Surface Water and Ocean Topography (SWOT) Project

SWOT Product Description
Long Name: Level 1B KaRIn high rate single look complex data product
Short Name: L1B_HR_SLC

Revision B

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List of TBC Items

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List of TBD Items

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1 Introduction

1.1 Purpose

The purpose of this Product Description Document is to describe the Level 1B Ka-band Radar Interferometer (KaRIn) high rate (HR) single look complex (SLC) data product from the Surface Water Ocean Topography (SWOT) mission. This data product is also referenced by the short name L1B_HR_SLC.

1.2 Document Organization

Section 2 provides a general description of the product, including its purpose and latency.

Section 3 provides the structure of the product, including granule definition, file organization, spatial resolution, temporal and spatial organization of the content, the size and data volume.

Section 4 provides qualitative descriptions of the information provided in the product.

Section 5 provides a detailed identification of the individual fields within the L1B_HR_SLC product, including for example their units, size, coordinates, etc.

1.3 Document Conventions

When the specific names of data variables and groups of the data product are given in the body text of this document, they are usually represented in italicized text.

1.4 Citing This Document

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2 Product Description

2.1 Purpose

The L1B_HR_SLC product provides high rate (HR) single look complex (SLC) images in response to the SWOT project requirements described in [1]. At any time, only one of the two KaRIn antennas is transmitting while both are receiving. The two receiving KaRIn antennas each provide an SLC image after the downlinked data undergo synthetic aperture radar (SAR) processing. The pixel-wise product of the SLC image acquired by one antenna with the complex conjugate of the SLC image acquired by the other antenna gives an interferogram whose phase can be used to estimate water surface heights. Height reconstruction from the interferometric phase requires knowledge of the viewing geometry, which is described by other parts of the data product. Therefore, in addition to the two SLC images (one for each antenna), the L1B_HR_SLC product contains platform ephemeris and attitude information, instrument state and calibration information, instrument noise estimates, and the surface topography information assumed for SLC processing, all of which are used in downstream processing. In particular, this product provides:

1. SLC images of either the left or right swath of both receive antennas.
2. Radiometric calibration factors (X factors) on the same grid as the SLC images that can be applied to convert the SLC power to radar backscatter (sigma0).
3. Estimates of the additive noise.
4. The time varying parameters (TVP) of the images, which include synchronized platform parameters and radar parameters.
5. Local ground-range digital elevation model (GrDEM) spanning the image, giving the reference surface to which the differential phase between the two SLCs is flattened.

The L1B_HR_SLC product is generated using the algorithms that are provided in [2]. The L0B high-rate data frames downlinked from the SWOT KaRIn instrument are the instrument inputs to these algorithms. Data from the KaRIn HR mode are available mostly over land, as defined by the HR mask. The input includes data from each of the two KaRIn interferometric antennas for each of the half swaths to the left and right of nadir as well as platform ephemeris and attitude information. The SLC outputs for the left and right half swaths are given in different granules. This product is generated at the full horizontal resolution of the KaRIn HR downlink data; downstream products may use spatial averaging in order to improve height accuracy.

2.2 Latency

The L1B_HR_SLC product is generated with a latency of less than 45 days from data collection, in accordance with the SWOT project requirements provided in [1]. Versions of the L1B_HR_SLC product may be produced based on either Medium-accuracy Orbit Ephemeris (MOE) or Precise Orbit Ephemeris (POE) information of the spacecraft position and velocity, with the former enabling considerably shorter latencies.

3 Product Structure

3.1 Granule Definition

The L1B_HR_SLC product is organized into overlapping, swath-aligned tiles as described in [3]. Without overlap, each tile would be approximately 64 km long in along track and covers half of the SWOT swath (left or right) for about 64 km in cross track. With an additional 4 km on each end of the tile for overlap used by downstream product generation, the total along-track length of each SLC tile is approximately 72 km, as illustrated in Figure 1.

The SLC tile boundaries remain approximately fixed geographically, following a predefined swath-aligned system described in [3], although the precise boundaries depend on the particular spacecraft position and velocity and the KaRIn pulse timing when the data were collected. An SLC granule includes the full slant-range extent of the KaRIn radar echoes, thereby covering as much in the cross-track direction as is measured by the instrument, but the actual cross-track extent when the slant-range samples are projected onto the local ground surface will depend on the local topography and the spacecraft altitude.

The tile boundaries are defined by a set of ideal, geographically fixed reference tile boundaries (see [3]). These reference tiles are numbered sequentially by pass number in the ideal reference orbit repeat cycle, along-track tile number within the pass, and side (left or right). A pass here refers to half of an orbit from extreme south to extreme north latitudes or vice versa. Along-track tile numbers are numbered sequentially following the spacecraft flight direction, so the tile numbers increase from south to north for ascending passes and from north to south for descending passes. The left and right half swaths are defined relative to the spacecraft velocity vector.

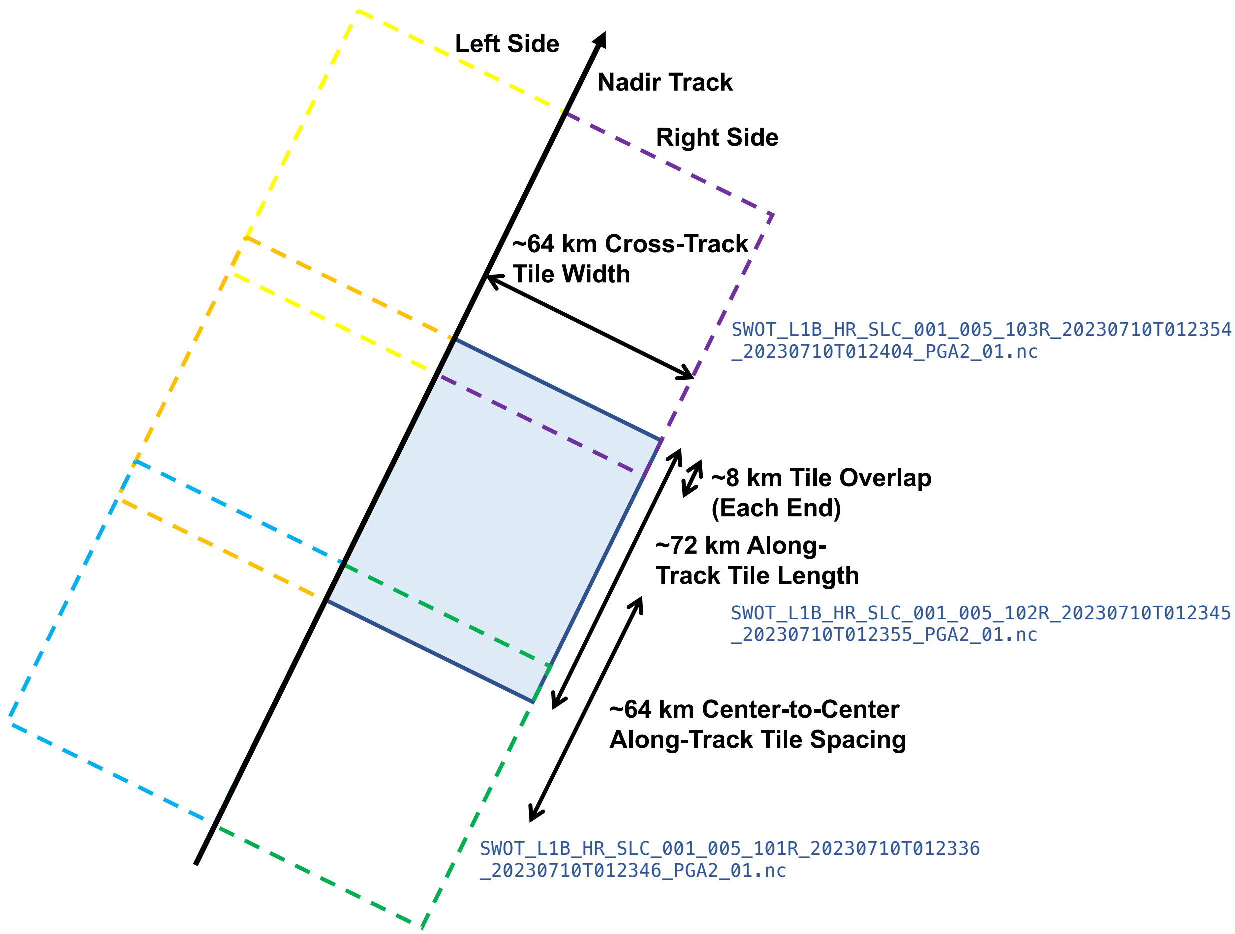

Figure 1. SLC product granulate illustration.

3.2 File Organization

The L1B_HR_SLC science data product adopts the NetCDF-4 file format. The product is provided as one single NetCDF file that has a section of global attributes and five groups of data: *slc*, *xfactor*, *noise*, *tvp*, and *grdem*.

Table 1. Description of file comprising the L1B_HR_SLC product.

File	Name	Description
1	Level 1B KaRIn high-rate single look complex data product.	Provides Level 1B SLC, X-factor, noise, TVP, and GrDEM data in separate NetCDF groups.

The *slc* group contains the two 2-D SLC images themselves. The *xfactor* group contains the two 2-D arrays of radiometric calibration (X factor) information for converting the power of each SLC to normalized radar cross section (NRCS) or sigma0. The *noise* group contains the 1-D arrays of radar noise estimates, which vary only in the along-track direction given the normalization of the data. These can be subtracted from the SLC power to better estimate sigma0. The *tvp* group contains the 1-D arrays of platform and radar parameters that vary with time (or equivalently with the along-track position of the spacecraft) rather than with location on the Earth surface. The *grdem* group contains the 2-D, swath-aligned ground-range digital elevation model (GrDEM) to which the SLC phase information is referenced, along with 1-D arrays of indexing information. A summary of the five groups of the L1B_HR_SLC product is provided in Table 2.

Table 2: Description of the NetCDF groups in the SLC product.

File	Group Name	Description
L1B_HR_SLC	*slc*	Single look complex images of either the left or right half swath of both left and right antennas for each tile. The image grid locations and the sensor illuminating positions are not explicitly saved, but can be reproduced from the other information in the product.
	xfactor	Radiometric calibration factors of either the left or right swath of both left and right antennas for each tile.
	noise	Noise estimate with number of pulses used to estimate the noise as a one-dimensional array for each SLC line.
	tvp	Provides synchronized time varying parameters of the platform and the radar.
	grdem	Local ground-range digital elevation model (GrDEM) calculated for the current tile based on the reference DEM used during SLC processing.

Fundamentally, SLC images are 2-D arrays of complex values, where a complex value is comprised of a real part and an imaginary part. Because there is no native type for a complex floating-point value in NetCDF-4, the 2-D arrays of complex values are represented in the L1B_HR_SLC product as 3-D arrays, where the third dimension has a depth of 2 for the real and imaginary parts (the real part is given first) of each complex value. That is, because the real and imaginary parts of array *arr* at indices *m* and *n* cannot be represented as *arr*[*m*][*n*].*real* and *arr*[*m*][*n*].*imag*, the real and imaginary parts are represented as *arr*[*m*][*n*][0] and *arr*[*m*][*n*][1], respectively.

3.3 File Naming Convention

The L1B_HR_SLC product adopts the following file naming convention:

SWOT_L1B_HR_SLC_<CycleID>_<PassID>_<TileID>[L/R]_<RangeBeginningDateTime>_ <RangeEndingDateTime>_<CRID>_<ProductCounter>.nc

The <CycleID>, <PassID>, and <TileID> identify the repeat cycle, pass, and tile of the data. The <RangeBeginningDateTime> and <RangeEndingDateTime> provide the UTC time range of data used to derive the data product. The <CRID> above contains the composite release identifier. It contains the version code of the data product, which changes if the processing software and/or auxiliary inputs are updated. The <ProductCounter> identifies the version of product that may have been generated multiple times with the same version of processing software.

An example filename is:

```
SWOT_L1B_HR_SLC_001_005_001L_20210612T072103_20210612T072113_PGA2_03.nc
```

3.4 Spatial Sampling and Resolution

In this document, the term "posting" refers to the spatial sampling of a horizontally gridded data set. The term "sampling" is used generically to refer to the manner or locations at which the data are discretized. One individual data value is called a sample. Samples from a 2-D spatial array are sometimes also called "pixels."

Following historical terminology in the synthetic aperture radar (SAR) community, rows of image samples with a common along-track or time index are called "lines" of pixels. The along-track and cross-track (or slant-range) dimensions of a 2-D array can therefore be characterized by the number of lines and the number of pixels per line, respectively. These are specified in the product by the *num_lines* and *num_pixels* dimensions as described in Table 12 and illustrated in Figure 2. Correspondingly, the term "pixel" is sometimes used in SWOT documents to indicate the cross-track or slant-range sample index within a line. The usage of the term "pixel" should be evident from context.

The KaRIn instrument implements an on-board presumming operation that filters and resamples the collected pulse echoes in the along-track dimension before the HR data are downlinked. Presumming reduces the Doppler bandwidth of the data, thereby reducing the downlink data volume at the expense of along-track resolution. The downlinked data are consequently sampled at a presummed rate that is lower than the pulse repetition frequency of the actual KaRIn transmit pulses. The finest-possible along-track resolution of KaRIn HR data is approximately 3 m.

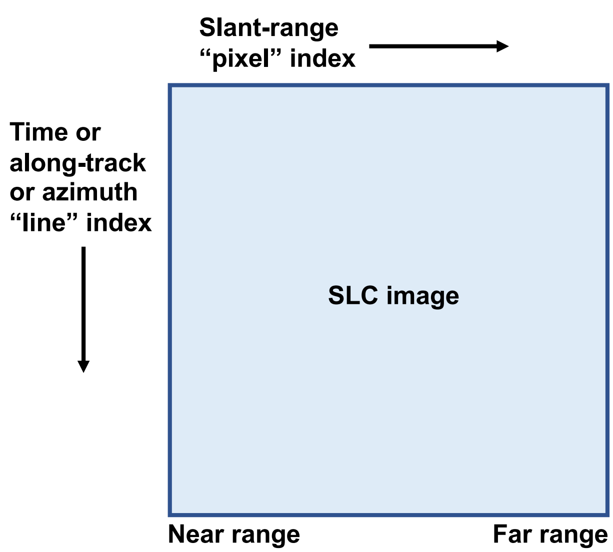

Figure 2. SLC image dimensions.

The L1B_HR_SLC product SLC and X factor are provided with a spatial posting of ~3 m in along track and ~0.75 m in slant range. The exact along track spacing is determined by the pulse repetition interval, the platform speed, and the presumming factor. The cross-track spacing is uniform in slant range, but it maps irregularly onto the ground plane due to variations in viewing geometry and surface topography. The data are sampled such that the slant range to the first sample of each line is constant (changes in the KaRIn data window position within an SLC tile are compensated). The along-track resolution of the SLC images is determined by the length of the synthetic aperture formed during azimuth-compression processing; this is specified by the processing beamwidth attribute given in the product. The range resolution is affected by the transmit signal bandwidth and the weighting applied during range-compression processing.

A noise estimate is given for each line of the SLC and X-factor images. These estimates, from the KaRIn dynamic calibration data, allow for downstream noise subtraction, which gives better estimates of sigma0 or noise-induced decorrelation. The SLC and X-factor data are normalized such that the noise estimates do not vary over a given line. The noise estimates are highly smoothed in the along-track direction.

The TVP data is given as a 1-D array of pulse index (time). It covers the input L0B raw data which is used to produce the SLC tile with some overlap (about one second of data) specified in the command parameters. The time (sensor UTC time and TAI time, see Section 4.1.5.1) is reported in the *tvp* group on the same azimuth posting as the SLC where the two overlap.

The GrDEM is a 2-D image that covers the along-track extent of the input L0B raw data. The GrDEM is resampled from the reference DEM that is input to the SLC algorithm such that the GrDEM is sampled on a grid that is aligned with the spacecraft nadir track. The grid spacing of the GrDEM is about 30–50 m to match the available reference DEM resolution. Note that the resolution of the GrDEM is independent of the resolution or posting of the SLCs. A finer-resolution reference DEM can be used for the GrDEM if desired, although the SLC processing algorithms are not especially sensitive to the accuracy of the GrDEM. The accuracy of the reference DEM used to generate downstream products is usually more critical, but the reference DEM used to generate the downstream products can be different than the DEM used as the GrDEM for SLC generation. The GrDEM is provided so that downstream processing can precisely reproduce the reference location in 3-D space of each SLC sample without having to store a position vector for each sample, which would be unattractively storage intensive.

3.5 Temporal Organization

The lines of the SLC image are stored in time order (increasing along-track position) relative to the spacecraft positions that defined each line of the sampling grid. However, it is possible that the times of peak antenna illumination of samples within a line will differ slightly if the spacecraft yaw is not ideal. It is therefore possible that the peak illumination times of samples within the product will not be ordered. The illumination times of the SLC samples are not given explicitly in the L1B_HR_SLC product (because storing the time for each sample would increase the data volume considerably); it is expected that the illumination times will be computed from the TVP information as necessary.

Both the UTC time (*time*) and the TAI time (*time_tai*) are reported in the *tvp* group on the same azimuth posting as the SLC images.

3.6 Spatial Organization

The SLC and X-factor images are stored with along-track lines in time order and with range increasing with pixel index over each line. The intersections of the slant-plane grid locations with the reference surface specified by the GrDEM gives the 3-D reference locations of SLC images.

Specifically, an index *k_tvp* into a 1-D array for a variable in the *tvp* group (ranging from 0 to *num_tvps*-1) can be aligned with an along-track index *k_slc* (ranging from 0 to *num_lines*-1) into the 2-D SLC arrays through the global attribute *slc_first_line_index_in_tvp*:

k_tvp = k_slc + slc_first_line_index_in_tvp

Note, however, that the illumination time may not occur at the TVP line corresponding to *k_tvp* if non-ideal antenna pointing causes the antenna footprint to be slightly ahead of or behind the cross-track direction.

Samples in the *xfactor* and *noise* groups are aligned in the along-track direction with samples in the *slc* group, so *k_slc* applies to the variables in the *xfactor* and *noise* groups as well.

Samples in the *grdem* group can be aligned with or interpolated to locations of samples in the *tvp* group by aligning the value of the *platform_time_tai* variable in the *grdem* group with the value of the *time_tai* variable in the *tvp* group. The *grdem* samples can then be associated with variables in the *slc*, *xfactor*, and *noise* groups through the *slc_first_line_index_in_tvp* attribute as described above.

3.7 Volume

Table 3 provides the expected volumes of the L1B_HR_SLC product and its relevant parts. These estimates assume that no NetCDF compression has been applied. All volume estimates assume 64 km x 64 km tile size plus 4 km along-track overlap at the beginning and the end of each tile (72 km x 64 km total).

The data volumes here assume that the SLC images use 64-bit complex samples (32 bits for the real part and 32 bits for the imaginary part of each sample) and that the X factor images use 32-bit floating-point real numbers.

Table 3: Description of data volume of L1B_HR_SLC product.

Part	Group	Name	Volume/tile (GB)
1	*slc*	KaRIn HR SLC plus_y, minus_y	1.84
2	*xfactor*	X factor plus_y, minus_y	0.92
3	*noise*	Noise estimate	0.0003
4	*tvp*	TVP	0.004
5	*grdem*	GrDEM	0.025 (@ 30 m resolution)
		Total	**2.79**

4 Qualitative Description

4.1 Level 1B KaRIn HR SLC Data File

Several variables in the L1B_HR_SLC product are defined relative to a reference frame that is fixed to the KaRIn instrument called the KaRIn Metering Structure Frame (KMSF), illustrated in Figure 3. This frame is defined with the origin near the middle of the interferometric baseline, with the two antennas along the +*y* and –*y* axes. The +*z* axis of this frame is controlled to point approximately toward nadir, so the *x* axis is approximately parallel or antiparallel to the Earth-relative spacecraft velocity vector. However, the spacecraft periodically performs 180˚ yaw flips (for thermal management reasons, several times per year) such that sometimes the +*x* axis is in the direction of the velocity vector (i.e., satellite flying forward), and sometimes the –*x* axis is in the direction of the velocity vector (i.e., satellite flying backward). Which of the +*y* and –*y* antennas is to the left or right of the spacecraft along-track direction therefore depends on the yaw state of the spacecraft. As elsewhere in this document, "left" and "right" are defined as if standing on the Earth surface and facing the direction of the spacecraft velocity vector.

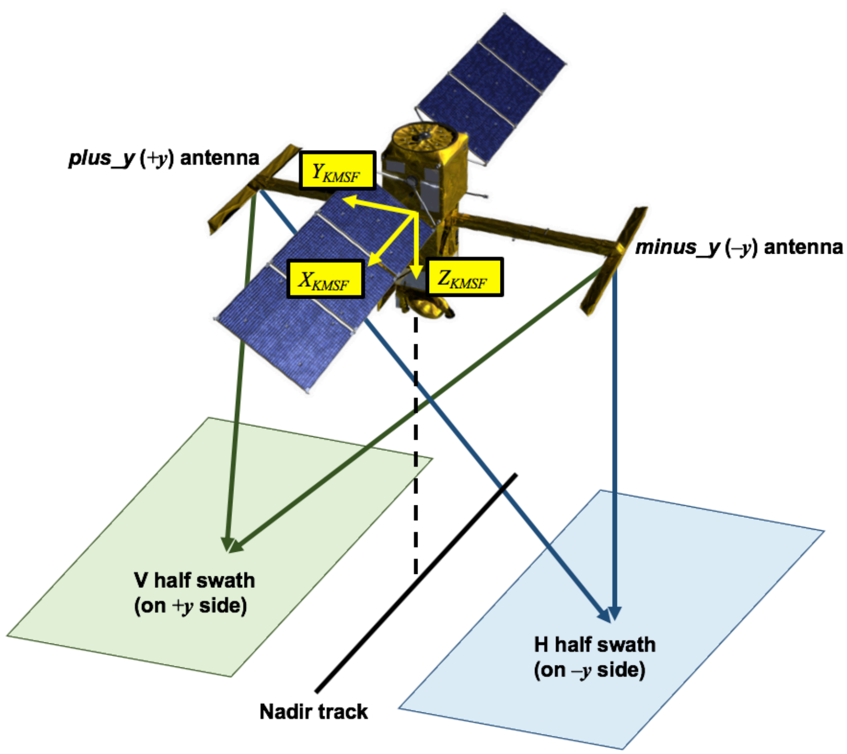

Figure 3. Illustration of the KMSF frame and the polarizations (V and H) of the two KaRIn half swaths. The velocity direction can be along $+X_{KMSF}$ or $-X_{KMSF}$ depending on the yaw state of the spacecraft.

In the L1B_HR_SLC product, variables that are associated with antenna channels are defined with respect to the physical antenna and receiver hardware of the channel (regardless of which side (left or right) or the nadir track the hardware was on given the yaw state of the spacecraft). Following KaRIn instrument conventions, these variables are named with the identifiers "plus_y" and "minus_y" in reference to the antennas on the +*y* and –*y* sides of the KaRIn frame. When the spacecraft yaw (from the *yaw* variable in the *tvp* group) is close to 0˚, the +*y* and –*y* antennas are to the right and left, respectively, of the nadir track when facing in the direction of the velocity vector; the opposite is true when the yaw is close to 180˚, which indicates a yaw-flipped state.

As noted above, the left and right half-swaths on the ground are given in separate product tiles; the mapping of how the +*y* and –*y* antennas are used for each of the left and right half swaths is handled during data processing.

KaRIn uses different polarizations for the two sides. The radar signal is horizontally (H) and vertically (V) polarized for the half swaths on the -*y* and +*y* sides of the KaRIn frame, respectively. Therefore, the polarizations for the left and right swaths are H and V, respectively, when the yaw is close to 0˚. The polarization is given by the global attribute *polarization*.

When the KaRIn prime high-power amplifier (HPA) is used, the +*y* antenna transmits regardless of the yaw state. The –*y* antenna transmits when the cold-spare HPA is used (likely only in the event of a failure of the prime unit). Which of the antennas is transmitting is given by the global attribute *transmit_antenna*.

All variables that give position, velocity, and attitude relative to the Earth frame are defined with respect to the International Terrestrial Reference Frame (ITRF). In this Earth-Centered Earth-Fixed (ECEF) frame, the +*z* axis goes through the north pole, and the +*x* axis goes through both the equator (zero latitude) and the prime meridian (zero longitude).

All variables that are defined with respect to a reference ellipsoid assume the reference ellipsoid parameters that are given in the global attributes (*ellipsoid_semi_major_axis* and *ellipsoid_flattening*) of the product file itself.

4.1.1 Global Attributes

A complete list of global attributes is given in Table 6. In addition to common global attributes, several global attributes give information that describe the spatial sampling of the KaRIn measurement and its interpretation:

- *wavelength*: Wavelength corresponding to the effective radar carrier frequency that should be used for height reconstruction after accounting for spectral shifts and filtering.
- *near_range*: Slant range to the first range bin in the SLCs. Changes to the KaRIn starting range are compensated during ground processing so that the near-range value of the SLC data is constant within a tile (but varying from tile to tile).
- *nominal_slant_range_spacing*: Spacing between range samples in the SLCs.
- *time_coverage_start*, *time_coverage_end*: UTC times that the first and last measurements in the granule were collected.
- *polarization*: Flag indicating whether the tile is observed with a horizontal (H) or vertical (V) signal polarization. The KaRIn V half-swath is always on the +*y* side of the spacecraft, which is to the right of the nadir track if the yaw is near zero (or to the left if the yaw is near 180˚). The KaRIn H half swath is always on the -*y* side of the spacecraft, which is to the left of the nadir track if the yaw is near zero (or to the right if the yaw is near 180˚).
- *transmit_antenna*: Flag that indicates which of the KaRIn antennas (plus_y or

minus_y) is transmitting.

- *processing_beamwidth*: Angular extent of the synthetic aperture from a ground target. This parameter determines the single-look along-track resolution of the KaRIn measurement.
- *num_missing_bad_thresh*: Threshold number of missing or bad presummed KaRIn echoes within a synthetic aperture at or above which the SLC data are marked bad (see the *slc_qual* variable).
- *tile_first_line_index_in_tvp*, *tile_last_line_index_in_tvp*: Indices in the 1-D TVP array of the first and last TVP lines within the ideal reference tile granule that defines the current SLC granule.
- *slc_along_track_resolution*: Effective along-track resolution to compute the equivalent number of independent looks of the SLCs.
- *slc_range_resolution*: Effective slant-range resolution to compute the equivalent number of independent looks of the SLCs.
- *slc_first_line_index_in_tvp*, *slc_last_line_index_in_tvp*: Indices in the 1-D TVP array of the first and last SLC lines. These index values start from 0.
- *kmsf_to_dop_roll*, *kmsf_to_dop_pitch*, *kmsf_to_dop_yaw*: Angles defining a rotation bias between the spacecraft body-fixed KaRIn Metering Structure Frame (KMSF) and the common antenna Doppler frame that determines the processed Doppler centroid or illumination time during SLC azimuth compression. The Doppler frame (for each half swath) defines the common boresight direction for the pair of antennas illuminating the half swath, with the Doppler centroid desired to align with the antenna pointing. That is, the Doppler centroid for SAR processing is chosen assuming that the peak illumination of the surface occurs in the *yz* plane of the Doppler frame. The sign conventions of these angles is such that positive roll, pitch, and yaw give right handed rotations of the Doppler frame about the KMSF $+x$, $+y$, and $+z$ axes, respectively. The rotation is a quasi-static calibration parameter.

4.1.2 SLC Group Data

The two SLC images are phase flattened by the reference DEM (i.e, referenced to zero interferometric phase if the true target location were on the reference DEM) and are both sampled on the same slant-plane image grid so that they are coregistered. The magnitude units of the complex SLC values are arbitrary and dependent on processing parameters, but the values can be related to the normalized radar cross section (sigma0) via the X factor described in Sect. 4.1.3. The X factor is not applied to the reported SLC values in order to facilitate downstream interferometric processing. During SLC processing, the SLC values are normalized in a spatially relative manner such that the additive noise of the instrument (typically thermal noise) can be assumed to be constant for each line (see Sect. 4.1.4).

The 3-D coordinates of each image grid sample can be determined using the GrDEM and TVP information. The image grids are based on the platform track broadside geometry in the along-track direction (each SLC is a deskewed SAR image). That is, each row of grid samples is arranged in a line that is perpendicular to the nadir track. In the cross-track direction, the grid locations are the intersections of the reference DEM and equally spaced slant-range contours.

The near range for each line in a tile will be set to be constant for a given tile, choosing the nearest range of pulses used to generate a tile. The first near range sample will be chosen to be an integer multiple of the slant-range resolution cell spacing (approximately 75 cm) such that adjacent tile range lines can be aligned by a range shift of an integer number of range cells.

The illuminating sensor position of an image pixel is the sensor position where the image pixel is illuminated with the azimuth peak of the antenna pattern. The illuminating sensor positions are used to produce the SLC images. They are also needed to reconstruct the geolocation of each image grid. They are re-calculated in downstream processing.

- *slc_plus_y*, *slc_minus_y*: SLC image arrays from the +*y* and –*y* antenna channels.

The *slc* group also includes a flag *slc_qual* that indicates the quality of the SLC and associated X factor and noise data. The flag array is one dimensional, with only one value per along-track index, since the mechanisms that make the SLC data invalid generally affect entire lines of data. Because the data from the +*y* and -*y* antenna channels are expected to be used together in interferometric processing, there is a single flag that represents both channels. The flag should nominally be zero; a nonzero flag value indicates suspect data quality.

- *slc_qual*: Bit flag whose individual bits indicate conditions that may affect the quality of the SLC data. Off-nominal conditions do not necessarily always imply that the data are not useful, but users should exercise caution in interpreting the data. The bits are defined in rough order of increasing expected measurement degradation from least significant bit to most significant bit. Therefore, if the flag is interpreted as an unsigned, 8 bit integer, then a value of zero (all bits = 0) represents nominal (good) SLC data, nonzero values less than 16 represent “use with caution” (may be degraded, but possibly useful), and values of 16 or greater represent bad measurement quality. The meanings of the flag bits are defined as follows:
    - 1 (Bit 0=1): At least one sample in the line has at least one echo in its synthetic aperture with 0 < *tvp_qual* < 20.
    - 2 (Bit 1=1): At least one sample in the line has at least one echo in its synthetic aperture with 0 < *sc_event_flag* < 64.
    - 4 (Bit 2=1): At least one sample in the line has at least one but fewer than *num_missing_bad_thresh* echoes in its synthetic aperture with bad or missing KaRIn data.
    - 8 (Bit 3=1): Unused spare; always zero.
    - 16 (Bit 4=1): Unused spare; always zero.
    - 32 (Bit 5=1): At least one sample in the line has at least one echo in its synthetic aperture with *tvp_qual* >= 20.
    - 64 (Bit 6=1): At least one sample in the line has at least one echo in its synthetic aperture with *sc_event_flag* >= 64.
    - 128 (Bit 7=1): At least one sample in the line has at least *num_missing_bad_thresh* echoes in its synthetic aperture with bad or missing KaRIn data.

4.1.3 X Factor Group Data

This group provides the X factor for each sample in each of the two SLCs. The X factor is given in linear units such that it can be applied to the magnitude squared of the complex values of the SLCs. That is, when the power of the complex samples of the SLC data (minus the noise power) are divided by the X factor (in linear units), the result represents radiometrically calibrated, linear sigma0 estimates. The X factor values are given in linear units, not decibels.

- *xfactor_plus_y*, *xfactor_minus_y*: X factor arrays for the +*y* and –*y* antenna channels.

4.1.4 Noise Group Data

The noise estimate for each pulse is based on the thermal noise power estimate from KaRIn internal calibration measurements, which are smoothed over many pulses. The SLCs are normalized such that a single noise estimate is applicable to an entire line of range samples (even though the synthetic aperture length, as defined by the processing beamwidth, varies with range), so the noise estimates are 1-D along-track arrays. The SLC and noise values in the L1B_HR_SLC product are scaled such that the noise estimates can be directly subtracted from the square magnitude of the SLC samples. The noise estimates are given as linear power quantities (not decibels).

- *noise_plus_y*, *noise_minus_y*: Noise power estimates for the +*y* and –*y* antenna channels.

4.1.5 TVP Group Data

The *tvp* group contains platform and radar system parameters as a function of time, including the spacecraft position, velocity and attitude, as well as the lever arm information of the two antennas comprising the KaRIn interferometer. See Figure 3 and its associated description for the definition of the KMSF frame.

4.1.5.1 Time

Time tags for each TVP data record are provided in the UTC and TAI time scales using the variables *time* and *time_tai*, respectively.

- *time*: Time in UTC time scale (seconds since January 1, 2000 00:00:00 UTC which is equivalent to January 1, 2000 00:00:32 TAI)
- *time_tai*: Time in TAI time scale (seconds since January 1, 2000 00:00:00 TAI, which is equivalent to December 31, 1999 23:59:28 UTC)

The variable *time* has an attribute named *tai_utc_difference*, which represents the difference between TAI and UTC (i.e., total number of leap seconds) at the time of the first measurement record in the product granule.

- *time_tai[0] = time[0] + tai_utc_difference*

The above relationship holds true for all measurement records unless an additional leap second occurs within the time span of the product granule. To account for this, the variable *time* also has an attribute named *leap_second* which provides the date at which a leap second might have occurred within the time span of the product granule. The variable *time* will exhibit a jump when a leap second occurs. If no additional leap second occurs within the time span of the product granule *time:leap_second* is set to “0000-00-00T00:00:00Z”.

The table below provides some examples for the values of *time*, *time_tai*, and *tai_utc_difference*. With this approach, the value of *time* will have a 1 second regression during a leap second transition, while *time_tai* will be continuous. That is, when a positive leap second is inserted, two different instances will have the same value for the variable *time*, making time non-unique by itself; the difference between *time* and *time_tai*, or the *tai_utc_difference* and *leap_second* fields, can be used to resolve this. Some examples are provided in the table below.

UTC Date	TAI Date	time	time_tai	tai_utc_difference
January 1, 2000 00:00:00	January 1, 2000 00:00:32	0.0	32.0	32
December 31, 2016 23:59:59	January 1, 2017 00:00:35	536543999.0	536544035.0	36
December 31, 2016 23:59:59.5	January 1, 2017 00:00:35.5	536543999.5	536544035.5	36
December 31, 2016 23:59:60	January 1, 2017 00:00:36	536543999.0	536544036.0	37
January 1, 2017 00:00:00	January 1, 2017 00:00:37	536544000.0	536544037.0	37
January 1, 2017 12:00:00	January 1, 2017 12:00:37	536587200.0	536587237.0	37

4.1.5.2 Location, Velocity and Attitude

The position, velocity, and attitude of the KaRIn reference frame (i.e., KMSF) are given relative to the ITRF in the variables described in this section.

The attitude angles are defined as follows. Let v_{KMSF}, v_{NED}, and v_{ENU} be the same vector represented in KMSF, in the local north-east-down (NED) frame, and in the local east-north-up (ENU) frame, respectively, with the rotation matrices R_{NED}^{KMSF} and R_{ENU}^{NED} giving the transformations between the three vectors representations:

$$v_{KMSF} = R_{NED}^{KMSF} v_{NED}$$
$$v_{NED} = R_{ENU}^{NED} v_{ENU}.$$

These rotation matrices are given by

$$R_{NED}^{KMSF} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos r & \sin r \\ 0 & -\sin r & \cos r \end{bmatrix} \begin{bmatrix} \cos p & 0 & -\sin p \\ 0 & 1 & 0 \\ \sin p & 0 & \cos p \end{bmatrix} \begin{bmatrix} \cos h_p & \sin h_p & 0 \\ -\sin h_p & \cos h_p & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$R_{ENU}^{NED} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

where r and p represent the *roll* and *pitch* variables, and the platform heading h_p is defined as the sum of the *velocity_heading* variable h_v and the *yaw* variable h_y

$$h_p = h_v + h_y$$

with all of these angles defined modulo 360°.

- *latitude*, *longitude*, *altitutde*: Geodetic latitude, longitude, and altitude above the reference ellipsoid of the origin of the KMSF frame. The global attributes *ellipsoid_semi_major_axis* and *ellipsoid_flattening* define the reference ellipsoid.
- *roll*, *pitch*, *yaw, velocity_heading*: Attitude of the KMSF frame with respect to the local frame at the location given by *latitude* and *longitude*. The *velocity_heading* is the angle with respect to true north of the nadir track direction such that if the spacecraft were flying due east, the velocity heading would be 90˚. The *yaw* is the angle of right-handed rotation of the nominal KMSF +*x* axis about the nadir direction. If the KMSF +*x* axis is aligned with the horizontal projection of the Earth-relative spacecraft velocity vector, the yaw will be zero. If the KMSF -*x* axis is aligned with the horizontal projection of the Earth-relative spacecraft velocity vector, the yaw will be 180˚. The heading of the KMSF +*x* axis relative to true north is consequently the sum of the *velocity heading* and the *yaw* (modulo 360˚). The *pitch* is defined such that a positive pitch moves the KMSF axis +*x* up. The *roll* is defined such that a positive roll moves the +*y* antenna down. Note that when the yaw is near 180˚, the sense of pitch and roll may be counterintuitive to users who are accustomed to airborne platforms since the spacecraft would be flying "tail first." Note that in the SLC product, if the processed Doppler is derived from the KaRIn radar echoes either on board or in the SLC processor itself rather than from the input attitude information (see the global attribute *doppler_estimation_mode*), then the attitude that is output to the SLC product in the variables *roll, pitch, yaw,* and *velocity_heading* includes a Doppler-derived correction. Therefore, the processed Doppler and the illumination time are always computable from the TVP *roll, pitch, yaw,* and *velocity_heading* and the global attributes *kmsf_to_dop_roll*, *kmsf_to_dop_pitch*, and *kmsf_to_dop_yaw.* However, the TVP *roll, pitch, yaw,* and *velocity_heading* may then be inconsistent with the ground-reconstructed attitude, particularly in pitch. Consequently, one should **not** attempt to use the TVP *roll, pitch, yaw,* and *velocity_heading* to compute the antenna phase center positions; rather one should use the phase center positions provided in the TVP (see Section 4.1.5.3).
- *x*, *y*, *z*: Position vector of the KMSF origin in ECEF coordinates.
- *vx*, *vy*, *vz*: Earth-relative velocity vector of the KMSF origin in ECEF coordinates. This velocity vector describes the spacecraft motion in an Earth-fixed (not inertial) frame.

4.1.5.3 Antenna Phase Center Positions

The positions of the phase centers of the two interferometric antennas for the given swath are given at each time point in ECEF coordinates in the following variables:

- *plus_y_antenna_x*, *plus_y_antenna_y*, *plus_y_antenna_z*: Position vector of the +*y* KaRIn antenna phase center in ECEF coordinates.
- *minus_y_antenna_x*, *minus_y_antenna_y*, *minus_y_antenna_z*: Position vector of the –*y* KaRIn antenna phase center in ECEF coordinates.

The phase center positions are computed from the static lever arms and the ground-reconstructed attitude, independent of whether the processed Doppler is derived from the ground-reconstructed attitude or the KaRIn radar echoes (either on board or in the SLC processor itself). See the global attribute *doppler_estimation_mode*.

4.1.5.4 Index in HR Data Collection

The index of the presummed line corresponding to the TVP record relative to the start of the HR data collection captures information about the KaRIn state and allows for decimation in processing to maintain the continuity of sampling across tile boundaries.

- *record_counter*: Index (from 1) relative to the start of the HR datatake of the presummed line corresponding to the TVP record. This counter is used to align data samples across granules.

4.1.5.5 Flags

Flags in the TVP group capture information about the spacecraft and instrument state as described below. The flags should nominally be zero; nonzero values indicate off-nominal conditions. These flags typically give additional information for off-nominal conditions that are reported in the *slc_qual* flag.

- *sc_event_flag*: Bit flag whose individual bits indicate spacecraft events that may affect the characteristics of the KaRIn data. An off-nominal spacecraft state does not necessarily always imply that the data are not useful, but users should exercise caution in interpreting the data. The bits are defined in rough order of increasing expected measurement degradation from least significant bit to most significant bit. Therefore, if the flag is interpreted as an unsigned, 8 bit integer, then a value of zero (all bits = 0) represents the nominal spacecraft state, nonzero values less than 64 represent "use with caution" (may be degraded, but possibly useful), and values of 64 or greater represent bad measurement quality. The meanings of the flag bits are defined as follows:
    - 1 (Bit 0=1): The measurement may be affected by a yaw-flip maneuver.
    - 2 (Bit 1=1): The measurement may be affected by a gyro calibraton maneuver.
    - 4 (Bit 2=1): The measurement may be affected by an orbit control maneuver.
    - 8 (Bit 3=1): The measurement may be affected by a solar array rotation.
    - 16 (Bit 4=1): The measurement may be affected by an entry of the spacecraft into Earth eclipse.
    - 32 (Bit 5=1): The measurement may be affected by an exit of the spacecraft from Earth eclipse.
    - 64 (Bit 6=1): The measurement is likely bad due to an eclipse event.
    - 128 (Bit 7=1): The measurement is likely bad due to an event other than an eclipse event.
- *tvp_qual*: Flag that indicates the quality of the reconstructed attitude and orbit ephemeris. A value of 0 indicates that the reconstructed attitude and orbit ephemeris are both good. A nonzero value indicates that these data are off-nominal or bad, with the expected degradation of measurement quality roughly increasing with flag value. The value in the tens digit indicates the quality of the reconstructed attitude, and the value in the ones digit represents the quality of the orbit ephemeris for the spacecraft center of mass (but note that the attitude is required to compute the KMSF origin from the center of mass). Non-zero values of *tvp_qual* less than 20 indicate suspect data; values greater than or equal to 20 indicate bad data. The values are as follows:

- 0: The reconstructed attitude is good and the ephemeris is adjusted on actual tracking data.
- 4: The reconstructed attitude is good and the ephemeris is estimated during a maneuver.
- 5: The reconstructed attitude is good and the ephemeris is interpolated over a data gap.
- 6: The reconstructed attitude is good and the ephemeris is extrapolated over a duration less than 1 day.
- 7: The reconstructed attitude is good and the ephemeris is extrapolated over a duration between 1 and 2 days.
- 8: The reconstructed attitude is good and the ephemeris is extrapolated over a duration greater than 2 days.
- 10: The reconstructed attitude is suspect and the ephemeris is adjusted on actual tracking data.
- 14: The reconstructed attitude is suspect and the ephemeris is estimated during a maneuver.
- 15: The reconstructed attitude is suspect and the ephemeris is interpolated over a data gap.
- 16: The reconstructed attitude is suspect and the ephemeris is extrapolated over a duration less than 1 day.
- 17: The reconstructed attitude is suspect and the ephemeris is extrapolated over a duration between 1 and 2 days.
- 18: The reconstructed attitude is suspect and the ephemeris is extrapolated over a duration greater than 2 days.
- 20: The reconstructed attitude is bad and the ephemeris is adjusted on actual tracking data.
- 24: The reconstructed attitude is bad and the ephemeris is estimated during a maneuver.
- 25: The reconstructed attitude is bad and the ephemeris is interpolated over a data gap.
- 26: The reconstructed attitude is bad and the ephemeris is extrapolated over a duration less than 1 day.
- 27: The reconstructed attitude is bad and the ephemeris is extrapolated over a duration between 1 and 2 days.
- 28: The reconstructed attitude is bad and the ephemeris is extrapolated over a duration greater than 2 days.

4.1.6 GrDEM Group Data

An advantage of the time-domain backprojection approach used for forming the SLCs is that each sample of each SLC can be focused to its own reference location, which accounts for interferometric coregistration and phase flattening as a matter of course [2]. The reference location for each sample must be known for downstream processing, as this is the location to which the interferometric phase is referenced. Storing the reference locations explicitly in the

SLC product is unattractive due to the required data volume, however. Instead, the SLC product includes the GrDEM, at a lower resolution than the SLC posting, from which the reference locations can be recomputed following the methods of the SLC algorithms [2].

The GrDEM is a 2-D DEM that has been resampled to a swath-aligned pseudo-grid from the reference DEM. The rows (slower varying dimension) of the GrDEM are perpendicular to the spacecraft nadir track. The along-track spacing between rows is not exactly uniform because it is tied to (decimated from) the TVP sampling, which is in turn tied to the non-uniform KaRIn presum sampling. This decimation factor is chosen to approximately match the reference DEM resolution. The time that the spacecraft passed over the nadir location of each row of the GrDEM is given as a 1-D array, along with the spacecraft position and velocity vector at that time.

The GrDEM is not intended for any purpose other than for recomputing reference locations in a manner consistent with the SLC processing. Users are cautioned against assuming any particular level of agreement between the GrDEM and the original reference DEM.

- *height*: Height of the GrDEM ground surface relative the reference ellipsoid.
- *platform_time*, *platform_time_tai*: UTC and TAI times that the spacecraft passed over the nadir location associated with the corresponding row of the GrDEM. See the discussion on the UTC and TAI time representations in Sect 4.1.5.1.
- *platform_latitude*, *platform_longitude*, *platform_altitude*: Latitude (degrees north of the equator), longitude (degrees east of the prime meridian), and altitude relative to the reference ellipsoid of the KMSF origin when the spacecraft passed over the nadir location associated with the corresponding row of the GrDEM.
- *platform_velocity_x*, *platform_velocity_y*, *platform_velocity_z*: Earth-relative velocity of the KMSF origin, expressed in ECEF coordinates, when the spacecraft passed over the nadir location associated with the corresponding row of the GrDEM. This velocity vector describes the spacecraft motion in an Earth-fixed (not inertial) frame.

5 Detailed Product Description

The L1B_HR_SLC product adopts the NetCDF-4 file format and conventions. This is a self-documenting format that contains metadata as global attributes, dimensions, variables, and attributes for variables. Each file contains multiple NetCDF groups of data as described above. Global attributes are defined both outside and potentially inside the groups. The global attributes that are defined outside of the groups (i.e., the root netcdf group) apply to all groups in the file, while global attributes that occur within each data group apply to only all of the data within that single group. Variable attributes only apply to the associated variable. The NetCDF command "ncdump –h product.nc" can be used to view the header of the product, which describes the content of the product.

5.1 NetCDF Variables

Variables are used to store the various measurements. Each variable is assigned a name and a particular data type. Variables can be scalar values (i.e. 0 dimension), or can have one or more dimensions. Each variable then has attributes that provide additional information about the variable. Table 4 below identifies the data types used in the L2_HR_SLC product, and Table 5 identifies the attributes that may be assigned to each variable.

Table 4. Variable Data Types in NetCDF Product.

Data Type	Description
char	characters (ASCII)
byte	8-bit signed integer
unsigned byte	8-bit unsigned integer
short	16-bit signed integer
unsigned short	16-bit unsigned integer
int	32-bit signed integer
unsigned int	32-bit unsigned integer
long	64-bit signed integer
unsigned long	64-bit unsigned integer
float	IEEE single precision floating point (32 bits)
double	IEEE double precision floating point (64 bits)

Table 5. Common variable attributes in NetCDF file.

Attribute	Description
_FillValue	The value used to represent missing or undefined data. (Before applying add_offset and scale_factor).
add_offset	If present this value should be added to each data element after it is read. If both scale_factor and add_offset attributes are present, the data are first scaled before the offset is added.
calendar	Reference time calendar
comment	Miscellaneous information about the data or the methods to generate it.
coordinates	Coordinate variables associated with the variable
flag_meanings	Used in conjunction with flag_values or flag_masks. Describes the meanings of each of the elements of flag_values or flag_masks.
flag_values	Used in conjunction with flag_meanings. Possible values of the flag variable.

flag_masks	Used in conjunction with flag_meanings. Describes a number of independent Boolean conditions using bit field notation by setting unique bits in each flag_masks value. A flagged condition is identified by performing a bitwise AND of the variable value and each flag_masks value; a non-zero result indicates a true condition. Thus, any or all of the flagged conditions may be true, depending on the variable bit settings.
institution	Institution which generates the source data for the variable, if applicable.
leap_second	UTC time at which a leap second occurs within the time span of data within the file.
long_name	A descriptive variable name that indicates its content.
quality_flag	Names of variable quality flag(s) that are associated with this variable to indicate its quality.
scale_factor	If present, the data are to be multiplied by the value after they are read. If both scale_factor and add_offset attributes are present, the data are first scaled before the offset is added.
source	Data source (model, author, or instrument)
standard_name	A standard variable name that indicates its content.
tai_utc_difference	Difference between TAI and UTC reference time.
units	Unit of data after applying offset (add_offset) and scale_factor.
valid_max	Maximum theoretical value of variable before applying scale_factor and add_offset (not necessarily the same as maximum value of actual data)
valid_min	Minimum theoretical value of variable before applying scale_factor and add_offset (not necessarily the same as minimum value of actual data)

5.2 Level 1B KaRIn HR SLC File

5.2.1 Global Attributes

Global attributes for the L1B_HR_SLC product are provided in Table 6 below.

Table 6. Global attributes for all data groups in the L1B_HR_SLC product file.

Attribute	Format	Description
Conventions	string	NetCDF-4 conventions adopted in this group. This attribute should be set to CF-1.7 to indicate that the group is compliant with the Climate and Forecast NetCDF conventions.
title	string	Level 1B KaRIn High Rate Single Look Complex Data Product
institution	string	Name of producing agency.
source	string	The method of production of the original data. If it was model-generated, source should name the model and its version, as specifically as could be useful. If it is observational, source should characterize it (e.g., 'Ka-band radar interferometer').
history	string	UTC time when file generated. Format is: 'YYYY-MM-DDThh:mm:ssZ : Creation'
platform	string	SWOT
references	string	Published or web-based references that describe the data or methods used to product it. Provides version number of software generating product.
reference_document	string	Name and version of Product Description Document to use as reference for product.
contact	string	Contact information for producer of product. (e.g., 'ops@jpl.nasa.gov').
cycle_number	short	Cycle number of the product granule.
pass_number	short	Pass number of the product granule.
tile_number	short	Tile number in the pass of the product granule.
swath_side	string	'L' or 'R' to indicate left and right swath, respectively.

tile_name	string	Tile name using format PPP_TTTS, where PPP is a 3 digit pass number with leading zeros, TTT is a 3 digit tile number within the pass, and S is a character 'L' or 'R' for the left and right swath, respectively.
short_name	string	L1B_HR_SLC
crid	string	Composite release identifier (CRID) of the data system used to generate this file
product_version	string	Version identifier of this data file
pge_name	string	Name of the product generation executable (PGE) that created this file
pge_version	string	Version identifier of the product generation executable (PGE) that created this file
time_coverage_start	string	UTC time of first measurement. Format is: YYYY-MM-DDThh:mm:ss.ssssssZ
time_coverage_end	string	UTC time of last measurement. Format is: YYYY-MM-DDThh:mm:ss.ssssssZ
geospatial_lon_min	double	Westernmost longitude (deg) of granule bounding box
geospatial_lon_max	double	Easternmost longitude (deg) of granule bounding box
geospatial_lat_min	double	Southernmost latitude (deg) of granule bounding box
geospatial_lat_max	double	Northernmost latitude (deg) of granule bounding box
inner_first_longitude	double	Nominal swath corner longitude for the first range line and inner part of the swath (degrees_east)
inner_first_latitude	double	Nominal swath corner latitude for the first range line and inner part of the swath (degrees_north)
inner_last_longitude	double	Nominal swath corner longitude for the last range line and inner part of the swath (degrees_east)
inner_last_latitude	double	Nominal swath corner latitude for the last range line and inner part of the swath (degrees_north)
outer_first_longitude	double	Nominal swath corner longitude for the first range line and outer part of the swath (degrees_east)
outer_first_latitude	double	Nominal swath corner latitude for the first range line and outer part of the swath (degrees_north)
outer_last_longitude	double	Nominal swath corner longitude for the last range line and outer part of the swath (degrees_east)
outer_last_latitude	double	Nominal swath corner latitude for the last range line and outer part of the swath (degrees_north)
wavelength	double	Wavelength (m) of the transmitted signal, which is determined based on the transmitter center frequency of the transmit chirp.
near_range	double	The slant range (m) for the first image pixel.
nominal_slant_range_spacing	double	The range spacing (m) corresponding to the 200 MHz sampling frequency
polarization	string	Flag indicating whether the tile was observed with a horizontal (H) or vertical (V) radar signal polarization.
transmit_antenna	string	Flag indicating which of the KaRIn antennas (plus_y or minus_y) is transmitting.
processing_beamwidth	double	Beamwidth (deg) used to integrate the range compressed data in azimuth compression. The 3 dB nominal azimuth antenna pattern beamwidth is about 0.1 degrees. After on-board presum with a presum factor of 2.125, the effective beamwidth is reduced to about 0.05 degrees.
num_missing_bad_thresh	int	Threshold number of missing or bad echoes in a synthetic aperture for declaring a sample bad.
tile_first_line_index_in_tvp	int	The TVP index (from 0) corresponding to the starting boundary of the reference tile granule.
tile_last_line_index_in_tvp	int	The TVP index (from 0) corresponding to the ending boundary of the reference tile granule.
slc_along_track_resolution	double	Along-track or azimuth resolution (m) corresponding to the processing beamwidth for the SLC data. The resolution is approximately the width between half-power points of the main lobe of the image point target response assuming that targets do not decorrelate over the focusing aperture time (which is not the case for water because of the short coherence time).
slc_range_resolution	double	Range resolution (m) for the SLC data. The resolution is approximately the half-power width of the range point target response.

slc_first_line_index_in_tvp	int	The TVP index (from 0) corresponding to the first SLC image line in the overlapped tile.
slc_last_line_index_in_tvp	int	The TVP index (from 0) corresponding to the last SLC image line in the overlapped tile.
doppler_estimation_mode	string	Indicator of how the processed Doppler is derived for the granule. Possible values are 'no_doppler_estimation' (use attitude information only), 'use_OBP_doppler' (use on-board estimated Doppler), and 'use_ground_estimation' (use ground estimate of Doppler based on radar echo data).
kmsf_to_dop_roll	double	The KMSF to Doppler frame roll bias angle in degrees. A positive sign moves the Doppler frame +y axis down relative to KMSF. This parameter is part of a common rotation used for both antennas so that the SLC images are processed to the same Doppler centroid.
kmsf_to_dop_pitch	double	The KMSF to Doppler frame pitch angle in degrees. A positive sign moves the Doppler frame +x axis up relative to KMSF. This parameter is part of a common rotation used for both antennas so that the SLC images are processed to the same Doppler centroid.
kmsf_to_dop_yaw	double	The KMSF to Doppler frame yaw angle in degrees. A positive sign moves the Doppler frame +x axis right relative to KMSF. This parameter is part of a common rotation used for both antennas so that the SLC images are processed to the same Doppler centroid.
xref_l0b_hr_frame_file	string	Name of input Level 0B high rate frame file.
xref_statickarincal_files	string	Names of input static KaRIn calibration files.
xref_int_kcal_dyn_file	string	Name of input dynamic KaRIn calibration file.
xref_param_l1b_hr_slc_file	string	Name of input Level 1B high rate single look complex processor configuration parameters file.
xref_orbit_ephemeris_file	string	Name of input orbit ephemeris file.
xref_attd_reconst_file	string	Name of input reconstructed attitude quaternion file that represents the rotation between the spacecraft body-fixed reference frame and the Geocentric Celestial Reference Frame (GCRF).
xref_q_gcrf_itrf_file	string	Name of input quaternion file that represents the rotation between the Geocentric Celestial Reference Framce (GCRF) and the International Terrestrial Reference Frame (ITRF).
xref_sat_com_file	string	Name of input satellite center of mass file.
xref_leapsec_file	string	Name of input leap second file.
xref_histo_oef_file	string	Name of input satellite event file.
xref_eclipse_files	string	Names of input satellite eclipse files.
xref_events_param_file	string	Name of input parameter file for satellite event processing.
xref_refdem_file	string	Name of input reference digital elevation model file.
xref_reforbittrack_files	string	Names of input reference orbit track files.
ellipsoid_semi_major_axis	double	Semi-major axis of reference ellipsoid in meters.
ellipsoid_flattening	double	Flattening of reference ellipsoid

5.2.2 Group Names, Attributes, and Dimensions

As described in Table 2, the L1B_HR_SLC product file contains five NetCDF data groups called the *slc*, *xfactor*, *noise*, *tvp*, and *grdem* groups.

Each group has a 'description' attribute that elaborates on what the data in the group represents. There are also extra group attributes for the *grdem* group. These are described in Table 7–Table 11.

Each NetCDF group uses the dimensions attributes to identify the physical dimensions of variables within that single group. The L1B_HR_SLC product uses the dimensions shown in Table 12 for each group.

Table 7. Attributes of the *slc* group of the L1B_HR_SLC product.

Attribute	Format	Description
description	string	Single look complex images for plus_y and minus_y channels

Table 8. Attributes of the *xfactor* group of the L1B_HR_SLC product.

Attribute	Format	Description
description	string	X factor images for the plus_y and minus_y channels

Table 9. Attributes of the *noise* group of the L1B_HR_SLC product.

Attribute	Format	Description
description	string	Measured noise power for each receive echo of the plus_y and minus_y SLC channels

Table 10. Attributes of the *tvp* group of the L1B_HR_SLC product.

Attribute	Format	Description
description	string	Time varying parameters group including spacecraft attitude, position, velocity, and antenna position information
mean_pitch_correction	double	Mean effective pitch correction in degrees over the granule as derived from the Doppler estimate of the KaRIn data, if applicable. This value is 0 if the processed Doppler is based only on attitude information.

Table 11. Attributes of the *grdem* group of the L1B_HR_SLC product.

Attribute	Format	Description
description	string	Ground-range digital elevation model, which is swath aligned with the same along-track sampling as the SLC slant-plane images, but sampled along the ellipsoid in the ground-range direction
grdem_near_range	double	The first pixel slant range (m) used to define the GrDEM
grdem_cross_track_spacing	double	Cross track spacing (m) used to define reference GrDEM grid sampling
grdem_min_cross_track	double	Starting cross track distance (m) from nadir

Table 12. Dimensions of variables within each NetCDF data group.

Name	Description
num_lines	The number of along-track lines of the SLC and X factor image data.
num_pixels	The number of range pixels of the SLC and X factor image data.
complex_depth	complex_depth is the name of the 3rd dimension of the SLC data. Each pixel of the SLC data is a complex number with a floating point value for each of the real and imaginary components. In the NetCDF file, the 2-D complex SLC data are represented as 3-D arrays of real values with the 3rd dimension being the real or imaginary part. Therefore, the value of the 3rd dimension is always 2.
num_tvps	The number of TVP records inherited from the raw data from which the SLC image is processed.
num_grdem_lines	The number of GrDEM along-track lines to cover the raw data.
num_grdem_pixels	The number of GrDEM samples per line to cover the raw data.

5.2.3 Detailed NetCDF Format Description

This section provides a detailed listing of each of the variables within each of the groups of the L1B_HR_SLC product and their associated variable attributes.

Table 13. Variables of the slc group of the L1B_HR_SLC product.

Group slc Variables		
float slc_plus_y(num_lines, num_pixels, complex_depth)		
	_FillValue	9.96921e+36
	long_name	single look complex image for the plus_y channel
	units	1
	valid_min	-1e+20
	valid_max	1e+20
	comment	SLC complex image for the plus_y channel (arbitrary scaling consistent with the X factor).
float slc_minus_y(num_lines, num_pixels, complex_depth)		
	_FillValue	9.96921e+36
	long_name	single look complex image for the minus_y channel
	units	1
	valid_min	-1e+20
	valid_max	1e+20
	comment	SLC complex image for the minus_y channel (arbitrary scaling consistent with the X factor).
unsigned byte slc_qual(num_lines)		
	_FillValue	255
	long_name	SLC quality flag
	standard_name	status_flag
	flag_meanings	tvp_suspect sc_event_suspect small_karin_gap tvp_bad sc_event_bad large_karin_gap
	flag_masks	1 2 4 32 64 128
	valid_min	0
	valid_max	231
	comment	Flag indicating conditions that may affect the quality of the SLC data.

Table 14. Variables of the xfactor group of the L1B_HR_SLC product.

Group xfactor Variables		
float xfactor_plus_y(num_lines, num_pixels)		
	_FillValue	9.96921e+36
	long_name	X factor for the plus_y channel
	units	1
	valid_min	-1e+20
	valid_max	1e+20
	comment	X factor to scale the SLC noise-subtracted power to get sigma0 (expressed as a linear quantity) for the plus_y channel.
float xfactor_minus_y(num_lines, num_pixels)		
	_FillValue	9.96921e+36
	long_name	X factor for the minus_y channel
	units	1
	valid_min	-1e+20
	valid_max	1e+20

	comment	X factor to scale the SLC noise-subtracted power to get sigma0 (expressed as a linear quantity) for the minus_y channel.

Table 15. Variables of the noise group of the L1B_HR_SLC product.

Group noise Variables		
float noise_plus_y(num_lines)		
	_FillValue	9.96921e+36
	long_name	Noise estimate for the plus_y channel
	units	1
	valid_min	0.0
	valid_max	1e+20
	comment	Noise power for the plus_y channel expressed in linear units (arbitrary units that give noise-equivalent sigma0 when normalized by the X factor).
float noise_minus_y(num_lines)		
	_FillValue	9.96921e+36
	long_name	Noise estimate for the minus_y channel
	units	1
	valid_min	0.0
	valid_max	1e+20
	comment	Noise power for the minus_y channel expressed in linear units (arbitrary units that give noise-equivalent sigma0 when normalized by the X factor).

Table 16. Variables of the tvp group of the L1B_HR_SLC product.

Group tvp Variables		
double time(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	time in UTC
	standard_name	time
	calendar	gregorian
	tai_utc_difference	[Value of TAI-UTC at time of first record]
	leap_second	YYYY-MM-DDThh:mm:ssZ
	units	seconds since 2000-01-01 00:00:00.000
	comment	Time of measurement in seconds in the UTC time scale since 1 Jan 2000 00:00:00 UTC. [tai_utc_difference] is the difference between TAI and UTC reference time (seconds) for the first measurement of the data set. If a leap second occurs within the data set, the attribute leap_second is set to the UTC time at which the leap second occurs.
double time_tai(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	time in TAI
	standard_name	time
	calendar	gregorian
	units	seconds since 2000-01-01 00:00:00.000
	comment	Time of measurement in seconds in the TAI time scale since 1 Jan 2000 00:00:00 TAI. This time scale contains no leap seconds. The difference (in seconds) with time in UTC is given by the attribute [time:tai_utc_difference].
double latitude(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	latitude (positive N, negative S) of the spacecraft
	standard_name	latitude
	units	degrees_north

	valid_min	-80.0
	valid_max	80.0
	comment	Geodetic latitude of the KMSF origin with respect to the reference ellipsoid.
double longitude(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	longitude (degrees East) of the spacecraft
	standard_name	longitude
	units	degrees_east
	valid_min	-180.0
	valid_max	180.0
	comment	Longitude of the KMSF origin, with positive values indicating longitudes east of the Greenwich meridian.
double altitude(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	altitude of the spacecraft
	units	m
	valid_min	0.0
	valid_max	1000000.0
	coordinates	longitude latitude
	comment	Altitude above the reference ellipsoid of the KMSF origin.
double roll(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	roll of the spacecraft
	units	degrees
	valid_min	-180
	valid_max	180
	coordinates	longitude latitude
	comment	KMSF attitude roll angle; positive values move the +y antenna down.
double pitch(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	pitch of the spacecraft
	units	degrees
	valid_min	-180
	valid_max	180
	coordinates	longitude latitude
	comment	KMSF attitude pitch angle; positive values move the KMSF +x axis up.
double yaw(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	yaw of the spacecraft
	units	degrees
	valid_min	-180
	valid_max	180
	coordinates	longitude latitude
	comment	KMSF attitude yaw angle relative to the nadir track. The yaw angle is a right-handed rotation about the nadir (downward) direction. A yaw value of 0 deg indicates that the KMSF +x axis is aligned with the horizontal component of the Earth-relative velocity vector. A yaw value of 180 deg indicates that the spacecraft is in a yaw-flipped state, with the KMSF -x axis aligned with the horizontal component of the Earth-relative velocity vector.
double velocity_heading(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	heading of the spacecraft Earth-relative velocity vector
	units	degrees

	valid_min	0
	valid_max	360
	coordinates	longitude latitude
	comment	Angle with respect to true north of the horizontal component of the spacecraft Earth-relative velocity vector. A value of 90 deg indicates that the spacecraft velocity vector pointed due east. Values between 0 and 90 deg indicate that the velocity vector has a northward component, and values between 90 and 180 deg indicate that the velocity vector has a southward component.
double x(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	x coordinate of the spacecraft in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	x coordinate of the KMSF origin in the ECEF frame.
double y(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	y coordinate of the spacecraft in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	y coordinate of the KMSF origin in the ECEF frame.
double z(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	z coordinate of the spacecraft in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	z coordinate of the KMSF origin in the ECEF frame.
double vx(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	x component of the spacecraft velocity in the ECEF frame
	units	m/s
	valid_min	-10000.0
	valid_max	10000.0
	coordinates	longitude latitude
	comment	KMSF velocity component in x direction in the ECEF frame.
double vy(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	y component of the spacecraft velocity in the ECEF frame
	units	m/s
	valid_min	-10000.0
	valid_max	10000.0
	coordinates	longitude latitude
	comment	KMSF velocity component in y direction in the ECEF frame.
double vz(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	z component of the spacecraft velocity in the ECEF frame
	units	m/s
	valid_min	-10000.0
	valid_max	10000.0
	coordinates	longitude latitude
	comment	KMSF velocity component in z direction in the ECEF frame.

double plus_y_antenna_x(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	x coordinate of the plus_y antenna phase center in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	x coordinate of the plus_y antenna phase center in the ECEF frame.
double plus_y_antenna_y(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	y coordinate of the plus_y antenna phase center in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	y coordinate of the plus_y antenna phase center in the ECEF frame.
double plus_y_antenna_z(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	z coordinate of the plus_y antenna phase center in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	z coordinate of the plus_y antenna phase center in the ECEF frame.
double minus_y_antenna_x(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	x coordinate of the minus_y antenna phase center in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	x coordinate of the minus_y antenna phase center in the ECEF frame.
double minus_y_antenna_y(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	y coordinate of the minus_y antenna phase center in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	y coordinate of the minus_y antenna phase center in the ECEF frame.
double minus_y_antenna_z(num_tvps)		
	_FillValue	9.969209968386869e+36
	long_name	z coordinate of the minus_y antenna phase center in the ECEF frame
	units	m
	valid_min	-10000000.0
	valid_max	10000000.0
	comment	z coordinate of the minus_y antenna phase center in the ECEF frame.
int record_counter(num_tvps)		
	_FillValue	2147483647
	long_name	record counter
	units	1
	valid_min	1
	valid_max	999999999
	coordinates	longitude latitude
	comment	Index of the TVP record used to align data samples across granules.
unsigned byte sc_event_flag(num_tvps)		
	_FillValue	255
	long_name	spacecraft event flag

	standard_name	status_flag
	flag_meanings	yaw_flip_maneuver gyro_calibration_maneuver orbit_control_maneuver solar_array_rotation eclipse_entry eclipse_exit karin_bad_due_to_eclipse_event karin_bad_due_to_non_eclipse_event
	flag_masks	1 2 4 8 16 32 64 128
	valid_min	0
	valid_max	255
	coordinates	longitude latitude
	comment	Flag indicating spacecraft events that may affect the characteristics of the KaRIn data. The spacecraft is in a nominal state when all bits equal 0. The KaRIn measurement may be affected by a spacecraft event when any of bits 0 to 5 are equal to 1. The KaRIn measurement is likely bad when bits 6 or 7 are equal to 1.
unsigned byte tvp_qual(num_tvps)		
	_FillValue	255
	long_name	TVP quality flag
	standard_name	status_flag
	flag_meanings	good orbit_estimated_during_a_maneuver orbit_interpolated_over_data_gap orbit_extrapolated_for_a_duration_less_than_1_day orbit_extrapolated_for_a_duration_between_1_to_2_days orbit_extrapolated_for_a_duration_greater_than_2_days attitude_suspect attitude_suspect_and_orbit_estimated_during_a_maneuver attitude_suspect_and_orbit_interpolated_over_data_gap attitude_suspect_and_orbit_extrapolated_for_a_duration_less_than_1_day attitude_suspect_and_orbit_extrapolated_for_a_duration_between_1_to_2_days attitude_suspect_and_orbit_extrapolated_for_a_duration_greater_than_2_days attitude_bad attitude_bad_and_orbit_estimated_during_a_maneuver attitude_bad_and_orbit_interpolated_over_data_gap attitude_bad_and_orbit_extrapolated_for_a_duration_less_than_1_day attitude_bad_and_orbit_extrapolated_for_a_duration_between_1_to_2_days attitude_bad_and_orbit_extrapolated_for_a_duration_greater_than_2_days
	flag_values	0 4 5 6 7 8 10 14 15 16 17 18 20 24 25 26 27 28
	valid_min	0
	valid_max	28
	coordinates	longitude latitude
	comment	Flag indicating the quality of the reconstructed attitude and orbit ephemeris. A value of 0 indicates the reconstructed attitude and orbit ephemeris are both good. Non-zero values less than 20 indicate suspect data. Values greater than or equal to 20 indicate bad data.

Table 17. Variables of the grdem group of the L1B_HR_SLC product.

Group grdem Variables		
float height(num_grdem_lines, num_grdem_pixels)		
	_FillValue	9.96921e+36
	long_name	height of the surface
	units	m
	valid_min	-1500.0
	valid_max	15000.0
	comment	Local DEM height of the Earth surface relative to the reference ellipsoid.
double platform_time(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform time in UTC
	standard_name	time

	calendar	gregorian
	tai_utc_difference	[Value of TAI-UTC at time of first record]
	leap_second	YYYY-MM-DDThh:mm:ssZ
	units	seconds since 2000-01-01 00:00:00.000
	comment	UTC time that the spacecraft flew over each cross-track line of the GrDEM.
double platform_time_tai(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform time in TAI
	standard_name	time
	calendar	gregorian
	units	seconds since 2000-01-01 00:00:00.000
	comment	TAI time that the spacecraft flew over each cross-track line of the GrDEM.
double platform_latitude(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform latitude
	units	degrees_north
	valid_min	-80
	valid_max	80
	comment	Geodetic latitude (positive N, negative S) relative to the reference ellipsoid along the nadir track for each cross-track line of the GrDEM.
double platform_longitude(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform longitude
	units	degrees_east
	valid_min	-180
	valid_max	180
	comment	Longitude (east of the Greenwich meridian) along the nadir track for each cross-track line of the GrDEM.
float platform_altitude(num_grdem_lines)		
	_FillValue	9.96921e+36
	long_name	platform altitude
	units	m
	valid_min	800000.0
	valid_max	1000000.0
	coordinates	platform_longitude platform_latitude
	comment	Altitude of the KMSF orgin relative to the reference ellipsoid for each cross-track line of the GrDEM.
double platform_velocity_x(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform velocity x component in ECEF
	units	m/s
	valid_min	-10000.0
	valid_max	10000.0
	coordinates	platform_longitude platform_latitude
	comment	x component of the KMSF origin velocity in the ECEF frame for each cross-track line of the GrDEM.
double platform_velocity_y(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform velocity y component in ECEF
	units	m/s
	valid_min	-10000.0
	valid_max	10000.0
	coordinates	platform_longitude platform_latitude

	comment	y component of the KMSF origin velocity in the ECEF frame for each cross-track line of the GrDEM.
double platform_velocity_z(num_grdem_lines)		
	_FillValue	9.969209968386869e+36
	long_name	platform velocity z component in ECEF
	units	m/s
	valid_min	-10000.0
	valid_max	10000.0
	coordinates	platform_longitude platform_latitude
	comment	z component of the KMSF origin velocity in the ECEF frame for each cross-track line of the GrDEM.

6 References

[1] JPL D-61923, "SWOT Science Requirements Document," Jet Propulsion Laboratory Internal Document, 2018.

[2] JPL D-105503, "SWOT Algorithm Theoretical Basis Document: L1B_HR_SLC," Jet Propulsion Laboratory Internal Document, 2023.

[3] JPL D-102104, "SWOT Project Science Data Product Granule Boundary and Sampling Definition," Jet Propulsion Laboratory Internal Document, 2018.

Appendix A. **Acronyms**

CNES	Centre National d'Études Spatiales
DEM	Digital Elevation Model
ECEF	Earth-Centered, Earth-Fixed (frame)
GrDEM	Ground-range Digital Elevation Model
H	Horizontally polarized signal
HPA	High Power Amplifier
HR	High Rate
ITRF	International Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
KaRIn	Ka-band Radar Interferometer (instrument)
KMSF	KaRIn Metering Structure Frame
MOE	Medium-accuracy Orbit Ephemeris
NASA	National Aeronautics and Space Administration
NRCS	Normalized Radar Cross Section
POE	Precise Orbit Ephemeris
SAR	Synthetic Aperture Radar
SLC	Single-Look Complex (radar image)
SNR	Signal-to-Noise Ratio
SWOT	Surface Water and Ocean Topography (mission)
TAI	Temps Atomique International / International Atomic Time
TBC	To Be Confirmed
TBD	To Be Determined
TVP	Time Varying Parameters

UTC	Coordinated Universal Time
V	Vertically polarized signal
X factor	Radiometric normalization and calibration factor (not an acronym)