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Level 1b Algorithm Theoretical Basis Document
(L1b ATBD)</td></tr>
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Prepared Date</td><td colspan="3">31 May 2023</td></tr>
<tr><td>所　属
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日本電気（株）　NEC EarthCARE Project
富士通（株）　FUJITSU EarthCARE Project
欧州宇宙機関　ESA EarthCARE Project
日欧科学者会議 JMAG</td></tr>
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改訂記録 Change Record

符号 Revision	承認年月日 Approved Date	改訂箇所 Changed Section	改訂内容、理由等 Description of Change
NC	Jan. 2015	N/A	初版制定 First Issue
A	Mar. 2015	Table 6 navigationLandSea Flg	"65535=no data" and "This flag is based on GLOBCOVER" were added. (MOS-CDR-ME-04)
B	Feb. 2017	General	Modify the name of parameters so that those can be consistent with the definition in the PDD with respect to MOS-CDR-DL-05.
		Section 1.1	Add the explanation that off-line calibrations, which mean the external calibration and sea surface calibration, are out of scope with respect to MOS-CDR-DL-01.
		Section 2.2	Add the reference document.
		Section 3	Update the documents with respect to the RDs and Figure 3. Add Table 3.1 with respect to a part of MOS-CDR-RK-03. Specify the database of DEM and Land/water mask with respect to MOS-CDR-RK02.
		Section 4.1	Update the documents with respect to the updated Figure 4.1. Update the description from -0.5km to -1.0km with respect to CPR-ATB-PK-02. Update the vertical sampling window to 16,18 or 20km.
		Section 4.2	Update the documents generally.
		Section 4.3	Update the documents with respect to CPR-ATB-PK-02 and use of Land/Water mask (based on GlobCover) to distinguish land and ocean.
		Section 4.4	Update the documents with respect to CPR-ATB-HO-02/03/04, CPR-ATB-PK-03, CPR-ATB-ME-04. Add the numerical formula for measuring the radar beam direction and its explanation with respect to CPR-ATB-RK-01 (same with CPR4ALL-SY-4, MOS-CDR-ME-05).
		Section 4.5	Update the documents and Add the equation with respect to the spectrum width (sw).
		Section 4.6	Update the documents with respect to the updated Figure 4.6.
		Section 5	Add the explanation with respect to CPR-ATB-ME-06.
		Figure 3	Update the Figure 3 which is the flowchart of L1 processing with respect to CPR-ATB-ME-01
		Figure 4.1	Update the figure with respect to CPR-ATB-HO-05.
		Figure 4.4	Update the figure with respect to CPR-ATB-HO-04.
		Figure 4.7	Update the figure with respect to CPR-ATB-PK-05.

C	Apr. 2021	Section 2.2 Section 4.6	Add the reference document of RD-9 Add the explanation about alternative method (new method) for transmit power calculation as per CtS-PERF-9-1
D	See top page	Figure 3 Section 4.4 Figure 4.4 Figure 4.6 Section 4.7 Table 6	Add Doppler velocity at surface bin product Add the explanation of new products Add satellite velocity contamination and Doppler velocity at surface bin Modified figure caption Add the explanation of the surface range bin Modified explanation and add parameter

Table of Contents

1. INTRODUCTION
1.1 Scope

This document describes theoretical basis of Level 1b algorithm, except for the spacecraft data processing. In other words, this ATBD describes algorithm relating to calculation of physical radar data and radar calibration of EarthCARE/CPR. Since results of sea surface calibration or external calibration are not online type calibration, they are out of scope of this document. B

2. DOCUMENTS
2.1 Applicable documents
NONE

2.2 Reference documents

1) EarthCARE Mission Requirements Documents Issue 5 Revision 0-2, November 2006
2) EarthCARE Algorithm Description Document, ver.1.2 (4 Aug 2003)
3) Phase A study report on cloud profiling radar for EarthCARE (part2) issue 1, November 2005
4) EC.ICD.ASD.SY.00004 EarthCARE Product Definitions Volume 0 - Introduction
5) EC.ICD.ASD.SY.00005 EarthCARE Product Definitions Volume 1 - Common Products Definitions
6) MAS-110009A EarthCARE/CPR Level1 Product File Format Specification
7) MAS-140030NC EarthCARE Product Definitions –JAXA L2 product format- B
8) EC-ICD-ESA-SYS-299 Land/water mask for EarthCARE data processors: Format description
9) SEC-080013 Rev.G EarthCARE/CPR Performance Model and Performance Prediction C

3. PRODUCT DEFINITION FOR LEVEL 1B PRODUCT
In CPR level 1b products, received echo power, radar reflectivity factor, NRCS (normalized surface scattering cross section), Doppler velocity, spectrum width, and data flag are included (see Fig. 3). Gaseous attenuation corrected radar reflectivity factor, unfolded Doppler velocity and various cloud microphysical parameters are not included in level 1b and are processed in level 2a and 2b of JAXA processing (RD7). B
Figure 3 shows the flow chart of L1 algorithm. Major L1b output is designated as colored boxes. Input data list to L1b processing are shown in Table 3.1. In the L1 Processor, the database of DEM is ACE2. And Land/Water mask is prepared by ESA (RD8). B
In Level 1a processing, order and continuity of level 0 data are checked before level 1b processing. The list of level 1b products, data format of products, time and location information of products, detail explanation of level 1b flags, and etc. are shown in RD6. B

Table 3.1 List of input data for CPR L1 processing

Input data	Contents
Configuration files	Setting parameters and option for L1 processing
Level 0 product (ISP)	Science packet of CPR (Log detector, Pulse-Pair covariance, Tx monitor, observation configuration and parameter, etc.)
Satellite ancillary data	Orbit information file (GPS, reconstruction, predicted) Attitude information file
Auxiliary data	Instrument calibration data, PRF table, DEM, Land/Water mask

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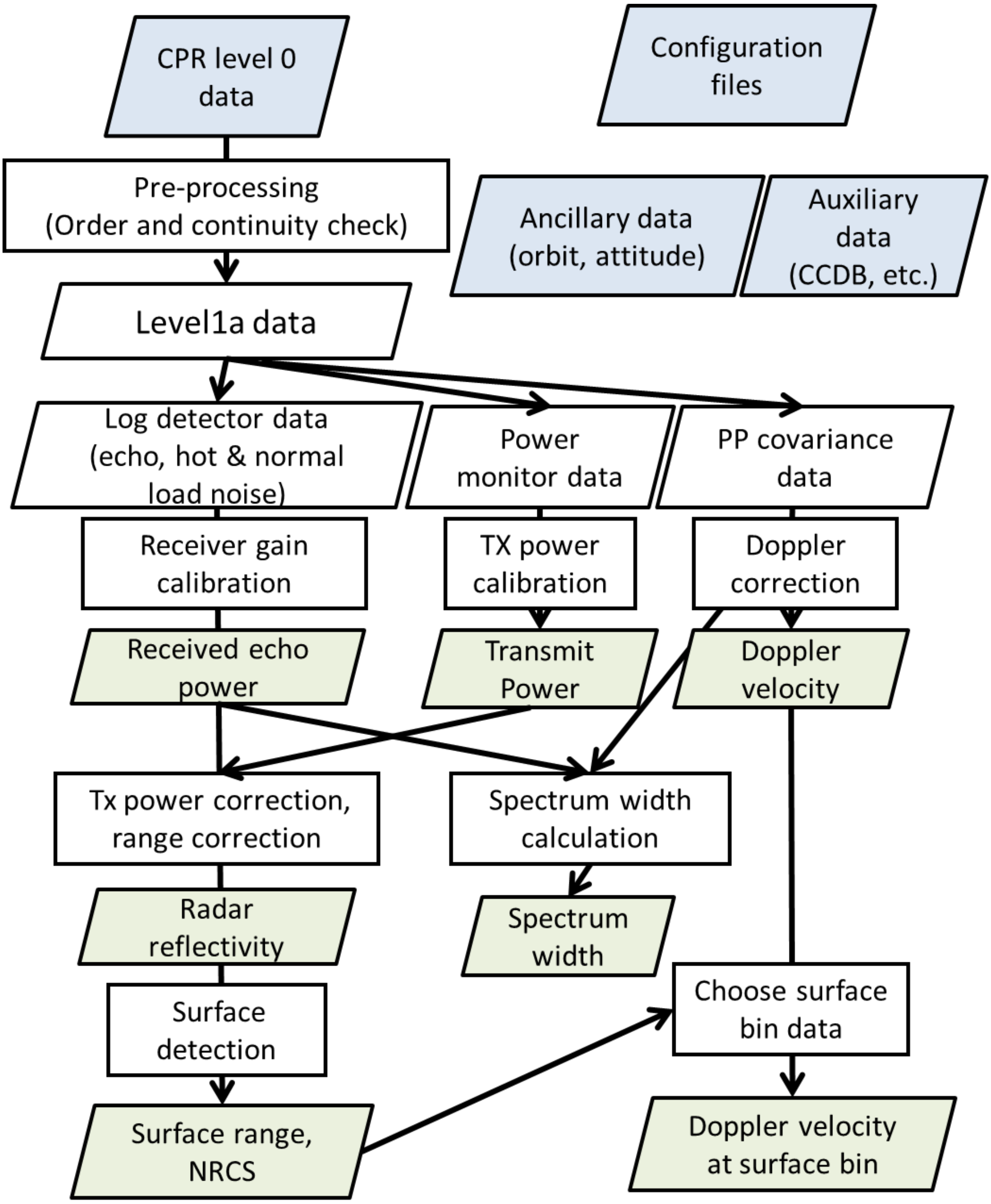


Figure 3 Flowchart for level 1 processing

4. THEORETICAL DESCRIPTION OF L1b RADAR PROCESSING ALGORITHM

4.1 Received echo power

Received echo power (P_r) is converted from the log detector output of CPR level 0 data. It is integrated with about 500m horizontal length on orbit. Mean Pr is calculated from division with integration number echo. Mean Pr is calibrated using receiver temperature, and calibration load data (hot & normal). Received echo power is distributed before noise power subtraction in consideration of horizontal integration in level 2 processing. Unit of received echo power is ‘W’. B

The vertical sampling window depends on the observation modes from -1.0 km below the ellipsoid model surface (WGS-84) to 16, 18 or 20 km above the ellipsoid surface for normal observation mode. Figure 4.1 shows the processing flow for received echo power and radar reflectivity factor.

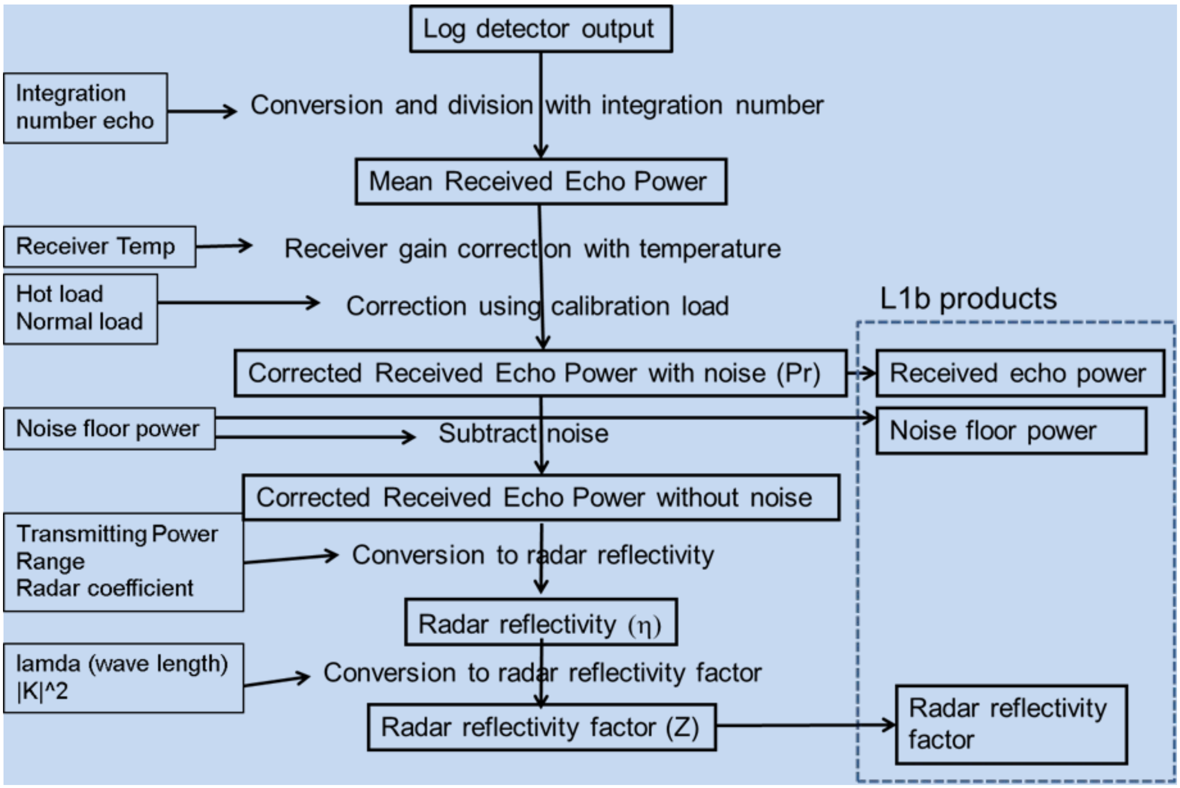


Figure 4.1 Processing for received echo power and radar reflectivity factor

4.2 Radar reflectivity factor

Radar reflectivity factor (Z) is converted from Received echo power (P_r) mentioned above. First, radar reflectivity (η) (volume scattering cross section) is calculated from the received echo powers (P_r), transmit power (P_t), and the radar calibration constant (C) as follows.

$$\eta = C \times \frac{P_r}{P_t} \times r^2$$

Where r is range to a target and P_t is calibrated with the transmit power monitor as written in sec 4.6. C is expressed as follows.

$$C = \frac{2^{10}(\ln 2)\pi^2 L}{G^2 \lambda^2 \theta^2 c\tau}$$

Where G is antenna gain at boresight, θ is half power beam width of antenna, λ is wave length of the radio wave, c is velocity of light, τ is pulse width, and L is loss factor. Then, the radar reflectivity factor Z is calculated as follows.

$$Z = \frac{\lambda^4}{\pi^5 |K|^2} \times \eta \times 10^{18}$$

Where $|K|^2$ is the normalizing dielectric factor. For EarthCARE/CPR, 0.75 is used for the normalizing dielectric factor $|K|^2$ corresponding to the liquid water value at 10 degree in 94GHz. Unit of radar reflectivity factor is 'mm^6/m^3'.

4.3 sigma zero (Normalized surface scattering cross section)

Sigma zero (σ^0) is the normalized radar reflectivity which corresponds to the land or ocean surface range. Sigma zero is a radar cross section divided by the real cross section. Using radar reflectivity at surface range ($\eta_{surface}$), sigma zero is calculated as follows. B

$$\sigma^0 = \eta_{surface} \times \frac{c\tau}{2}$$

Unit of sigma zero is a ratio in 'dB'. Land and ocean surfaces range are inferred by surface estimation program written in section 4.7. In order to distinguish land or ocean, Land/Water mask prepared by ESA is used.

4.4 Doppler velocity

Doppler velocities represent vertical movement speeds of echoes if the beam direction of the EarthCARE/CPR is precisely nadir. Doppler velocity is derived from IQ detector output instead of log detector output of CPR level 0 data. Unit of Doppler velocity is 'm/s'. The echo phase angle (ϕ) (in radians) is converted from the ratio of the real and imaginary parts of pulse-pair covariance coefficients (*PP*). A phase change of transmit pulse (ϕ_0) measured from leak signal to CPR receiver during transmit is used for collection of echo phase angle (ϕ). Also, a phase correction (ϕ_{sat}) from satellite velocity contamination to the radar beam direction (V_{sat}) is also calculated from ancillary data (satellite velocity, attitude, beam direction). Satellite velocity contamination to the radar beam direction (V_{sat}) is calculated by dot product of the satellite velocity vector ($\vec{v}_{sat}$) and the unit vector of CPR beam direction ($\vec{n}_{cpr}$) as follows. Both bias offset of CPR pointing from the nadir after antenna deployment in space and CPR pointing change by thermal distortion of CPR main reflector are considered to calculate $\vec{n}_{cpr}$. Calculated V_{sat} value is included in L1b products for reference. B D

$$V_{sat} = \vec{v}_{sat} \cdot \vec{n}_{cpr}$$

$$\phi_{sat} = 4\pi \cdot V_{sat} / (\lambda \times PRF)$$

$$\phi = \arctan(\operatorname{Im} PP / \operatorname{Re} PP) - \phi_0 - \phi_{sat}$$

The Doppler velocity (V) is calculated as follows.

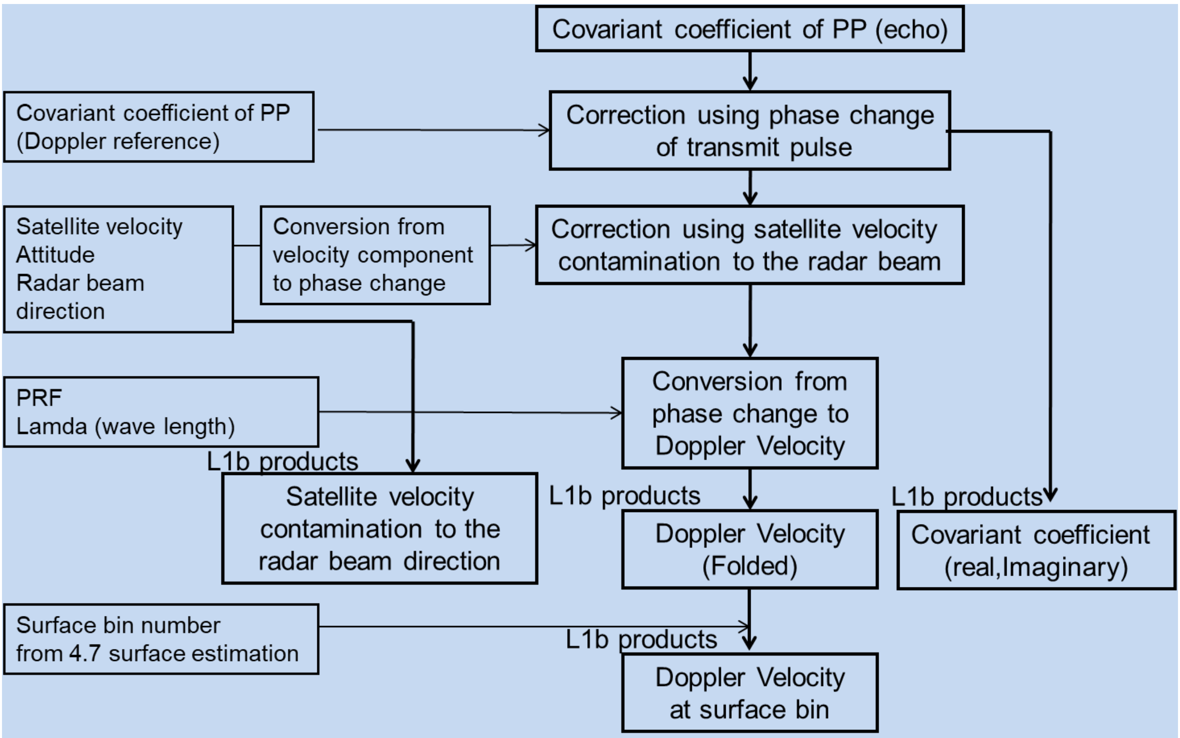
$$V = \frac{\phi \times \lambda \times PRF}{4\pi}$$

Where PRF is pulse repetition frequency. Since the maximum ambiguity Doppler velocity $V_{\max}$ is defined as follows, unfolding process should be introduced in level 2 processing.

$$V_{\max} = \frac{\lambda \times PRF}{4}$$

Finally, vertical Doppler velocity from $-V_{\max}$ to $+V_{\max}$ is derived. Correction of non-uniform reflectivity effect is considered as Level 2 processing. Doppler velocity at surface bin is chosen from Doppler velocity product. The surface bin is calculated in surface estimation routine in Sec. 4.7. D

Figure 4.4 illustrates Doppler velocity processing in L1b.



B D

Figure 4.4 Doppler processing in L1b.

4.5 Spectral width

The spectrum width (sw) is the width of the Doppler velocity spectrum including spectrum spreading due to satellite velocity. Unit of spectral width is 'm/s'. In the pulse-pair method adopted in the EarthCARE/CPR, spectral width is calculated from the two covariance coefficients and radar reflectivity of the pulse-pair in level 0 data. B

For this calculation, both the corrected covariance coefficient of pulse pair processing and received power are needed for the calculation.

$$sw = \frac{\lambda \times PRF}{2\sqrt{2}\pi}\sqrt{\left|\ln\left(\frac{f(\mathrm{Pr}-N)}{\left|\sqrt{\mathrm{Re}(PP)^2+\mathrm{Im}(PP)^2}\right|}\right)\right|}$$

4.6 Transmit power

Power detector diode is installed in the QOF and it can receive a part of RF transmit power. RF power is converted DC signal and transferred to the SPU. DC signal is converted to digital data and integrated pulse shape is recorded in level 0 data. Received leak pulse signal during transmit is additionally used for transmit power monitor. Figure 4.6 shows the processing flow of the transmit power. Firstly, pulse shape is checked, and if it has fine shape, pulse amplitude and pulse width is estimated. QOF and AD converter temperatures are used for calibration of DC signal. Transmit power is estimated from pulse amplitude with reference of the ground test data before launch. B

As a new method for transmit power calculation which does not use power monitor telemetry is established because the power level of the power monitor telemetry was not stable at the long period monitoring test on the ground. This method is to calculate the transmit power level from EIK temperature, the Tx pulse width and HPT power consumption. The details are described in 3.2.4 (2) of [RD9]. This method is an alternative C method and if the soundness of the power monitor is confirmed in orbit, the original method using power level from power monitor telemetry will be acceptable.

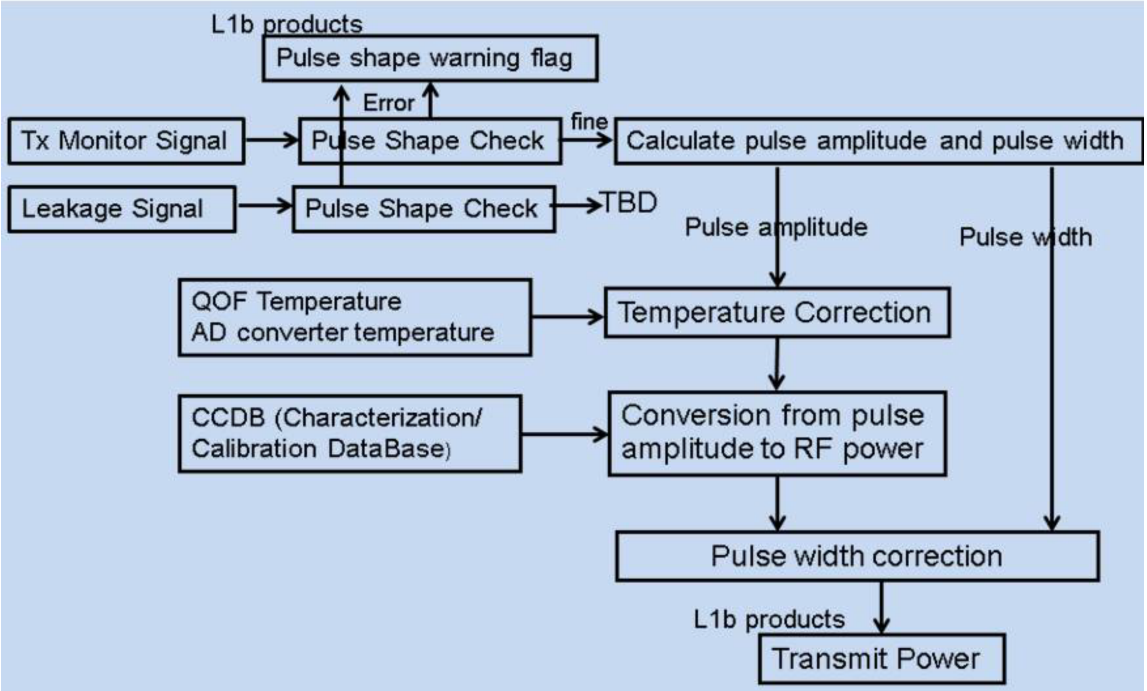


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Figure 4.6 Transmit power calculation flow using Tx power monitor

4.7 Surface estimation

Surface echo range is important for the higher level CPR algorithm. In L1b, surface echo range bin is determined using received echo power profile with the help of DEM information. Also, the exact location of the surface within a pulse is calculated. In presence of drizzle and/or rainfall, CPR data suffer attenuation and the surface echo may disappear in heavy rainfall case. This processing produces both the range bin information of the surface and the quality flag of the surface estimation. The surface range bin information is used for determining surface Doppler velocity at surface bin product. D

Figure 4.7 shows the processing flow for the surface echo detection.

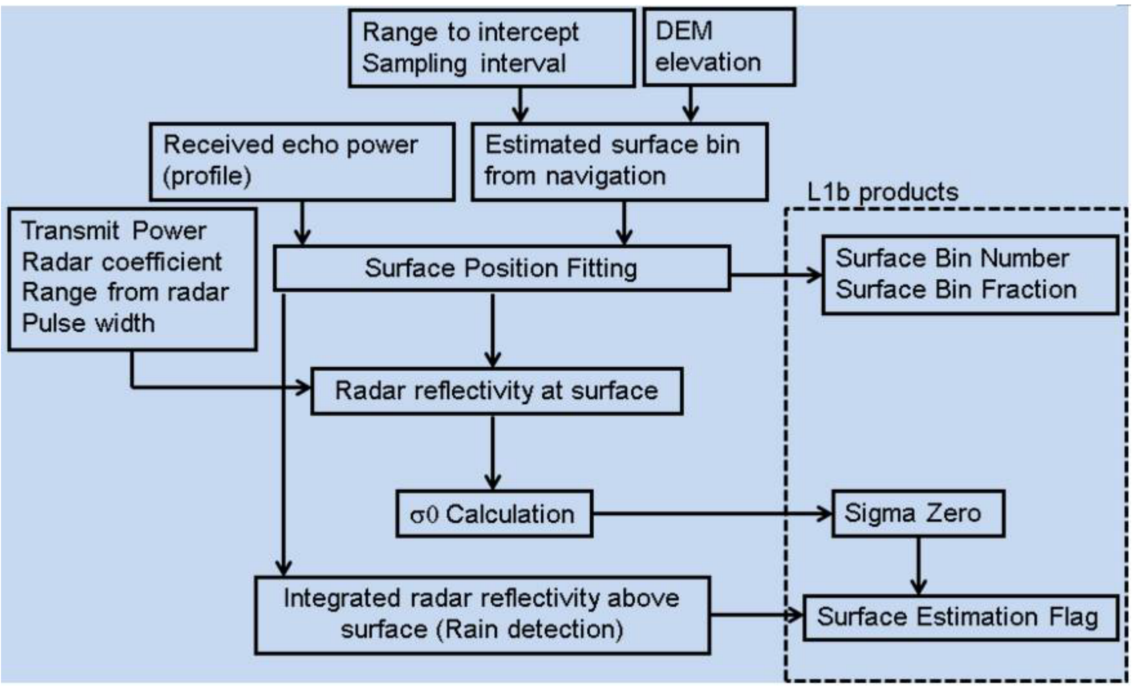

Figure 4.7 Processing flow for surface echo range B

5 OBSERVATION TIME

CPR observation time (Profile time) of level 1b product is the time when CPR antenna beam footprint is located in the center of 500 m integration frame (shown in Figure 5 “B”). The profile time is defined by the RF pulse transmitting time. B

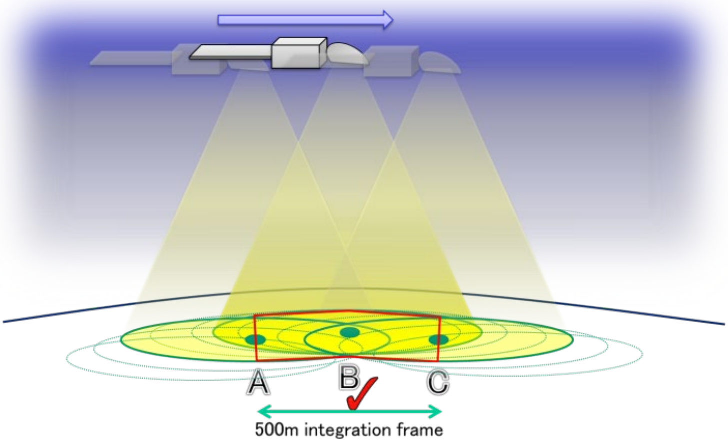

Figure 5 Definition of CPR observation time (Profile time)

6 GEO LOCATION INFORMATION

Geo location of CPR level 1b product shows the center of 500m integration frame on the ground as latitude and longitude (deg) with DEM elevation (m). Table 6 shows list of output contents of level 1b product relevant to geo location information.

Table 6. List of output contents of level 1b product relevant to geo location information

	name	explanation	unit	definition
1	Latitude	Latitude	deg	Geodetic latitude
2	Longitude	Longitude	deg	Geocentric Longitude
3	surfaceElevation	DEM elevation	m	Elevation from WGS84 reference ellipsoid
4	pitchAngle	pitch angle	deg	Rotation angle around rotated -Xs. Positive rotation angle is forward direction from the nadir. See the figure (*1). Note that this angle includes the satellite attitude and the CPR antenna's offset angle determined by CPR bias error and thermal distortion of the antenna.
5	rollAngle	roll angle	deg	Rotation angle around -Ys. Positive rotation angle is offset to the left side from the nadir. See the figure (*1). Note that this angle includes the satellite attitude and the antenna's offset angle determined by CPR bias error and thermal distortion of the antenna.
6	yawAngle	yaw angle	deg	Rotation angle around rotated +Z[1]s axis. Positive rotation angle is clock wise direction from the flight direction. See the figure (*1). Note that this angle includes the satellite attitude and the antenna's offset angle determined by CPR bias error.
7	satelliteVelocityX	satellite velocity X	m/s	X axis component of satellite velocity in Earth fixed coordinate
8	satelliteVelocityY	satellite velocity Y	m/s	Y axis component of satellite velocity in Earth fixed coordinate
9	satelliteVelocityZ	satellite velocity Z	m/s	Z axis component of satellite velocity in Earth fixed coordinate (the south pole to the north pole)
10	xPosition	satellite position X	m	Earth fixed coordinate
11	yPosition	satellite position Y	m	Earth fixed coordinate
12	zPosition	satellite position Z	m	Earth fixed coordinate
13	navigationLandWaterFlg	navigation land water flag	-	This flag is based on Land/Water mask (RD8)
14	rayHeaderSpatAvg	ray header spatial average	m	Horizontal Satellite-Track Length (integrated distance) for one Ray. It is almost 500m but correctly depends on PRF)
15	binHeight	hight of each bin	m	Representative height from the WGS84 ellipsoid corresponding to each bin
16	processingFrameNo	processing frame number	-	This is the sequential number of ray in a data processing control cycle. (1-14)
17	profileTime	profile time	sec	Representative Time of each ray

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18	rangeBinMaxNumber	range bin max number	-	Maximum number of Range Bin in CPR L1B product (218 for Normal Observation or 544 for Contingency Observation)
19	rangeToFirstBin	range to first bin	m	Distance from Satellite to the first bin
20	rangeToIntercept	range to Intercept	m	Distance from Satellite to the WGS84 surface
21	rayHeaderRangeBinSize	range bin size	m	One sample Bin Range (Fixed as 100 m)
22	rayNumber	ray number	-	Sequential number of each ray from start to end in the CPR L1B Product
23	solarAzimuthAngle	solar azimuth angle	degree	Solar azimuth angle
24	solarElevationAngle	solar elevation angle	degree	Solar elevation angle
25	timeFlag	time flag	-	Synchronization Flag between CPR time and Satellite time

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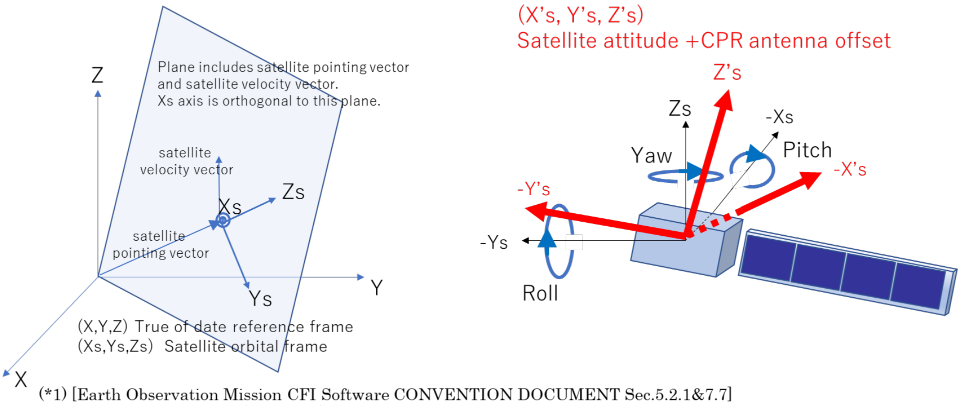

(*1) [Earth Observation Mission CFI Software CONVENTION DOCUMENT Sec.5.2.1&7.7]
The Satellite Orbit Frame (Xs, Ys, Zs) is defined by the satellite position vector and satellite velocity vector as shown in the left figure.
The CFI libraries apply the following convention when using Euler angles to Satellite orbit frame to Satellite reference frame.
The satellite reference frame (X's, Y's, Z's) is obtained by applying three consecutive rotations to the satellite orbit frame (Xs, Ys, Zs) :
1. Rotation around -Ys over a roll angle η
2. Rotation around the rotated -Xs over a pitch angle ξ
3. Rotation around the rotated Z's over a yaw angle ζ.