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contents

0. Preface 1
1. Purpose and scope 1
2. Overview of CPR pulse-pair Doppler measurement 1
3. Measured Doppler information including various error factor 2
4. Modification of ESSS Doppler relating processing 4
5. Potential limitation of the Doppler Simulation 6
6. Operating conditions of the CPR ESSS 6

Applicable Document

1. SEC-2017039 D Technical note on modification of CPR ESSS for Doppler information

0. Preface

The following contents (chapter 1 to 6) of this documentation are derived from the document of SEC-2017039D “technical note on modification of CPR ESSS for Doppler information” [AD-1] in order for the EarthCARE/CPR PI scientists to refer the technical approach for Doppler simulation in CPR ESSS (EarthCARE Satellite System Simulator) because the distribution of the original document is restricted.

1. Purpose and scope

CPR ESSS makes CPR ISP (L0) product using cloud echo information produced by the scene generator (ECSIM). This note explains concept of new Doppler products processing in ESSS in order to response ESA side request. Expected bias and random errors to the Doppler velocities are explained and their Doppler simulation ways are introduced. A Doppler error caused by non-uniform reflectivity is not included in this modification.

2. Overview of CPR pulse-pair Doppler measurement

CPR measures Doppler velocities of echo by a pulse-pair method. It measures Doppler velocity from phase change of echoes between two transmitted pulses. Real and imaginary parts of pulse-pair are independently integrated within some duration corresponding 500m horizontal movement. It is called a pulse-pair covariance (R(τ)) and this covariance is a base of Doppler information in ISP (L0). From the pulse-pair covariance, measured Doppler velocities V_m are calculated as follows.

$$V_m = \frac{\lambda\cdot\mathrm{PRF}}{4\pi}\tan^{-1}\left(\frac{\mathrm{Im}(\mathrm{R}(\tau))}{\mathrm{Re}(\mathrm{R}(\tau))}\right) \quad (1)$$

λ: wave length of radio PRF: Pulse Repetition Frequency τ: inter pulse period (1/PRF)

The range of V_m is from $-\lambda\cdot\mathrm{PRF}/4$ to $+\lambda\cdot\mathrm{PRF}/4$.

With opposite calculation of (1), we can calculate real and imaginary pulse-pair covariance as follows

$$\mathrm{Im}\big(\mathrm{R}(\tau)\big) = \mathrm{A}\cdot\sin\left(\frac{4\pi\cdot V_m}{\lambda\cdot\mathrm{PRF}}\right) \quad (2)$$

$$\mathrm{Re}(\mathrm{R}(\tau)) = \mathrm{A}\cdot\cos\left(\frac{4\pi\cdot V_m}{\lambda\cdot\mathrm{PRF}}\right) \quad (3)$$

A: arbitrary positive value

A is arbitrary value, but it will be chosen such as proportional to echo intensity for considering horizontal integration in L2 processing.
If V_m is less than $-\lambda \cdot \mathrm{PRF}/4$ or more than $+\lambda \cdot \mathrm{PRF}/4$, Doppler folding occurs to V_m. It means velocity of $V_m \pm n \cdot \frac{\lambda \cdot \mathrm{PRF}}{2}$ has the same covariance value in case of V_m.

3. Measured Doppler information including various error factor

Measured Doppler velocity (V_m) obtained by CPR is assumed to include several kinds of Doppler errors. Here, we assumed V_m as follows.

$$\begin{aligned} V_m &= V_c + \mathrm{DOP\_ERROR} \\ &= V_c + (BIAS\_ERROR + RANDOM\_ERROR) \\ &= V_c + \left(\mathrm{V}_{\mathrm{los}} + \mathrm{V}_{txphase} + \mathrm{V}_{residual}\right) + \left(\mathrm{V}_{theoretical} + \mathrm{V}_{\mathrm{CPRphase}}\right) \qquad (4) \end{aligned}$$

V_c: Doppler velocity of cloud echo (in ESSS, it is obtained by scene generator)
V_{los}: CPR beam direction's line of sight satellite velocity
$V_{txphase}$: Velocity bias error caused by constant phase change of CPR transmitter
$V_{residual}$: Residual bias error of Doppler
$V_{theoretical}$: Theoretical limit of Doppler measurement caused by spread of Doppler velocities within the beam width
$V_{CPRphase}$: Random error came from CPR phase measurement accuracy

In L1 processing, V_{los} and $V_{txphase}$ are corrected. So, measured Doppler velocity of L1 products (V_{m_L1}) is as follows.

$$V_{m\_L1} = V_c + (\mathrm{V}_{residual}) + \left(\mathrm{V}_{theoretical} + \mathrm{V}_{\mathrm{CPRphase}}\right) \qquad (5)$$

Those errors above are explained more detail in the followings.
Figure 3.1 shows schematic view of Doppler measurement using EarthCARE CPR. CPR measures its beam direction's line of sight velocity.
Since EC satellite moves CPR beam direction (beam direction is not perpendicular to the satellite velocity), the line of sight satellite velocity (V_{los}) is added to the Doppler velocities of cloud (Vc) which are provided from the ECSIM scene generator.
V_{los} is calculated from unit vector of CPR beam direction ($\overrightarrow{n_{\mathrm{beam}}}$) and satellite velocity information ($\overrightarrow{V_{\mathrm{sat}}}$) as follows.

$$V_{los} = \overrightarrow{n_{beam}} \cdot \overrightarrow{V_{sat}} \quad (6)$$

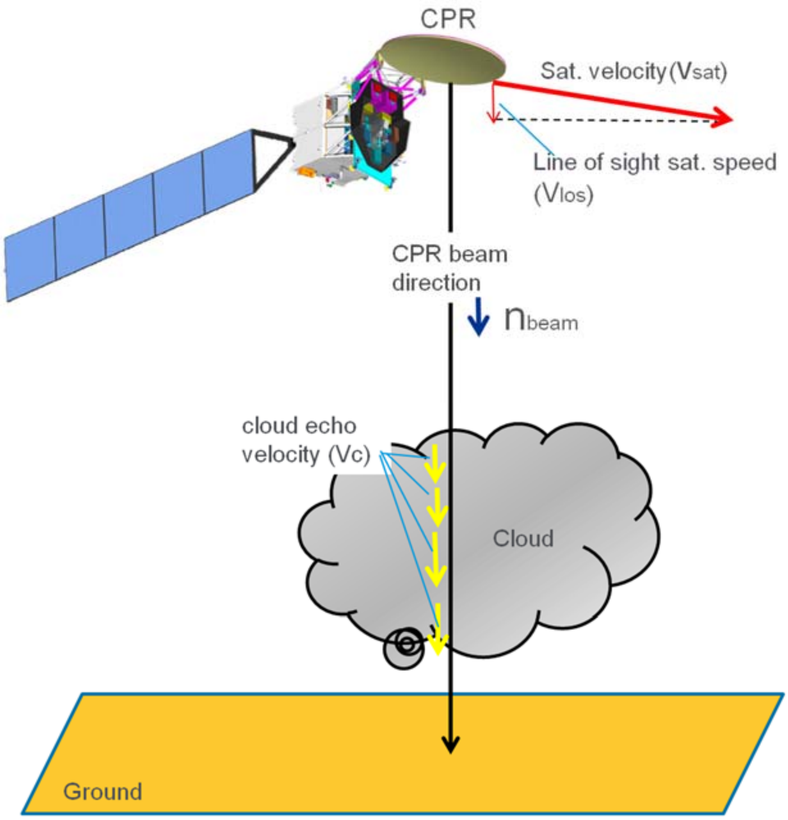

Figure 3.1: Schematics of satellite velocity and CPR Doppler measurement

In order to measure Doppler velocities from pulse-pair method, phase of transmitter radio wave should be constant. If there is constant phase change in CPR transmit radio wave, it causes bias error of Doppler measurement. Actually, the phase of CPR transmit radio wave is almost constant, however CPR have a function to measure phase of transmit radio using weak leek transmit signal to the receiver (Doppler reference signal). Pulse-pair covariance is calculated for Doppler reference signal in the same way as Doppler measurement of echoes and this covariance is one of the information in ISP (L0). In L1 processing, bias error caused by transmitter's phase change ($V_{txphase}$) is calculated from covariance of Doppler reference in the same way of equation (1) and V_m is corrected using $V_{txphase}$.

$V_{residual}$ in (4) includes various bias errors such as errors caused by the attitude measurement error, CPR attachment error, CPR beam pointing error, etc. If detail of those bias errors will become clear, we will include bias correction of those errors in

L1 processing. However, we do not include this error in ESSS, yet. There is a plan to include error correction of beam pointing caused by thermal distortion of main reflector in L1 processing in the future.

Main part of random errors is theoretical limit error ($V_{theoretical}$) caused by spread of Doppler velocities within the beam width. It related pulse repetition frequency (PRF), satellite velocity, CPR beam width, signal to noise ratio (S/N) and pulse integration number. PRF changes with the latitude because PRF is determined by the satellite altitude. S/N is proportional to the echo's reflectivity, or the radar reflectivity factor. Standard deviation of $V_{theoretical}$ ($STD_{theoritical}$) is calculated from PRF, S/N, and pulse integration number using perturbation approximation of Doppler error estimation in Doviak and Zrnic (1993). Then, Gaussian error distribution which has zero mean value and standard deviation of $STD_{theoritical}$ is calculated. Using this error distribution, $V_{theoretical}$ is simulated.

Phase measurement error ($V_{CPRphase}$) is a random error caused by the CPR receiver and signal processor. $V_{CPRphase}$ is simulated from Gaussian error distribution in the same way as $V_{theoretical}$ case. However, its standard deviation is a constant in correspondence with CPR phase error measurement obtained by CPR ground test.

4. Modification of ESSS Doppler relating processing

Main part of ESSS modification is adding $V_{theoretical}$ error to the pulse-pair covariance. In order to calculate this error, $STD_{theoretical}$ should be calculated from PRF and radar reflectivity factor using perturbation approximation method in Doviak and Zrnic. PRF and latitude relation is given by reference table previously.

$V_{CPRphase}$ is simulated in the same way as $V_{theoretical}$ error. Instead of use of $STD_{theoretical}$, standard deviation corresponding with CPR phase error measurement ($STD_{CPRphase}$) is used for making an error distribution of $V_{CPRphase}$. From this error distribution, $V_{CPRphase}$ is randomly selected.

In order to add V_{los}, satellite speed vector is calculated from satellite orbit simulation. If we do not include any bias error factor of beam direction in ESSS, the CPR beam direction is assumed as perpendicular to the earth reference ellipsoid. Using satellite speed vector and CPR beam direction, V_{los} is calculated using CFI function.

In order to add $V_{txphase}$ in ESSS, some small value of phase change in transmitter is assumed. This phase change is converted to the bias error of Doppler velocity ($V_{txphase}$) and real and imaginary parts of pulse-pair covariance of Doppler reference signal (R_{dop_ref}) are simulated as follows.

$$\mathrm{Im}\left(R_{dop\_ref}\right) = \mathrm{AA}\cdot\sin\left(\frac{4\pi \cdot V_{txphase}}{\lambda\cdot\mathrm{PRF}}\right) \quad (7)$$

$$\mathrm{Re}\left(R_{dop\_ref}\right) = \mathrm{AA}\cdot\cos\left(\frac{4\pi \cdot V_{txphase}}{\lambda\cdot\mathrm{PRF}}\right) \quad (8)$$

In this case, we do not care about arbitrary value of AA, because only the phase of the covariance is used in L1 processing.

After calculation of $V_{theoretical}$, $V_{CPRphase}$, V_{los}, $V_{txphase}$ written above, simulated measured Doppler (V_{m_L0}) is in ESSS as follows.

$$V_{m\_L0} = V_c + \left(\mathrm{V_{los}} + \mathrm{V}_{txphase}\right) + \left(\mathrm{V}_{theoretical} + \mathrm{V_{CPRphase}}\right) \qquad (9)$$

Using (2) and (3), pulse-pair covariance including errors ($R(\tau)_{L0}$) is calculated in ESSS as follows.

$$\mathrm{Im}(\mathrm{R}(\tau)_{\mathrm{L0}}) = \mathrm{A}\cdot\sin\left(\frac{4\pi \cdot V_{m\_L0}}{\lambda\cdot\mathrm{PRF}}\right) \quad (10)$$

$$\mathrm{Re}(\mathrm{R}(\tau)_{\mathrm{L0}}) = \mathrm{A}\cdot\cos\left(\frac{4\pi \cdot V_{m\_L0}}{\lambda\cdot\mathrm{PRF}}\right) \quad (11)$$

As mentioned before, A is chosen such as proportional to echo intensity for considering horizontal integration in L2 processing.

5. Potential limitation of the Doppler Simulation

Firstly, this Doppler simulation assumed a uniform atmospheric condition. Then an error caused by non-uniform reflectivity is not included.

As described above chapters, the simulated Doppler value is considering the error components such as $V_{theoretical}$, $V_{CPRphase}$ and $V_{txphase}$. These are dominant components of Doppler velocity measurement errors. Some bias errors ($V_{residual}$) caused by the attitude measurement error, CPR attachment error, and CPR beam pointing error are not included in current ESSS v2.4. However, there is a plan to include error correction of beam pointing caused by thermal distortion of main reflector in L1 processing in the future.

6. Operating conditions of the CPR ESSS

The CPR ESSS v2.4 which includes this Doppler simulation can work for the cloud information produced by the scene generator (ECSIM) and output the CPR ISP (L0) product.

The CPR ESSS v2.4 supports constant phase error components which are not only for CPR phase error but also for additional bias and harmonic errors. These configurable parameters will be able to set on the configuration file of ESSS in v2.4 and later.