients</td>
<td>GTS&lt;sub&gt;ri&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth time reference for each set of coefficients</td>
<td>ZDT&lt;sub&gt;SRGR&lt;/sub&gt;&lt;sub&gt;ri&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Summarising the above sections, the parameters required for each product type are listed in Table 7. Note that the first rows contain the primary geometry information, namely the radar timing annotations that are necessary to geocode an image. In the case of IW/EW SLC products, it is assumed that it is a (derivative) mosaic that is being geocoded.

4.1.2 Detection and Multi-looking

Before geocoding, if the input product contains complex values (SM/IW/EW SLC), they may be “detected” to radar backscatter intensity values. Next, those values may optionally be multi-looked in one or both of the range and azimuth dimensions to generate a radar geometry image with approximately “square” sample sizes.

First, the complex radar signal is converted to scalar intensity values by taking the sum of the squares of the real and imaginary parts; this is called detection. The intensity for a given cell, commonly expressed as the square of the image raster value, or digital number $DN_{i,j}$, for input position $(i,j)$ is:

$$\text{Intensity} \equiv DN_{i,j}^2 = (SLC_{\text{real}})^2 + (SLC_{\text{imag}})^2$$

where $DN_{i,j} = \text{input digital number}$

$SLC_{\text{real}}$ and $SLC_{\text{imag}} = \text{real and imaginary components of the complex input value.}$

To by default generate a multi-look output image with approximately square sample dimensions at mid-range, the following method is applied.

The mid-range distance is retrieved from the FastTime input array as:

$$\text{FastTime}_{\text{mid}} = \frac{\text{FastTime}_1 + \text{FastTime}_{11}}{2}$$

Although the timing annotations have primacy (as discussed above), it is also useful to have the spatial equivalents. The two-way slant range sampling rate in time is converted to one-way slant range distance via:

$$RgSpacing = \frac{c}{2 \cdot RgSampleRate}$$

Default range and azimuth multi-looking factors can be calculated to satisfy the following relation:

$$\frac{nAzLooks}{nRgLooks} = \frac{RgSpacing}{AzSpacing \cdot \sin(IncAngle_{\text{mid}})}$$

If one of the multi-looking factors is specified manually, then the other can be calculated using the above relation and then rounded to the nearest integer. When factors are applied that satisfy the above relation, one produces samples that are as “square” as possible on the ground.

Modified multi-look sample intervals

The timing interval between successive azimuth lines is of primary importance in geolocation. The multi-looked interval is derived simply as:

$$\text{LineTimeInterval}_{\text{ML}} = \text{LineTimeInterval} \cdot nAzLooks$$

The spatial multi-look sample intervals are derived from the input spacings simply as:

$$RgSpacing_{\text{ML}} = RgSpacing \cdot nRgLooks$$
Calculation of multi-look near-range and azimuth-start times

Given a sample-centred annotation convention (generally used within this document unless otherwise noted), the equations relating the original product’s annotated values and the new, adjusted multi-looked values are:

\[
AzSpacing_{ML} = AzSpacing \cdot nAzLooks
\]  

\(6\)

The 2-way near slant range time value (FastTime) is extracted from the product annotation XML (see Table 4). The multi-look near range fast time value is obtained from it:

\[
FastTimeNear_{ML} = FastTime + \left[ \frac{nRgLooks - 1}{c} \right] \cdot RgSpacing 
\]

\(8\)

where \(c\) is the speed of light.

Modified Multi-look Boundaries

Image near and far range values are referred to as \(r_{near}\) and \(r_{far}\). They are obtained from the near-range value \(FastTimeNear_{ML}\), the image sample dimensions and sample intervals, as:

\[
r_{near} = \frac{FastTimeNear_{ML} \cdot c}{2} \]

\(9\)

where \(c\) is the speed of light.

For slant range images, the image width (number of slant range samples) is known to be:

\[
Width_{SR} = \frac{r_{far} - r_{near}}{(RgSpacing \cdot nRgLooks)} + 1
\]

\(10\)

Alternatively:

\[
r_{far} = r_{near} + (Width_{SR} - 1) \cdot RgSpacing_{ML}
\]

\(11\)

where \(Width_{SR}\) is the number of range samples in a slant range image.

The image height \(Height_{az}\) (azimuth extent in samples) should be consistent with the other multi-look boundary information:

\[
Height_{az} = \frac{AzTimeLast_{ML} - AzTimeFirst_{ML}}{LineTimeInterval_{ML}} + 1 = \frac{SwathHeight}{nAzLooks}
\]

\(12\)

4.2 DEM Input and Map Geometry Initialisation

The interface to the reference DEM that is to be used must ensure that all required cartographic and geodetic parameters annotating the DEM are available during geocoding. These parameters (e.g. false easting, false northing, central meridian, standard parallel(s), datum shift) must be sufficient to specify the conversion of a point coordinate from cartographic (northing, easting, height) coordinates \((P_E, P_N, P_h)\) or geographic coordinates \((P_x, P_y, P_z)\) to first locally, and then globally-referenced Cartesian values \((P_x, P_y, P_z)\). The different coordinate systems are summarised in Table 8.
Cartographic coordinates are generally parameterised using a so-called “mapset” in a manner conforming to a small number of map projection types, such as Transverse Mercator (TM), Oblique Mercator (OM), Polar Stereographic (PS), Oblique Stereographic (OS), Lambert Conformal Conic (LCC) etc. – each maps a 3D position on the Earth into a defined 2D map projection. Each mapset also specifies a given *local ellipsoid* (semi-major and semi-minor axis lengths) as well as a seven-parameter “datum shift” (including 3D vector translation and rotation vectors as well as a scalar scale factor) that detail how to transform 3D Cartesian coordinates from that local ellipsoid into a *global geodetic ellipsoid reference* such as WGS84 or a reference frame such as ITRF2008. The geocoding software must be able to deal with a variety of map projection types and instances (typically through the use of a software library) to enable access to DEM rasters presented in a variety of projections, ellipsoids, and datum shifts.

Table 8: Cartographic & Geodetic Coordinate Systems

<table>
<thead>
<tr>
<th>Axes</th>
<th>Map Projection</th>
<th>Coordinate System</th>
<th>Cartographic (based on local Ellipsoid)</th>
<th>Cartesian (based on global Ellipsoid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easting $E$</td>
<td>Longitude $\lambda$</td>
<td>$x'$</td>
<td>$x$</td>
<td></td>
</tr>
<tr>
<td>Northing $N'$</td>
<td>Latitude $\phi$</td>
<td>$y'$</td>
<td>$y$</td>
<td></td>
</tr>
<tr>
<td>Height $h$</td>
<td>Height $h$</td>
<td>$z'$</td>
<td>$z$</td>
<td></td>
</tr>
<tr>
<td>Point</td>
<td>($P_E$, $P_N$, $P_h$)</td>
<td>($P_{\lambda}$, $P_{\phi}$, $P_h$)</td>
<td>($P_x'$, $P_y'$, $P_z'$)</td>
<td>($P_x$, $P_y$, $P_z$)</td>
</tr>
<tr>
<td>Examples</td>
<td>Swiss Oblique Mercator</td>
<td>Swiss lat/long (Bessel ellipsoid)</td>
<td>Bessel</td>
<td>WGS84</td>
</tr>
<tr>
<td></td>
<td>UTM Zone 32</td>
<td>WGS84 lat/long</td>
<td>WGS84 (no datum shift: local=global)</td>
<td>WGS84</td>
</tr>
</tbody>
</table>

Global ellipsoid-based Cartesian coordinates can be expressed either in Earth-Centred-Rotating (ECR) convention, or Earth-Centred-Inertial (ECI). Inertial is meant here in the sense that the frame of reference is not subject to accelerations (e.g. rotation): its frame is fixed with respect to the stars. The Cartesian coordinates of a point ($P_x$, $P_y$, $P_z$) derived from a DEM position are expressed more easily in the same Earth-Centred-Earth-Fixed (ECEF) coordinate system used also for satellite state vectors.

Given that both are expressed in the same ECR reference frame, it is relatively straightforward to use ($P_x$, $P_y$, $P_z$) during geolocation to determine the position of the satellite ($S_x$, $S_y$, $S_z$) corresponding to the Doppler annotation convention of the product. The details of that calculation are provided in section 4.6.

4.3 Orbital State Vectors

To achieve high geolocation accuracy, one must employ range-Doppler geocoding. For this, a set of highly accurate state vectors is required to enable straightforward tiepoint-free geolocation.

4.3.1 State Vector Input

Given a range-Doppler geocoding approach, the algorithm requires either satellite state vectors from the S-1 product annotations (see Table 5), or alternatively, values read from an external state vector product. The source (and therefore quality) of the state vectors included in the product annotations is itself annotated in the product. Validation experience has shown that restituted (AUX_RESORB) and precise (AUX_POEORB) state vectors generally produce geolocation results with comparably high quality.

The three different external state vector product types are summarised in Table 9, in order of increasing quality.
The S-1 product annotations usually provide state vectors spaced 10 seconds apart, typically distributed from ~1 minute before the image’s start (first line) to ~2 minutes after the image’s stop (last line) time. The external restituted and precise state vector files (RESORB or POEORB) also provide positions and velocities with 10 second sampling, but typically cover periods spanning several hours before and after the SAR product itself, permitting more sophisticated interpolation. Users may inspect the manifest.safe file delivered with an S-1 product to find out which state vector quality was used during product generation. The file should contain a “resource” string with a “name” attribute containing an AUX_RESORB file name (or AUX_POEORB, in rare cases), indicating the file used during processing. The geolocation quality difference between AUX_RESORB and AUX_POEORB is known to generally be < 3 cm, making RESORB sufficient for most geolocation requirements.

### 4.3.2 State Vector Initialisation and Timing

To expedite processing later, one can define a look-up table to hold the satellite position \((S_x, S_y, S_z)\) and velocity \((V_x, V_y, V_z)\) corresponding to each azimuth line. The positions must be interpolated from the sparser product annotation values or the external state vector file positions. Performing the interpolation once during this initialisation step speeds up the geocoding process later. B-Spline, Hermite, and Lagrange polynomial based interpolation schemes [6] [8] [24] (as well as the freely available S-1 EO CFI software [7]) use available position and velocity data points to model \((S_x, S_y, S_z)\) and \((V_x, V_y, V_z)\) at instances in time between the available state vectors. Each method has yielded acceptable results; in non-sparse short-arc cases, a simple polynomial fit (without consideration of the velocities) can also suffice.

The time corresponding to each azimuth line \((\forall j: 0…\text{Height}_{az}-1)\) is calculated as:

\[
t_j = AzLineTime = AzTimeFirst_{ML} + (j - 1) \cdot \text{LineTimeInterval}_{ML} \tag{13}
\]

where \(j\) denotes the image line in question. When \(L_{az} = \text{Height}_{az} - 1\) is the last line in the input image, with \(j\) varying from 0 to \(L_{az}\), the look-up table is constructed as follows:

\[
\tilde{S}_0 = (S_x(t_0), S_y(t_0), S_z(t_0)) \ldots \quad \tilde{S}_j = (S_x(t_j), S_y(t_j), S_z(t_j)) \ldots \quad \tilde{S}_{L_{az}} = (S_x(t_{L_{az}}), S_y(t_{L_{az}}), S_z(t_{L_{az}})) \tag{14}
\]

The values in this look-up table are used later during raster geocoding. Rather than recalculating them repeatedly within a raster geocoding algorithm, tabulating them as a look-up table during an initialisation step can speed up the geolocation performed later.

### 4.4 RADAR Geometry Image Input

The input file annotations are ingested, memory is allocated to hold the binary image, and the input dataset is read into the array. Alternately, the input raster file may be accessed on disk without first ingesting the entire raster. Depending on the map projection selected and location under investigation on the Earth, the relative

<table>
<thead>
<tr>
<th>Name</th>
<th>File Prefix</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>AUX_ORBPRE</td>
<td>Flight-segment Predicted Orbit (lowest quality)</td>
</tr>
<tr>
<td>Restituted</td>
<td>AUX_RESORB</td>
<td>Flight-segment Restituted Orbit (near-real time; typically available approx. 3 hours after acquisition)</td>
</tr>
<tr>
<td>Precise</td>
<td>AUX_POEORB</td>
<td>Precise orbit, typically available 3 weeks after acquisition</td>
</tr>
</tbody>
</table>

Table 9: External Sentinel-1 State Vector Product Types
orientations of the radar image and the map projection axes can vary from being nearly parallel (e.g. UTM near equator) to oblique or perpendicular (e.g. for some polar stereographic projections near the poles).

4.5 Orthorectification / DEM Traversal

DEM traversal refers to two loops within the geocoding algorithm, moving between a minimum and maximum northing (or latitude) coordinate, and at each of those DEM “lines” between a minimum and maximum easting (or longitude) coordinate “column”. The DEM boundaries are generally either (a) set by the user at run-time, or (b) set to “enclosing” values determined from the scene’s corner latitude and longitude corner coordinates. The latitude and longitude of the corners (the earliest and latest latitude and longitude values in range and azimuth provided within the geolocationGridPointList of the XML annotation files) can be converted into the DEM’s cartographic reference system to provide useful default values. That yields minimum and maximum northing values $N_0$ and $N_1$, as well as minimum and maximum easting values $E_0$ and $E_1$. Their values should be regularised to be exact integer sample multiples of the DEM’s reference sample centres. One can loop within the subset of a DEM file delineated by those values and output the resampled SAR backscatter measurements in the DEM’s map geometry.

One can choose the proper order of DEM traversal to allow simultaneous computation of the occurrence of local layover or radar shadow [11], but that is beyond the scope of this document.

Given a DEM defined between $E_{D0}$ and $E_{D1}$ in easting and $N_{D0}$ and $N_{D1}$ in northing, with sample intervals of $\Delta N$ (northing) and $\Delta E$ (easting), the DEM raster index of the point $(E, N)$ is for easting:

$$I_E = (E - E_{D0}) \div \Delta E$$

For the typical maximum northing at beginning of file convention, the northing DEM raster index is:

$$I_N = (N_{D1} - N) \div \Delta N$$

The number of range samples (i.e. width) of the output GTC image generated for the box delineated between $N_0$ and $N_1$, and $E_0$ and $E_1$ is:

$$Width_{GTC} = (E_1 - E_0) \div \Delta E + 1$$

Similarly in the northing dimension:

$$Height_{GTC} = (N_1 - N_0) \div \Delta N + 1$$

The DEM resolution in planimetry, as specified by $\Delta E$ and $\Delta N$, should be greater than or equal to the nominal ground resolution of the multi-looked image being geocoded. Complying with that requirement ensures that loss of image fidelity through the geocoding/resampling process is kept to a minimum. If only a poorly-resolved DEM is available, then depending on the user’s needs, either (a) the DEM should be oversampled to increase the ground sampling rate (of course the resolution remains unaltered), or (b) the input radar image should be multi-looked to a resolution more compatible with the DEM available. Choice (a) is generally implemented as a pre-processing step, as that type of processing falls outside the primary scope of a SAR geocoding software package. Choice (b) can be appropriate if the user is interested in using multi-looking to reduce the noise present in the radar image content or cutting the required processing time.

In an orthorectification procedure that employs “backward geocoding”, the range and azimuth image indices are retrieved for each DEM grid point (northing, easting). The reverse procedure “forward geocoding” takes a slant range and azimuth time as input and uses the same geolocation equations to determine a map geometry (northing, easting, height) coordinate that is compatible with the input radar geometry coordinates. Image product geocoding is best done using a “backward” technique – the remainder of this section therefore concentrates exclusively on the “backward geocoding” methodology.
After geolocation, once the range and azimuth indices are determined, a value is extracted from the input image content using the user-selected resampling kernel, and output in the DEM’s map geometry. The process of geolocation followed by resampling is illustrated in Figure 2. The details of how the range and azimuth raster indices are retrieved, and how those are used during resampling are discussed in the following sections. The next section gives a broad overview of the orthorectification procedure by reviewing the “backward geocoding” algorithm used in image geocoding, whereby the DEM is traversed along casting and northing axes.

Figure 2: SAR Image Orthorectification via Backward Geocoding

The orthorectification procedure (DEM traversal) proceeds as shown in the following pseudocode:

Initialise azimuth time look-up table $S_t = AzLineTime[0...Height_{azr}-1]$

Read available state vector information $(S_x, S_y, S_z)$ & $(V_x, V_y, V_z)$

Initialise azimuth satellite position and velocity look-up tables: interpolate $(S_x, S_y, S_z)$ & $(V_x, V_y, V_z)$ to generate $S1\_pos[0...Height_{azr}-1]$ and $S1\_vel[0...Height_{azr}-1]$

for $(N = N_1$ to $N_0$ step $-\Delta N)$

Update raster index $I_N$

Initialise line buffer to hold values for DEM positions from $E_0$ to $E_1$

for $(E = E_0$ to $E_1$ step $\Delta E)$

Update raster index $I_E$

Retrieve local height $h$ from DEM at index position $(I_E, I_N)$

Convert map coordinate $(P_E, P_N, P_h)$ to global geographic $P_{lat, lon, h}$ system
Convert map coordinate \((P_E, P_N, P_h)\) to global Cartesian \((P_x, P_y, P_z)\) system

Point geolocation (see devoted section for more detail):

If (RD geolocation active) then

\[ \text{Determine spacecraft position within } S1\_pos \text{ LUT fulfilling Doppler condition with point } (P_x, P_y, P_z) \]

Endif

Resample: retrieve radar geometry image content \(\sigma\) at coordinates \((I_r, I_s)\)

\[ \text{Place retrieved content } \sigma \text{ in current line buffer using index } (I_E, I_N) \]

end for

Write line buffer for current DEM line

end for

Write header information annotating complete GTC image produced

4.6 Geophysical fine perturbations on the target position

When performing accurate geolocation for a single target on the Earth's surface such as a corner reflector or an image product sample, certain influences on its position may need to be modelled and corrected. While a detailed description of these influences is beyond the scope of this document, they have been described in the literature. Below, we briefly describe the most important geophysical effects that may influence geolocation accuracy estimates for targets imaged by spaceborne SAR.

4.6.1 Atmospheric path delay (APD)

Radar pulses emitted by spaceborne SAR travel through the troposphere and ionosphere, and therefore do not travel at the speed of light in a vacuum. The ionosphere and troposphere slow down the pulses somewhat, resulting in delayed echo travel time, compared with a vacuum assumption. The total delay is referred to as the atmospheric path delay (APD). Not accounting for it can cause 1-way slant range errors (overestimates) between 3-4 m. For S-1, this is on the order of ~1-2 samples (depending on mode and product type). It represents the largest “fine” perturbation, and hindrance to accurate range geolocation.

Compensating the APD requires atmospheric modelling, which may be calibrated using near-real-time meteorological data for best results. However, even the use of a “nominal” model (dependent only on the time of year and the target latitude/longitude) provides great benefit. More information on this correction is provided in [1] and [17].

4.6.2 GPS reference frame shift caused by plate tectonics

For point targets that have been surveyed using DGPS, it is important to be able to transform the measured coordinates into the same geodetic reference frame used to define the sensor positions. For S-1, the International Terrestrial Reference Frame (ITRF) is used at a particular epoch. Surveyed GPS coordinates are generally provided in a local reference frame, which move with the particular continental plate in which it is embedded. It is generally not possible to transform the surveyed coordinates into the ITRF used by the SAR sensor without estimating the tectonically-induced offset between the frames.
Range Doppler

The most accurate geolocation algorithm solves the Doppler and range equations to determine the range and Doppler. Then its DEM index coordinates (x, y, z) are already known: Ix and Iy must now be obtained.

4.6.3 Solid Earth Tide (SET)

The gravitational influence of the moon and the sun controls not only the marine tides; it also has an effect on the solid planetary land masses. The position of an arbitrary target on the ground is therefore constantly changing, as the land mass it is sitting on is pushed and pulled both laterally and vertically according to changing relative solar and lunar positions throughout the day and month. This effect is called the solid Earth tide (SET). The deviations are generally at the ~cm level, but may reach up to ~50 cm near the equator. Fortunately, the perturbations are quite simple to model accurately, and doing so permits the reference target position to be updated in time.

Please consult [1] and [14] for a more detailed description of this effect. Reference [1] describes additional geodynamic perturbations similar to the SET that are of lesser magnitude, but these may also be of interest.

4.7 Point Geolocation

This section describes an algorithm for a single point (Px, Py, Pz), which could be either one of many within a greater DEM traversal algorithm (described in section 4.5), or just a single point (e.g. corner reflector) being used to validate a product’s geometry. The algorithm described here is called “range-Doppler”. It is used to retrieve the image indices within the S-1 product under study (Ix and Iy) that correspond to the input point (Px, Py, Pz) known to exist on the Earth’s surface. If the point is being geocoded within a DEM traversal, then its DEM index coordinates (Ix and Iy) are already known: Ix and Iy, must now be obtained.

4.7.1 Range-Doppler (RD) Geolocation

The most accurate geolocation algorithm solves the Doppler and range equations to determine the range and azimuth positions corresponding to the position (Px, Py, Pz) on the Earth.

Range Doppler (RD) geocoding for S-1 proceeds as follows:

Read state vector information (Sx, Sy, Sz) & (Vx, Vy, Vz) in ECR global Cartesian reference

Initialise azimuth satellite position and velocity look-up tables for an S-1 product: interpolate (Sx, Sy, Sz) & (Vx, Vy, Vz) to generate S1_pos[0...Heightar-1] and S1_vel[0...Heightar-1]

Read Earth terrain location: point (Px, Py, Pz) in global Cartesian reference

Determine the azimuth time T of an S-1 position corresponding to the Zero-Doppler condition

Given T: now calculate the slant range distance as \( R(T) = |S(T) - P| \)

Use knowledge of slant range to determine local bistatic bias – calculate corrected azimuth time \( T_s = T + R(T)^2/c \)

Given \( T_s \): calculate updated the slant range distance as \( R(T_s) = |S(T_s) - P| \)

If the product in question is in a ground range projection

Transform the slant range \( R \) to ground range \( G \)
Use the azimuth time $T_c$ to retrieve the azimuth image index value $I_a$

Use the slant or ground range distance (as appropriate) to retrieve the range image index $I_r$

Return the obtained values $I_a$ and $I_r$

Individual steps within the algorithm listed above are detailed in the following subsections.

**Azimuth Timing: Azimuth Index Computation**

For a point $P$ on the Earth’s surface, the following steps are performed:

If not already available, the native map geometry position $(P_x, P_N, P_h)$ is converted into global Cartesian coordinates $(P_x, P_y, P_z)$.

The orbit-position look-up table is searched (iteratively [11] or via bisection [13]), beginning at the most recent position, and the Doppler frequency corresponding to each position is calculated until a value greater than the expected zero reference is found (illustrated in Figure 3 by the red and blue dotted lines). As the search through positions $S_{-2}, S_{-1}, S_1,$ and $S_{+2}$ advances, two values are always retained in memory: the last Doppler that was lower than zero ($S_{-1}$), and the first one found to be greater ($S_{+1}$).

The Doppler frequency is a function of the sensor position $S$ for a given Earth position $(P_x, P_y, P_z)$:

$$f_D(t) = -\frac{2}{\lambda} \left[ \left( v_p(t) - v_S \right) \cdot \left( \frac{\vec{P} - \vec{S}(t)}{\vert \vec{P} - \vec{S}(t) \vert} \right) \right]$$

where

- $f_D(t)$ = Doppler frequency at time $t$
- $\lambda$ = wavelength of radar carrier frequency
- $v_S(t)$ = velocity of the sensor at time $t$
- $v_p$ = velocity of the Earth position $P$
- $\vec{P}$ = $(P_x, P_y, P_z)$, the position on the Earth
- $\vec{S}(t)$ = $(S_x(t), S_y(t), S_z(t))$, the position of the sensor at time $t$
- $t$ = azimuth (slow) time of sensor position

The velocity of $P$ depends on its location on the surface of the Earth, which has a rotational velocity $\vec{\omega}_E$:

$$\vec{v}_P = \vec{\omega}_E \times \vec{P}$$

Since the spacecraft positions are defined for an Earth-centred rotating (ECR) coordinate system where $\vec{\omega}_E \equiv \vec{0}$, we have
\[ \overrightarrow{v_p} = 0 \]  

(21)

The problem at hand is the determination of the appropriate azimuth time that results in a zero Doppler value.

For single points, a bisection algorithm such as Brent’s method [13] is an appropriate solution. In a raster geocoding context with many repeated similar but slightly varying computations, search through a look-up table may be more efficient.

The following algorithm implements such a search:

(Initialise spacecraft position look-up table if not already done in a previous step)

Read Earth surface location \((P_x, P_y, P_z)\) to be geolocated

Initialise azimuth LUT index \(j\) to zero (or keep at previous value if already set in a prior run)

\[ \text{NegDoppFound} \leftarrow \text{FALSE} \]

\[ \text{PosDoppFound} \leftarrow \text{FALSE} \]

\[
\textbf{while} \ (\neg \text{NegDoppFound} \text{ and } \neg \text{PosDoppFound} \text{ and } (j < j\text{Max}))
\]

\[ \text{Calculate } f_D \text{ between } (P_x, P_y, P_z) \text{ and spacecraft position } (S_x, S_y, S_z): S(j) \]

\[ \text{If } (f_D < 0) \text{ then} \]

\[ \text{NegDoppFound } \leftarrow \text{TRUE} \]

\[ \text{Endif} \]

\[ \text{If } (f_D \geq 0) \text{ then} \]

\[ \text{PosDoppFound } \leftarrow \text{TRUE} \]

\[ \text{Endif} \]

Increment azimuth index: \(j \leftarrow j + 1\)

\[ \textbf{endwhile} \]

Note relevant indices:

\[ AzZDT_{\text{neg}} \leftarrow j-1 \]

\[ AzZDT_{\text{pos}} \leftarrow j \]

Use linear interpolation to determine fractional index value \(f_j\) corresponding to actual \(f_D=0\)
Return fractional index value $f_j$ describing azimuth index and ZDT time when point $P$ was imaged.

Linear interpolation between the Doppler values at $S_{-1}$ and $S_{+1}$ yields an estimate of the sensor position $(S_x, S_y, S_z)$ corresponding to zero Doppler.

The azimuth time $t$ relative to the scene start $t_0$ is now also available, enabling calculation of the azimuth index:

$$I_a(t_D) = \frac{(t_D - t_0)}{\delta_t}$$  \hspace{1cm} (22)

where

$I_a(t_D) = \text{azimuth image index at time } t_D$

$t_D = \text{azimuth time satisfying Doppler condition}$

$t_0 = \text{azimuth start time } (AzTimeFirst_{ML})$

$\delta_t = \text{azimuth sample interval in time } (LineTimeInterval_{ML})$

**Figure 3:** Determining the sensor position (and time) when a given point was imaged

**Slant Range Index Computation**

The slant range $R(t_D)$ between $S(t_D)$ and $P$ at time $t_D$ is calculated as follows:

$$R(t) = \left| P - S(t_D) \right| = \sqrt{(P_x - S_x(t_D))^2 + (P_y - S_y(t_D))^2 + (P_z - S_z(t_D))^2}$$  \hspace{1cm} (23)
For slant range images (SM SLC, IW/EW SLC mosaic), the range index for the input image at time $t_D$ is calculated as:

$$I_r(P) = \frac{(R(t_D) - r_0)}{\delta_r}$$

(24)

where

- $I_r(P)$ = range image index for point $P$
- $R(t_D)$ = slant range satisfying Doppler condition
- $r_0$ = near range ($FastTimeNear_{ML}$ converted from time to distance)
- $\delta_r$ = range pixel spacing ($RgSpacing_{ML}$)

### 4.7.2 “Bistatic” Azimuth Bias Correction

SAR processors often advertise their level 1 output product as annotated with a Zero-Doppler time convention - geolocation algorithms then set the reference Doppler to zero to determine the azimuth coordinate of a given location on the Earth. However, it is important to pay attention to small nuances behind the meaning of that term.

The SAR processing in some cases does not truly annotate in a Zero-Doppler convention, as the distance that the satellite moved between pulse transmission and reception is in some processors not considered in the calculation. In the case of the S-1 Instrument Processing Facility (IPF), a correction is generally made by the processor. However, it is not guaranteed. A flag is annotated that specifies whether or not the correction was performed during product generation: in any of the XML annotation files delivered as part of a product, the keyword $bistaticDelayCorrectionApplied$ is set to true or false. If it is true, then the “residual” correction described in the next section was applied, and this needs to be taken into account. Table 10 provides an overview of the azimuth timing conventions used by the S-1 products, with ESA’s older ENVISAT ASAR SLC products listed alongside for comparison.

During SAR image focusing, the S-1 processor transforms the image matrix to “Zero-Doppler”, shifting each echo receive time to Zero-Doppler time. However, the time interval between S-1 pulse transmission and echo reception is not necessarily compensated. That interval is not Doppler-dependent - its extent depends on the swath imaged (affecting the slant range “fast” time), and can be understood as a “leakage” of range fast time into azimuth slow time. The issue is strictly an annotation convention, and can be easily compensated in post-processing during geolocation. Considering an ideal zero-Doppler case, the azimuth “bistatic” effect is illustrated in Figure 4. The relationship between slant range distance $r_i$ and slant range “fast” time $t_i$ is:

$$t_i^{range} = \frac{2 \cdot r_i}{c}$$

(25)

where $c$ is the speed of light. The slant range “fast” time corresponds to the time interval between pulse transmission and echo reception. To translate between time annotation conventions, the receive time is retrieved from Zero-Doppler time by adding half of the slant range “fast” time:

$$t_i^{receive} = t_i^{Zero-Doppler} + \frac{1}{2} \cdot t_i^{range}$$

(26)
Figure 4: Azimuth “Bistatic” Effect in idealised Zero-Doppler Case

Table 10: Azimuth timing conventions in ASAR and Sentinel-1 SLC products

<table>
<thead>
<tr>
<th>Sensor</th>
<th>“Bistatic” correction made for reference-range position</th>
<th>“Residual” bistatic correction made (section 4.7.3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENVISAT ASAR</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Sentinel-1A/B</td>
<td>Yes (1)</td>
<td>No (2)</td>
</tr>
</tbody>
</table>

(1) If bistaticDelayCorrectionApplied set to true in XML annotations. Note that for TOPS mode products (IW and EW), the reference-range position refers to the central swath (IW2 or EW3) mid-point between the sub-swath’s near and far range.

(2) Option exists in S-1 IPF, but is nominally not active

Once that correction is applied during geocoding, the location-dependent azimuth time shift may be calculated and compensated. Geolocation and geocoding proceeds otherwise normally. Comparisons of geolocation accuracies achieved with and without this compensation are presented in [17]. Note that the bias is larger at longer ranges (e.g. stripmap beam S6 or IW subswath 3) than shorter, also for different ranges within the swath of a single product. For that reason, the correction cannot be applied en bloc as a rigid shift. Due to its inherent geometry-dependency, it must instead be applied during geolocation.

Concerning the azimuth Doppler time solution \( t_D \), we add the correction factor to produce an azimuth time \( t_{Dc} \) that has been corrected for the “bistatic” effect:

\[
 t_{Dc} = t_D + \frac{1}{2} \cdot t_i^{\text{range}}
\]

The corrected azimuth raster index value is then:

\[
 I_a(t_{Dc}) = \frac{(t_{Dc} - t_0)}{\delta_i}
\]

where

\[
 I_a(t_{Dc}) = \text{azimuth image index at time } t_{Dc} \\
 t_{Dc} = \text{azimuth time satisfying Doppler condition corrected for bistatic bias}
\]
\[ t_0 = \text{azimuth start time (AzTimeFirstML)} \]
\[ \delta = \text{azimuth sample interval in time (LineTimeIntervalML)} \]

After correction for the “bistatic” effect, for slant range images (SM, IW and EW SLC products) the range index for the input image at the corrected azimuth time \( t_{dc} \) is calculated from \( R(t_{dc}) \) as:

\[ I_r(P) = \frac{(R(t_{dc}) - r_0)}{\delta_r} \]  
(28)

where

- \( I_r(P) \) = range image index for point \( P \)
- \( R(t_{dc}) \) = slant range at corrected azimuth time \( t_{dc} \)
- \( r_0 \) = near range (\( \text{FastTimeNearML} \) converted from time to distance)
- \( \delta_r \) = range pixel spacing (\( \text{RgSpacingML} \))

### 4.7.3 “Bistatic Residual” Azimuth Bias Correction

Given that the S-1 IPF has already implemented a nominal correction to the azimuth timing based on a near-range assumption (as of this writing, all tested products generated with IPF v2.91 have been observed to make this correction), then only a “residual” bistatic correction needs to be applied for a given target. The situation depicted in Figure 4 is only strictly correct for the point target shown. The bistatic correction is range dependent: if the target is situated closer to the sensor in Figure 4, the difference between the transmitted and received pulses decreases slightly. The converse is true for targets situated further from the sensor. However, only one azimuth zero Doppler time is recorded for a given line: the S-1 processor currently operates on a near-range assumption: a bistatic correction corresponding to the near-range sample is assumed (or the near-range sample of the central swath, IW2 or EW3, in the case of TOPS products). Thus, the default S-1 correction needs to be adjusted according to the target offset from the reference near-range sample. This is called the “bistatic residual correction,” described in more detail in [17].

Since v2.84 of the S-1 IPF, an optional, more complete azimuth timing correction is available. The updated processor includes a fuller bistatic residual correction in the form of an updated focusing algorithm. This can be used to ensure that each range line does in fact correspond to a single zero-Doppler time. However, it breaks with previous convention, and would complicate cross-convention interferogram generation, so it may not be implemented in the standard processing chain. At the time of this writing, the option is not activated by default; it must be explicitly set by the IPF operator.

### 4.7.4 Instrument Timing Correction

SAR instruments need to associate a time stamp with each received echo to identify its along-track position. The choice of which precise event to use within the pulse transmit-receive window depends on the processor convention. In the case of the S-1 IPF, the line time tag recorded by the instrument corresponds to the start of the transmission and needs to be adjusted to correspond to that of the first received sample. As the time of the first received sample is required for accurate geolocation, the annotated line time needs to be corrected by this amount - which is equal to the sampling window start time (SWST). Failing to do so can result in systematic, swath-dependent azimuth biases of up to ~1 m. The SWST varies along the orbit and is also swath dependent, as reflected in the product annotations. The improved azimuth ALE achievable with this correction was first demonstrated in [12].
4.7.5  Burst-Position Dependent Timing Corrections (TOPS Mode)

For TOPS products, the S-1 IPF fundamentally operates at the level of a single burst (an IW SLC product typically consists of 10 bursts per subswath). It makes assumptions about the topography and squint angle that do not apply equally to all samples within the burst. These simplifications permit more efficient processing and do not introduce geometrical errors large enough to be of general concern. However, when estimating product geolocation quality at the cm level, then such effects need to be compensated in an attempt to gain better insight into the intrinsic system accuracy.

Two effects (and corresponding corrections) that depend, at least in part, on the burst-level behaviour of the S-1 IPF are described briefly below.

**Intra-pulse motion correction (range bias)**

The Doppler frequency of a target varies along track (azimuth) even within a burst, whereas the burst-level processor assumes a single frequency for the duration of the burst. As a result, a range bias will be introduced for a given target that depends on its along-track offset from the burst centre. For IW products, this effect may cause azimuth geolocation errors up to ~0.5 m in either direction. The effect is described further in [12] and [14].

**Topography-dependent DC correction (azimuth bias)**

Another approximation made by the S-1 IPF is that of a constant terrain height within a burst (obtained with the help of a coarse digital terrain model). The height difference between a given target and the processed burst height causes the target's Doppler rate to vary more or less quickly than assumed by the IPF – depending on its azimuth position in the burst (offset from the burst centre). Targets near the burst edges (corresponding to a large squint) and with significant height differences can introduce azimuth location errors up to ~1 m or more for IW mode products. Detailed descriptions of this effect are available in [12] and [14].

4.7.6  Ground Range Index Computation (when necessary)

In the case of ground range imagery with multiple slant/ground range polynomials references (all GRD products), the neighbouring azimuth references are first determined, yielding two slant/ground range polynomials.

The ground to slant reference found to be valid **previous** to the current azimuth line is called \( GTS_p(t_p) \) (P for “previous”), where \( t_p \leq t_j \).

The ground to slant reference found to be valid **after** the current azimuth line is called \( GTS_N(t_N) \) (N for “next”), where \( t_N > t_j \).

The known slant range position \( r \) is transformed using the references into a ground range solution as:

\[
g_p = GTS_p^{-1}(r)
\]  \hspace{1cm} (29)

and similarly also using the second reference as:

\[
g_N = GTS_N^{-1}(r)
\]  \hspace{1cm} (30)

The ground range value valid at time \( t_j \) is then calculated using linear interpolation as:

\[
g = g_p + \frac{g_N - g_p}{t_N - t_p} (t_j - t_p)
\]  \hspace{1cm} (31)
For ground range images (all GRD products), the range index for the input image at time $t$ is calculated as:

$$I_r(P) = \frac{(g - GR_0)}{\delta g}$$  \hspace{1cm} (32)

where

- $I_r(P)$ = range image index for point $P$
- $g$ = ground range solution corresponding to point $P$
- $GR_0$ = ground range reference
- $\delta g$ = ground range sampling interval

As a test of the above (or any) algorithm to deal with the sliding definition of ground range with multiple updates along the azimuth dimension, it can be useful to terrain-geocode two S-1 products and overlay the results. If both products were generated from similar geometries, then any shifts noted between the two terrain-geocoded GTC products are likely caused by systematic influences within the SAR focussing & geocoding processing chain. No relative shift indicates that the software is performing correctly. Such an overlay test is therefore recommended before certifying a processor to be capable of accurately geocoding S-1 GRD products.

An example of such an overlay for two S-1 image acquisitions over Switzerland is shown in Figure 5. In the example, two terrain-geocoded ground-range products from the IW and EW modes were combined using an RGB overlay. The overlapping region shows no obvious colour fringes, indicating a good geolocation quality for both products.
4.7.7 Resampling

The above sections describe how the azimuth and range indices of the input radar geometry image are derived via geolocation for a point on the Earth’s surface $P$. Now that those indices are known, that point in the image may be resampled from radar geometry into the map geometry in question. An appropriate resampling method, such as nearest-neighbour, bilinear, or clipped cubic convolution may be employed for this purpose.

Nearest neighbour resampling proceeds by rounding the range and azimuth coordinate values to the nearest integer value, and transferring the radar image content from that location:

$$NI_r = \text{int} \left( I_r + 0.5 \right)$$

$$NI_a = \text{int} \left( I_a + 0.5 \right)$$

$$\sigma_{E,N} = \sigma \left( NI_r, NI_a \right)$$
In bilinear resampling, the four neighbouring values surrounding the (fractional) coordinate \((I_r, I_a)\) contribute to the estimate made for that location. The neighbouring grid points are identified:

\[
\begin{align*}
I_r^0 &= \text{(int)} (I_r) \\
I_r^1 &= I_r^0 + 1 \\
I_a^0 &= \text{(int)} (I_a) \\
I_a^1 &= I_a^0 + 1
\end{align*}
\]

Linear weights scaled from zero to one encapsulate the distance to each neighbouring “corner”:

\[
\begin{align*}
W_r &= I_r - I_r^0 \\
W_a &= I_a - I_a^0 \\
CW_r &= 1 - W_r \\
CW_a &= 1 - W_a
\end{align*}
\]

By applying the weights, the bilinear resampling image content estimate is made:

\[
\begin{align*}
\sigma_{EN} &= CW_r \cdot CW_a \cdot \sigma(I_r^0, I_a^0) + W_r \cdot CW_a \cdot \sigma(I_r^1, I_a^0) + \\
&\quad CW_r \cdot W_a \cdot \sigma(I_r^0, I_a^1) + W_r \cdot W_a \cdot \sigma(I_r^1, I_a^1)
\end{align*}
\]

Once the image has been resampled for all desired points and written as output, the geocoding process has completed its task.

### 4.7.8 Calculation of Absolute Location Error (ALE)

Points within an image that can be readily identified can have their positions both predicted via geometry, producing image index coordinates \((I_r, I_a)\), as well as measured directly from the image \((M_r, M_a)\).

The absolute location error is defined as the difference between the retrieved measured and predicted coordinates. The range error \(\Delta r_s\) (in image product’s range samples) is:

\[
\Delta r_s = I_r - M_r
\]

Note that this error is expressed by default in ground range samples for ground range products, and slant range samples for slant range products. The ground range ALE values can be converted to slant range units to enable comparisons within a common reference.

Similarly in the azimuth dimension, the error \(\Delta a_s\) (in image product azimuth samples) is:

\[
\Delta a_s = I_a - M_a
\]

The errors can be expressed as distance in metres rather than samples, as:

\[
\begin{align*}
\Delta r_d &= \Delta r_s \cdot \text{RgSpacing} \\
\Delta a_d &= \Delta a_s \cdot \text{AzSpacing}
\end{align*}
\]

The absolute location error (ALE) incorporates the error in both dimensions as:

\[
ALE = \sqrt{\Delta r_d^2 + \Delta a_d^2}
\]

The S-1A/B instruments and the associated ground processing system have succeeded in providing open-data products with unprecedented geometric accuracy for a civilian spaceborne C-band SAR system. The best tests of systemic geometrical accuracy use the SM mode products, as these are closest to the radar’s native
geometry and maximise the azimuth resolution, enabling the retrieval of $M_e$ at the highest fidelity. Note however, that no significant systematic biases have been found between, for example, the SM SLC and GRD product types [17][18]. The same good correspondence was found between IW and EW SLC and GRD products.

Many tests have shown that the ALE is generally well within a product sample [17][18]. Larger errors may be expected in the along-track (azimuth) dimension than in the line-of-sight (range) dimension, owing largely to the coarser sampling in azimuth and other processing effects not related to the ranging itself.

4.7.9 Impact of Local Height Variations and Ellipsoid- vs. Terrain-Geocoding

The effect of height errors within a DEM or even complete ignorance of local height values (e.g. as is the case in ellipsoid-geocoded “GEC” products) on geolocation accuracy is a horizontal shift of a magnitude that depends on the incident angle of the location under study. Vertical errors in hypsometry (height measurement) induce horizontal errors in planimetry (location information) of the product output from the geocoder.

DEM height overestimations cause the radar slant range estimate to be lower than the correct value: the geocoder therefore incorrectly retrieves raster content from a location too close to the image’s near range edge. DEM height underestimations cause the radar slant range estimate to be higher than the correct value: the geocoder therefore incorrectly retrieves raster information from a location closer to the far range edge than appropriate. These kinds of planimetric shifts can apply locally within a DEM or globally at the scene level (e.g. for a flat image of the Netherlands that is ellipsoid-geocoded using an incorrect mean height).

4.7.10 Applicability of Corrections to S-1 Products

Position and timing corrections applied during post-processing may not a priori be applicable to all product modes/types. For example, atmospheric path delay for a reference target on the ground may be modelled and corrected for all products types and modes. However, timing corrections that depend on the target position relative to the burst boundaries cannot be corrected in GRD products, as the boundaries are not included in the product annotations. Another example is the bistatic “residual” correction, which requires knowledge of the target-specific beam or sub-swath range timing. For TOPS mode, this is only known for SLC (and not GRD) products. Table 11 provides an overview of the corrections and their applicability to level-1 products modes and types.

4.7.11 Sentinel-1 “Out-of-the-Box” vs. Precise Geolocation Accuracy

The geolocation algorithm presented in this document was initially a “bare-bones” algorithm assuming that S-1 products are to be geocoded “as delivered”, without additional post-processing connected to the range and azimuth timing. The geometric accuracy achieved this way is already very high (typically sub-sample), and sufficient for many applications – including time series analysis in the IW and EW modes. However, if one hopes to achieve the best possible geolocation, a number of small effects separately affecting the range and azimuth dimensions have proven to be necessary. These finer corrections are typically tested using trihedral corner reflectors deployed in the field with positions surveyed to mm-scale accuracy [1][2][10][12][19].

Implementations of corrections for atmospheric path delay (APD: see section 4.6.1) as well as solid Earth tides (SET: see section 4.6.3), geodetic frame shift (see section 4.6.2), and instrument/processor timing biases (see sections 4.7.3 and 4.7.4) have been documented and implemented (to varying degrees) at different research institutes. The most important effect that systematically introduces a range bias (typically ~3 m) is the atmospheric path delay, described in section 4.6.1 and, for example, in [17].

Figure 6 provides a helpful indication of “out-of-the-box” product geolocation accuracy, which is shown alongside more refined “post-processed ALE” equivalents. The “out-of-the-box” accuracies may be achieved by performing simple geolocation as described in this document directly on the delivered S-1 product.
Further corrections for APD, SET, and instrument timing corrections may be applied in post-processing, following the methods described in the sections above and literature cited. For the SM, IW and EW modes, the current “out-of-the-box” and “post-processed” estimates of the ALE for corresponding SLC product time series acquired over Swiss calibration test sites are shown in Figure 6. In Figure 6(a), (c) and (e) the “out-of-the-box” ALE is shown for products geocoded without further post-processing steps. The corresponding, “post-processed” ALE is shown to the right of these in each case. The largest improvements are due to the path delay correction and several azimuth timing corrections: (1) the “residual bistatic” correction (2) the “improved bulk bistatic” correction, (3) the instrument timing correction, (4) the processing-height-dependent Doppler centroid correction and (5) the intra-pulse motion correction. These effects are described in [12] and [14]. The bistatic residual correction was described in more detail in [17]. The axis limits show the same range of values along each dimension, even where the absolute biases differ.

The mean biases and standard deviations from the scatterplots in Figure 6 are listed in Table 12.

Table 11:  Applicability of geolocation corrections to level-1 Sentinel-1 products (N.B. some effects may influence geolocation even if they cannot be corrected in practice)

<table>
<thead>
<tr>
<th>Correction</th>
<th>Section(s) described</th>
<th>Dimension affected (rg, az)</th>
<th>Stripmap mode</th>
<th>TOPS mode</th>
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<td>Intra-pulse motion compensation</td>
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<td>x</td>
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<td>✓</td>
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<tr>
<td>Solid Earth Tide (SET)</td>
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<td>✓</td>
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<td>x</td>
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<td>Topography-dependent DC correction</td>
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<td>az</td>
<td>x</td>
<td>✓</td>
</tr>
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</table>

(1) This correction is performed by default in the operational S-1 IPF; however, it may be turned off by the IPF operators if needed
(2) This correction is not performed by default in the operational S-1 IPF; however, it may be turned on by the IPF operators if needed
Guide to S-1 Geocoding

(a) SM SLC “out-of-the-box” ALE

(b) SM SLC current refined ALE

(c) IW SLC “out-of-the-box” ALE

(d) IW SLC current refined ALE
Figure 6: ALE for SM, IW and EW mode products over Swiss test sites. (a), (c) and (e) show the “out-of-the-box” accuracy, whereas (b), (d) and (f) are the equivalent measurements after compensation for fine perturbations. The most important corrections added to achieve the higher accuracy in the right hand plots are the atmospheric path delay (affecting range geolocation by typically ~3 m), and timing offsets connected to limitations in the way the products are processed (affecting mainly the azimuth ALE, ~2 m overall).

The ALE scatterplots in Figure 6 were generated using S-1 acquisitions over two Swiss test sites operated by the University of Zurich, Switzerland. The reference targets were installed for sensor calibration and validation. For readers interested in validating their own ALE estimates, the use of data acquired over an established site with publicly available target positions is recommended. One such site exists in the Surat Basin west of Brisbane, Australia. It includes 40 corner reflectors spread over an area roughly 100 km on a side, installed by Geosciences Australia in November 2014. The Surat site is described in detail that includes the surveyed corner reflector coordinates in [9]. The two largest differences between this site and the two Swiss sites are the number of reflectors (40 in Australia vs. 4 in Switzerland) and the relatively flat topography in the Surat basin, compared with the hilly-to-mountainous terrain in the region surrounding the Swiss sites.

The University of Zurich has been collecting mainly IW SLC products over the Surat site in support of S-1 validation, as well as to enable comparison with the Swiss sites. The “out-of-the-box” and refined estimates of the IW SLC product ALE are shown in Figure 7 for the Surat site. The time series includes acquisitions on 71 dates over a span of nearly two years. As before, colour-coding indicates the sub-swath the reflector is in (IW1 or IW2 in this case). The offsets in the fully-corrected scatter agree quite well with the equivalent estimates in Figure 6(c). It is worth noting that the Swiss scatter includes estimates from 1.0 m and 1.2 m reflectors in Dübendorf, whereas the Surat reflectors were all 1.5 m or larger. This is the main reason for the larger spread (esp. azimuth) in Figure 6(c), as more measurement noise is introduced when estimating image positions for smaller targets [19], whose signatures are not as strong (having “lower contrast” targets).
Figure 7: ALE for IW SLC products over the Australian Surat test site: (a) “out-of-the-box” accuracy; (b) equivalent measurements after compensation for further fine perturbations. The most important corrections that led to the plot in (b) are the atmospheric path delay (affecting range geolocation by typically ~3 m), and azimuth timing effects connected to limitations in the way the products are processed (affecting mainly the azimuth ALE on the order of ~2 m overall).

Table 12: ALE estimates over Swiss time series for SM, IW and EW mode SLC products, with and without post-processing timing corrections. The left column represents typical “out-of-the-box” ALE that may be expected after applying the geolocation algorithm and corrections described in this document.
4.8 Output Annotations

Before geocoding begins, the parameters listed in Table 4 must be extracted from the S-1 product and deposited into data structures, permitting them to be accessed during initialisation and processing.

After geocoding is completed, it is useful for users to have parameters describing the geometry annotated with the output geocoded product.

Important output geometry parameters are listed Table 13. The corresponding names used in this document are shown, where applicable.
Table 13: Important output geometry parameters

<table>
<thead>
<tr>
<th>Name Used in this Document</th>
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<td>Semi-minor axis</td>
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<td>Scale Parameter</td>
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5 REFERENCES


