Verification of Pointing Calibration Methods for Kompsat-6

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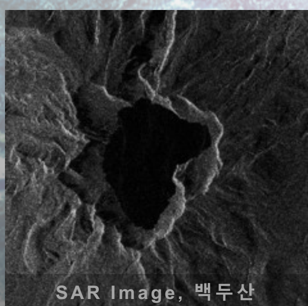
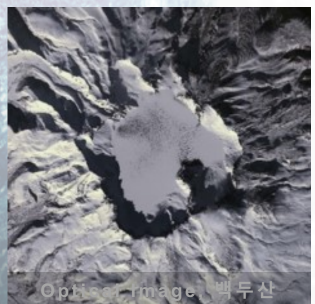
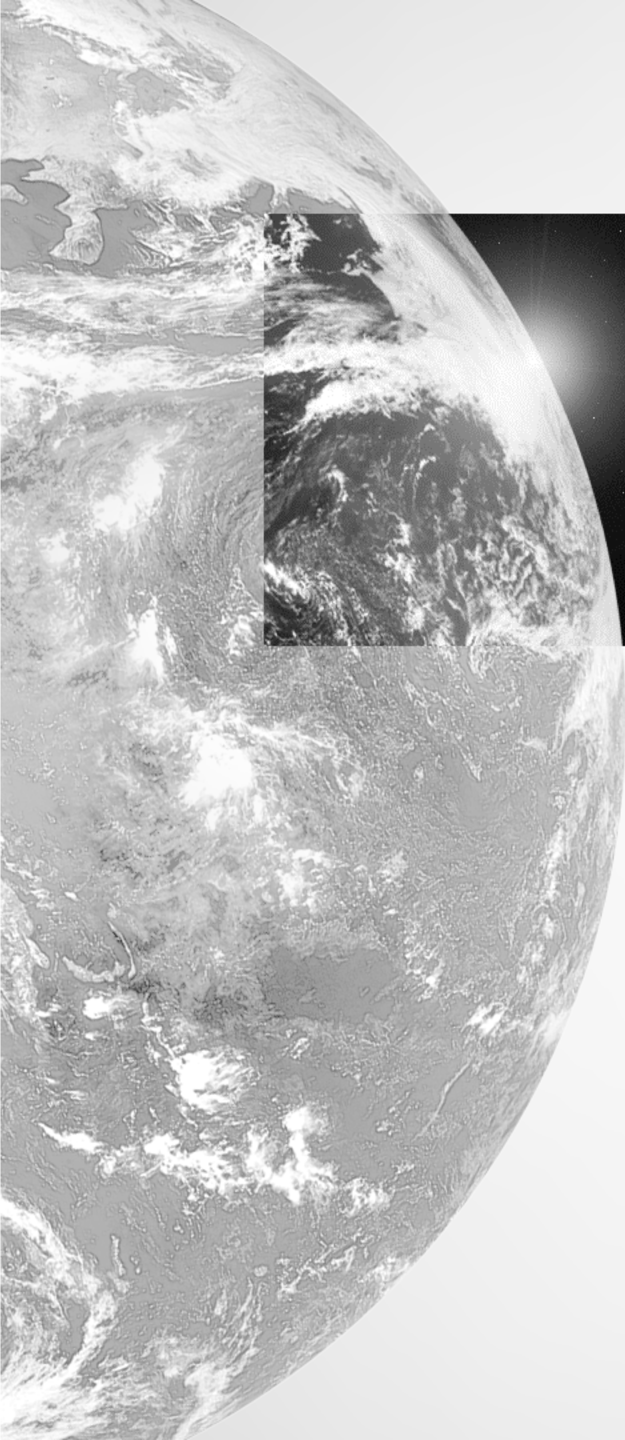




Agenda

- Introduction
- Method
- Verification
- Conclusions



Introduction

Kompsat-6 (K6)

Mission Objectives

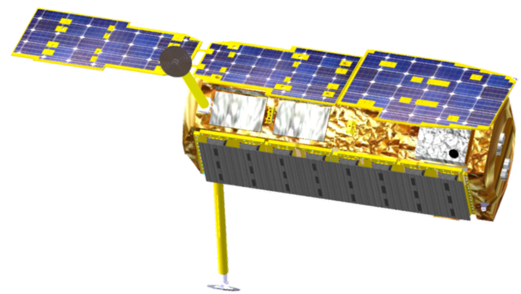
- "Expedite provision of the space-borne Synthetic Aperture Radar images with sub-meter resolution required for the national demand in GIS (Geographical Information Systems), Ocean & Land management, Disaster monitoring, and ENvironment monitoring"

Launch Date / Life Time

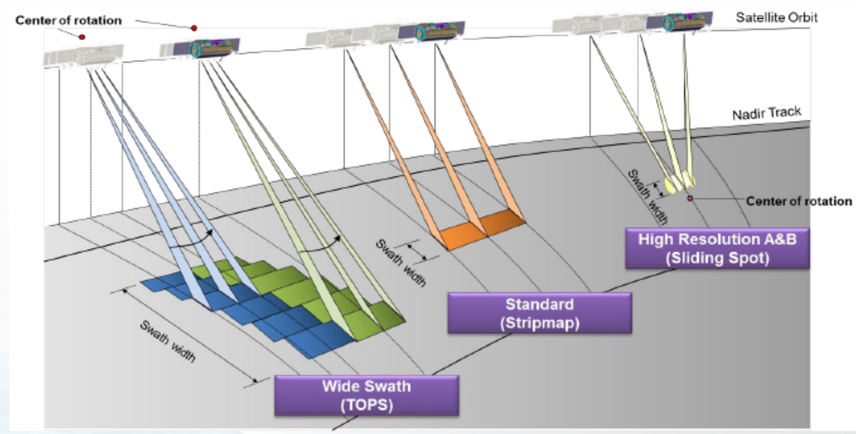
- November-2021 / 5 years

SAR Payload

- Space-borne Synthetic Aperture Radar
- X-band with an active phased array antenna
- Four Imaging modes
  - ✓ High Resolution-A: 0.5 m resolution, 5 km swath
  - ✓ High Resolution-B: 1 m resolution, 10 km swath
  - ✓ Standard: 3 m resolution, 30 km swath
  - ✓ Wide Swath (TOPS): 20 m res., 100 km swath
- Coherent Dual Polarization
- Quad Pol. & ATI/GMTI as Experimental Mode
- InSAR Capability (orbital tube with 250 m radius)



Kompsat-6 Configuration



K6 SAR Imaging Modes

Doppler Centroid (DC)

Definition

- Doppler frequency at the time that the beam center crosses a target

Importance

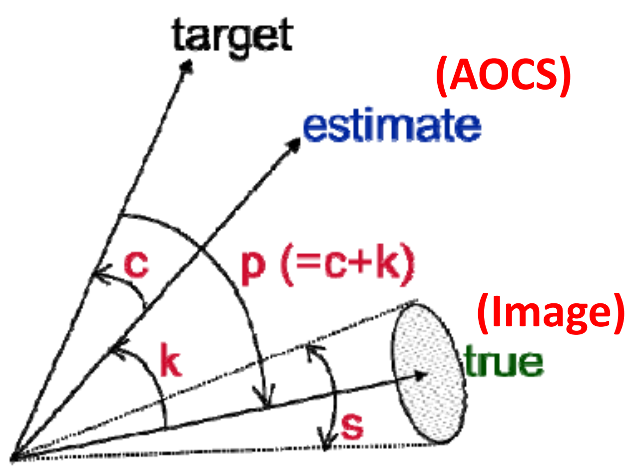
- SAR processing aspect
  - ✓ Necessary for SAR image processing in azimuth direction required for operations such as range cell migration correction, azimuth compression, and image registration.
- Calibration aspect
  - ✓ Necessary for satellite attitude correction or beam pointing calibration

Estimation Method

- Geometry method
  - ✓ DC is calculated from geometric information including the satellite's orbit, attitude, antenna misalignments, beam steering etc.
  - ✓ DC estimate is sometimes not accurate enough due to uncertainties in geometric information (especially attitude), but is stable not depending on image by image
- Image method
  - ✓ DC is calculated from magnitude or phase information of SAR images
  - ✓ DC estimate is accurate but depending on image quality (ex. Homogeneity)

Satellite Attitude Estimation from SAR

- Satellite Attitude Characteristics
  - ✓ Measured satellite attitude from attitude and orbit control system (AOCS) can be deviated from true attitude
  - ✓ Satellite attitude estimated directly from SAR images is considered close to true attitude
- Attitude Compensation
  - ✓ DC difference (delta DC) from geometric information and from image can be used to estimate satellite attitude error.



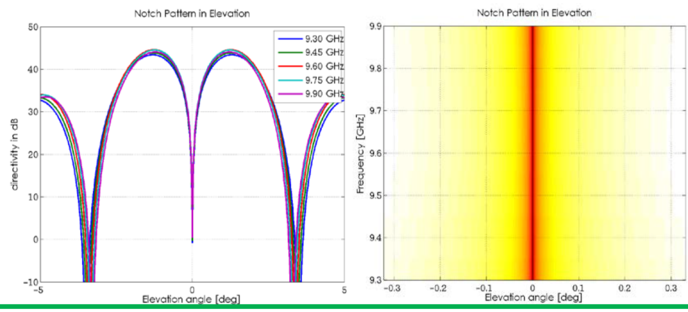
→	LOS direction
target	desired pointing direction
true	actual pointing direction (mean)
estimate	estimate of true (instantaneous)
p	pointing error (long-term)
s	stability (peak-peak motion)
k	knowledge error
c	control error

Satellite Attitude Error Definitions

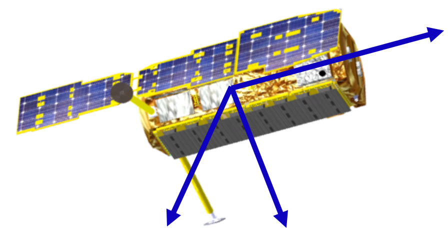
K6 Pointing Calibration Concept

Notch Method

- Elevation/Azimuth Notch Patterns
  - ✓ Compare reference vs. measured patterns

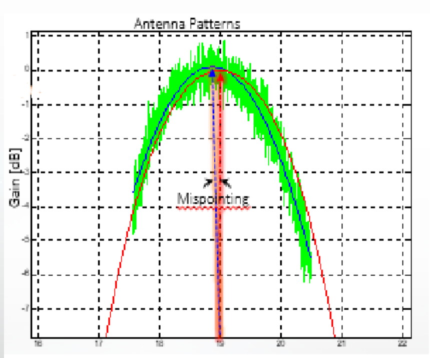


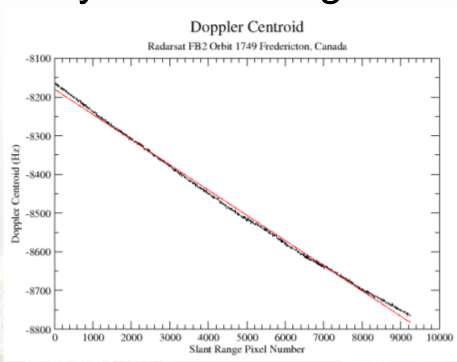
- Satellite Attitude Offset Estimation
  - ✓ Roll-Pitch-Yaw offsets



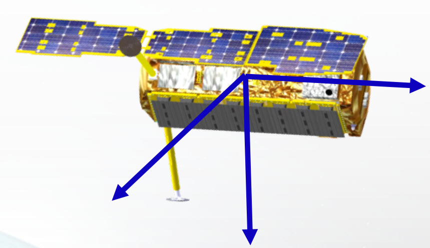
Doppler Centroid Method

- DC Geometry & DC Image Measurements
  - ✓ Compare DC geometry vs. DC image





- Satellite Attitude Offset Estimation
  - ✓ Pitch-Yaw offsets



Research Motivation & Objective

Motivation

- Accurate DC estimation and satellite attitude compensation are essential part of SAR processing and sensor calibration
- Kompsat-6 requires very high DC and satellite attitude estimation accuracy
  - ✓ K6 DC accuracy requirement: $\leq$ 5 Hz
  - ✓ K6 Pointing Knowledge req.: $\leq$ 0.032° (R), $\leq$ 0.024° (P), $\leq$ 0.017° (Y) [3σ]

Objective

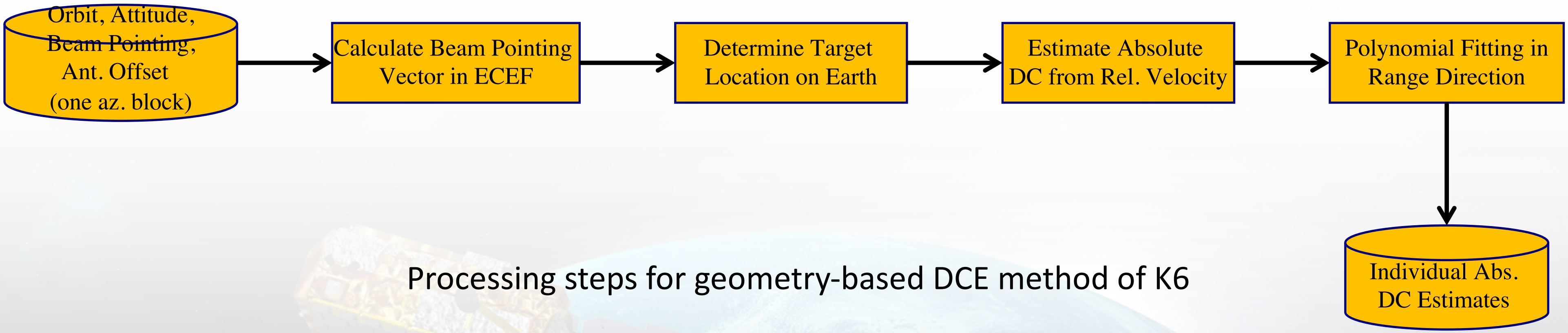
- To develop stable and accurate DC estimation algorithm for Kompsat-6
- To develop accurate satellite attitude offset estimation algorithm from DC measurements for Kompsat-6
- To verify the K6 satellite attitude compensation algorithm using simulated data and actual Kompsat-5 data

Method

K6 Doppler Centroid Estimation (DCE) Methods (1)

Geometry Method

- Consider all necessary geometric information required to determine DC
  - ✓ Satellite state vector, attitudes, attitude offsets, antenna position offsets, antenna misalignments, beam pointing direction, beam pointing offsets, etc.
- Apply satellite sensor modeling to determine precise location of a target on Earth
- Consider various time (range/azimuth) error sources including internal hardware delay, atmospheric delay, etc.
- DC estimation is performed at each block center after subdividing an image into blocks in the azimuth and range directions
- Polynomial fitting is performed for DC estimates in the range direction



Processing steps for geometry-based DCE method of K6

K6 DCE Methods (2)

Image Method

- DC is estimated after subdividing an image into blocks in the azimuth and range directions
- Doppler ambiguity is calculated from geometry-based method (may not necessary due to K6 accurate zero-Doppler steering)
- Baseband Doppler centroid within PRF is estimated from raw image using average cross correlation coefficient (ACCC) at lag one
- DC estimates are unwrapped in the range direction
- Absolute DC are estimated by combining the unwrapped DC estimates and Doppler ambiguity
- Polynomial fitting is performed for DC estimates in the range direction
- Calculation of ACCC at lag one in the azimuth direction:

$$c(\eta) = \sum_{\eta} s(\eta + \Delta\eta) s^*(\eta)$$

$$\phi_{accc} = \angle c(\eta)$$

$s(\eta)$ = a complex sample of an image

$\Delta\eta$ = the azimuth sample interval (1/PRF)

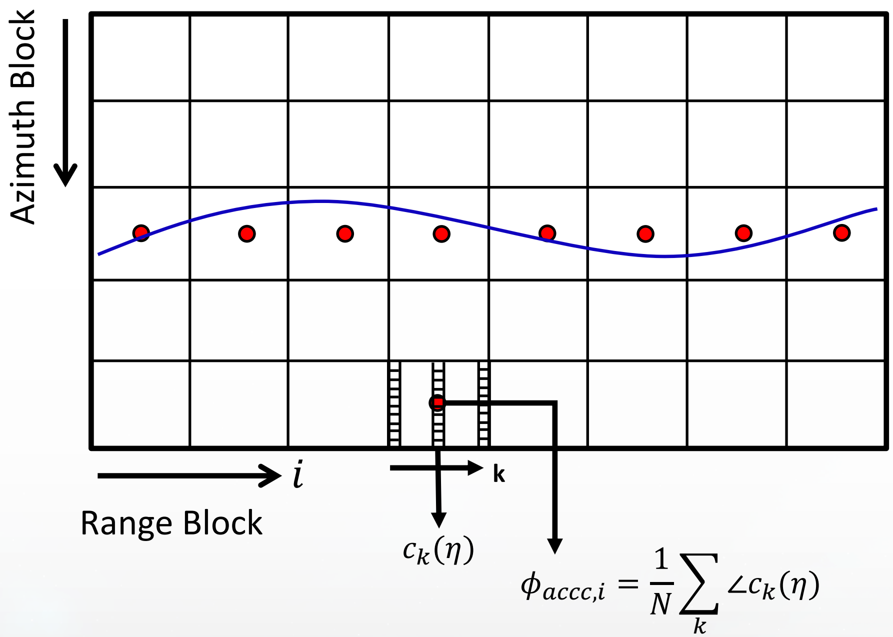
$s(\eta + \Delta\eta)$ = next complex sample in the azimuth direction

$$f_{DC} = \frac{\phi_{accc}}{2\pi} PRF$$

K6 DCE Methods (3)

Block Processing

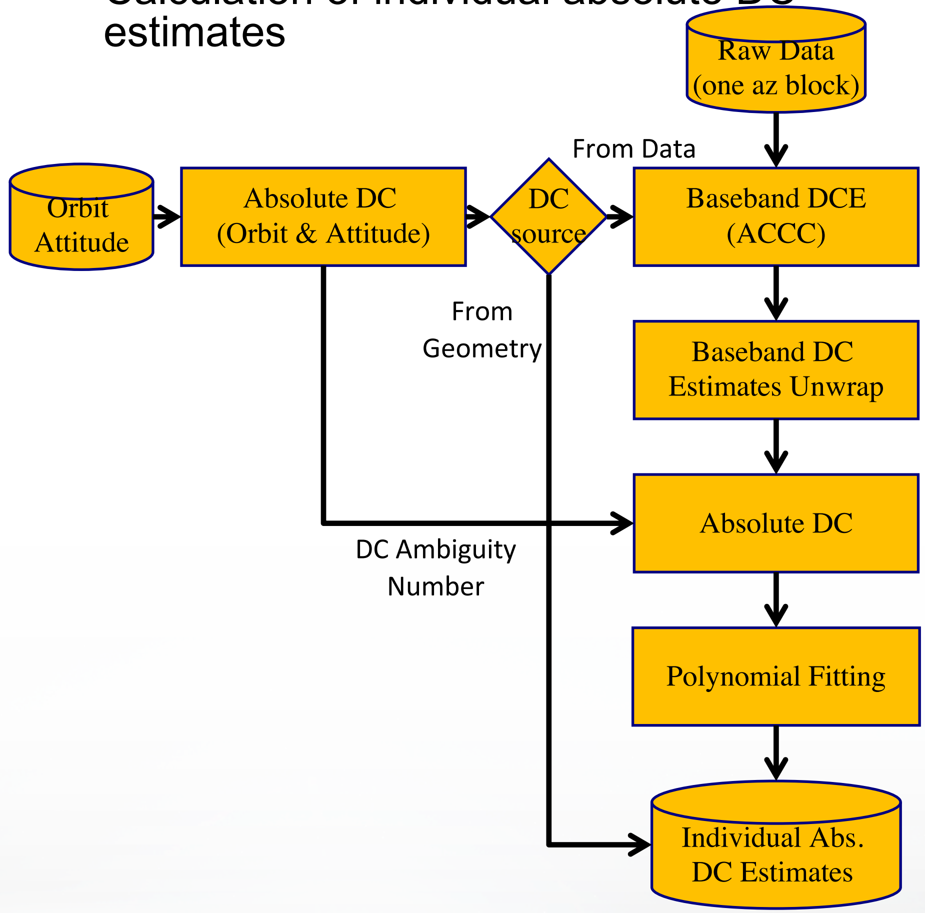
- ✓ The size and the number of the azimuth and range blocks are configurable



Schematic plot of DCE block processing

Processing Flow

- ✓ Calculation of individual absolute DC estimates



Processing steps for image-based DCE method of K6

K6 Satellite Attitude Estimation Methods (1)

Attitude Rotation and Azimuth Displacement

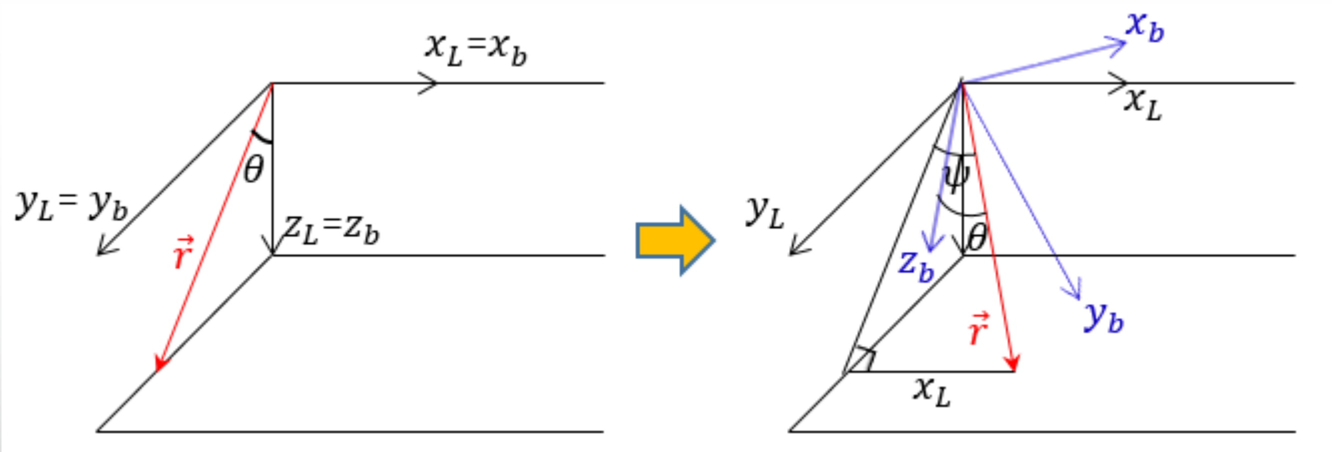
- Coordinates Systems
  - ✓ Zero Doppler frame: $\vec{X}_L = [x_L, y_L, z_L]$, Satellite body frame: $\vec{X}_b = [x_b, y_b, z_b]$
- Assumption: roll[R]-pitch[P]-yaw[Y] (1-2-3) rotation sequence & small angle rotation
- Relation

$$\vec{X}_b = R_Y R_P R_R \vec{X}_L \Leftrightarrow \vec{X}_L = R_R^{-1} R_P^{-1} R_Y^{-1} \vec{X}_b$$

$$\vec{X}_L = \begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} = \begin{bmatrix} 1 & -Y & P \\ Y + RP & 1 - RPY & -R \\ RY - p & R + PY & 1 \end{bmatrix} \begin{bmatrix} 0 \\ r sin\theta \\ r cos\theta \end{bmatrix}$$

- DC is related to azimuth displacement (x_L) & squint angle (ψ)

$$sin\psi = {}^{x_L}/_{r} = [-Y sin\theta + P cos\theta]$$



Beam pointing variation due to satellite attitude rotation

K6 Satellite Attitude Estimation Methods (2)

Doppler Centroid (f) and Azimuth Squint Angle (ψ)

- SAR imaging geometry

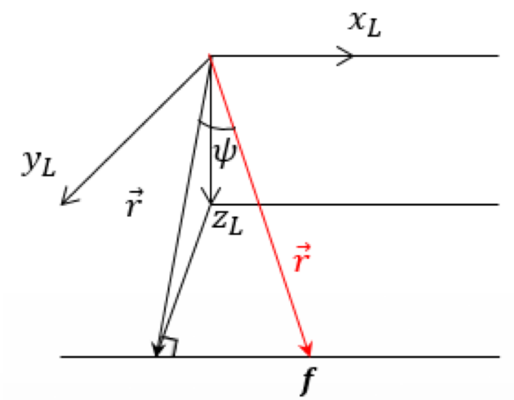
$$f = -\frac{2}{\lambda}|v_{st} - v_T|sin\psi$$

Attitude Rotation and DC

$$\frac{-\lambda f}{2|v_{st} - v_T|} = [-sin\theta \quad cos\theta]\begin{bmatrix} Y \\ P \end{bmatrix}$$

Measurements in wide elevation range

$$\begin{bmatrix} \frac{-\lambda f_1}{2\left|v_{st,\mathbf{1}} - v_{T,\mathbf{1}}\right|} \\ \vdots \\ \frac{-\lambda f_n}{2\left|v_{st,\mathbf{n}} - v_{T,\mathbf{n}}\right|} \end{bmatrix} = \begin{bmatrix} -sin\theta_1 & cos\theta_1 \\ \vdots & \vdots \\ -sin\theta_n & cos\theta_n \end{bmatrix}\begin{bmatrix} Y \\ P \end{bmatrix} \Leftrightarrow y = Hx$$



Doppler centroid and azimuth squint angle

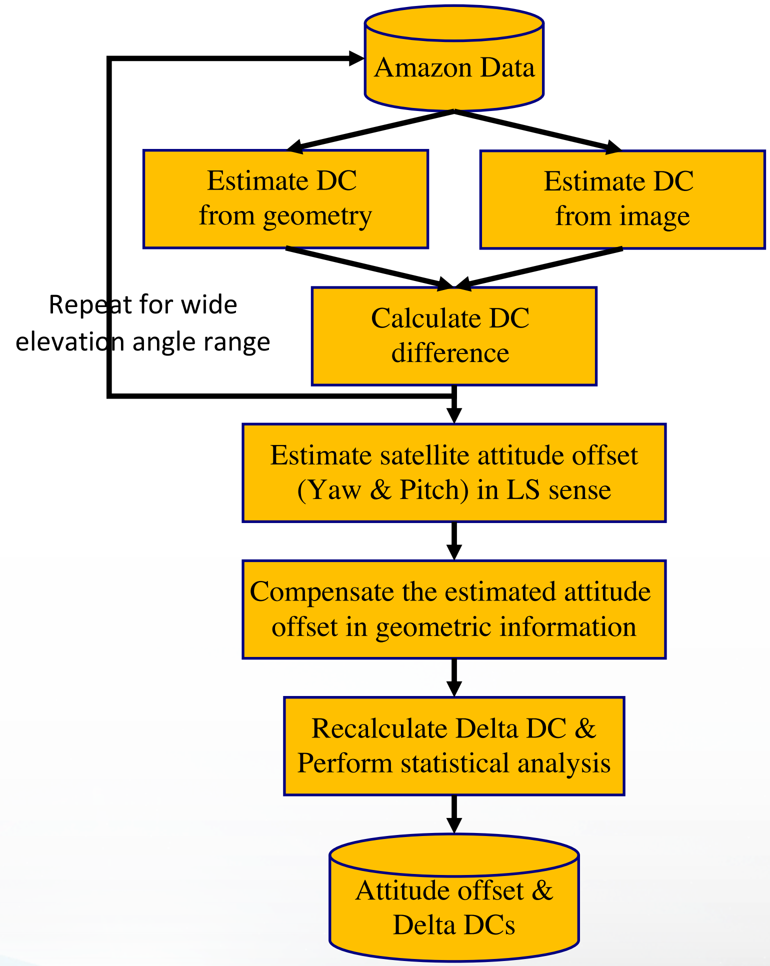
Least Square Estimation

$$\hat{x} = \begin{bmatrix} \hat{Y} \\ \hat{P} \end{bmatrix} = (H^T H)^{-1} H^T y$$

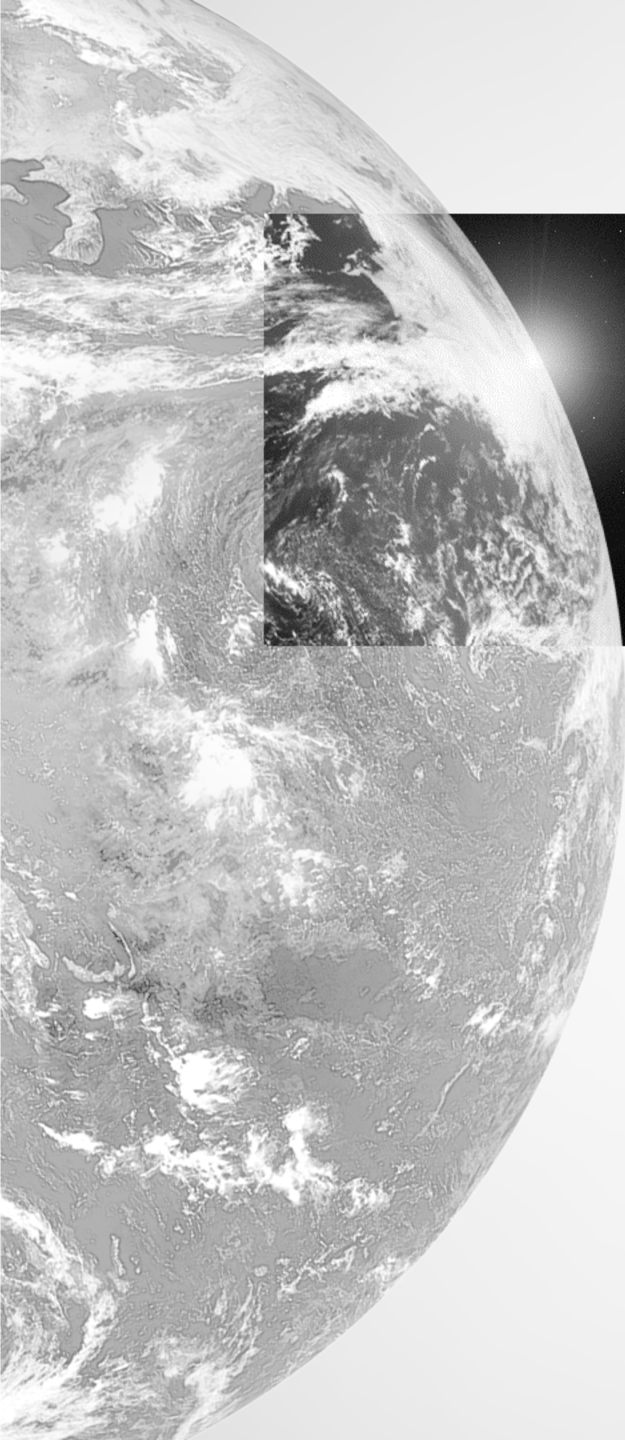
K6 Satellite Attitude Estimation Methods (3)

Processing Procedure

- Step 1: Calculate DC from geometry by extracting geometric information from Amazon SAR images.
- Step 2: Calculate DC from image using the phase information of the same Amazon images.
- Step 3: Calculate the DC difference (delta DC) between DC from geometry and DC from image.
- Step 4: Repeat step 1 through step 3 over wide beam elevation angle range.
- Step 5: Estimate the satellite yaw and pitch offsets using the delta DC measurements in the Least Square optimization sense.
- Step 6: Calculate DC from geometry using the updated satellite attitude after compensating the estimated offset, and calculate the delta DC and its statistics.



Processing steps for K6 attitude estimation



Verification

Test Approach

Simulated Data Test

- K6 satellite attitude offset estimation algorithm is tested with Kompsat-6 ICAS (Image Chain Analysis Software) Data
- Satellite attitude offset is intentionally applied to geometric (attitude) information
- Input satellite attitude offset is estimated using the difference between DC geometry and DC image
- Delta DCs are calculated after compensating attitude offset and statistical analysis is performed

Kompsat-5 Data Test

- K6 satellite attitude estimation algorithm is tested K5 data over Amazon rainforest
- Satellite attitude offset is estimated using the difference from DC geometry and DC image
- The estimated attitude offset is compensated in the geometric information, and delta DCs are calculated and compared to the results from K5 LEOP calibration activity
- Amazon rainforest has homogeneous radar backscattering and is perfect place for estimating satellite attitude offset from DC information

Test Results (1)

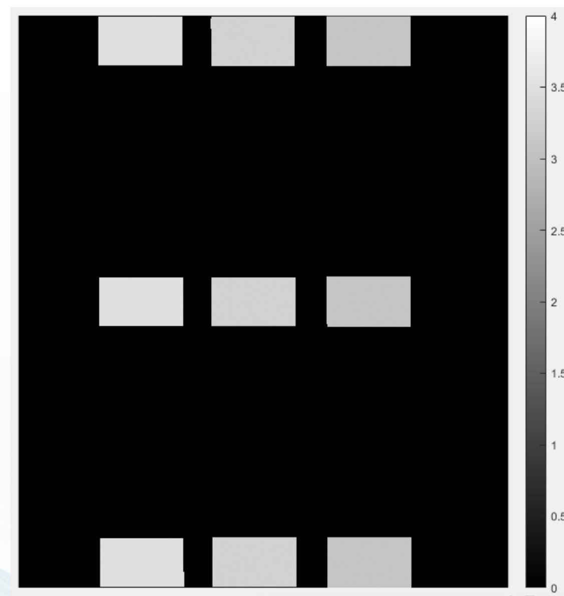
Simulated Data Test

- K6 satellite attitude estimation algorithm is tested with Kompsat-6 ICAS Data
  - ✓ Attitude offset ($\Delta Y = 0.007°, \Delta P = -0.014°$) is intentionally applied to geometric information

Image Name	DC Geometry (Hz) Offset (ΔY=0.007, ΔP=-0.014)	DC Image (Hz)	ΔDC (Hz) without offset correction	ΔDC (Hz) with offset correction
ST-01	-1603.1	-1506.85	96.25	-3.85
ST-10	-1338.9	-1216.55	122.35	-4.55
ST-19	-1102.3	-971.14	131.16	-4.53
RMSE			**117.5 Hz**	**4.5 Hz**

- Input attitude offset is re-estimated almost perfectly
- ΔDC after offset correction is reduced from 117.5 to $4.5\ Hz\ (RMSE)$

➡ K6 satellite attitude estimation algorithm works very precisely with K6 simulated data



K6 ICAS simulated raw image (ST-10)

Test Results (2)

K5 Data Test

- K6 satellite attitude estimation algorithm is tested with Kompsat-5 Amazon Data
  - ✓ Attitude offset ($\Delta Y = 0°, \Delta P = -0.012°$) from K5 LEOP calibration is compensated
  - ✓ New attitude offset ($\Delta Y = 0.007°, \Delta P = -0.014°$) is estimated and compensated

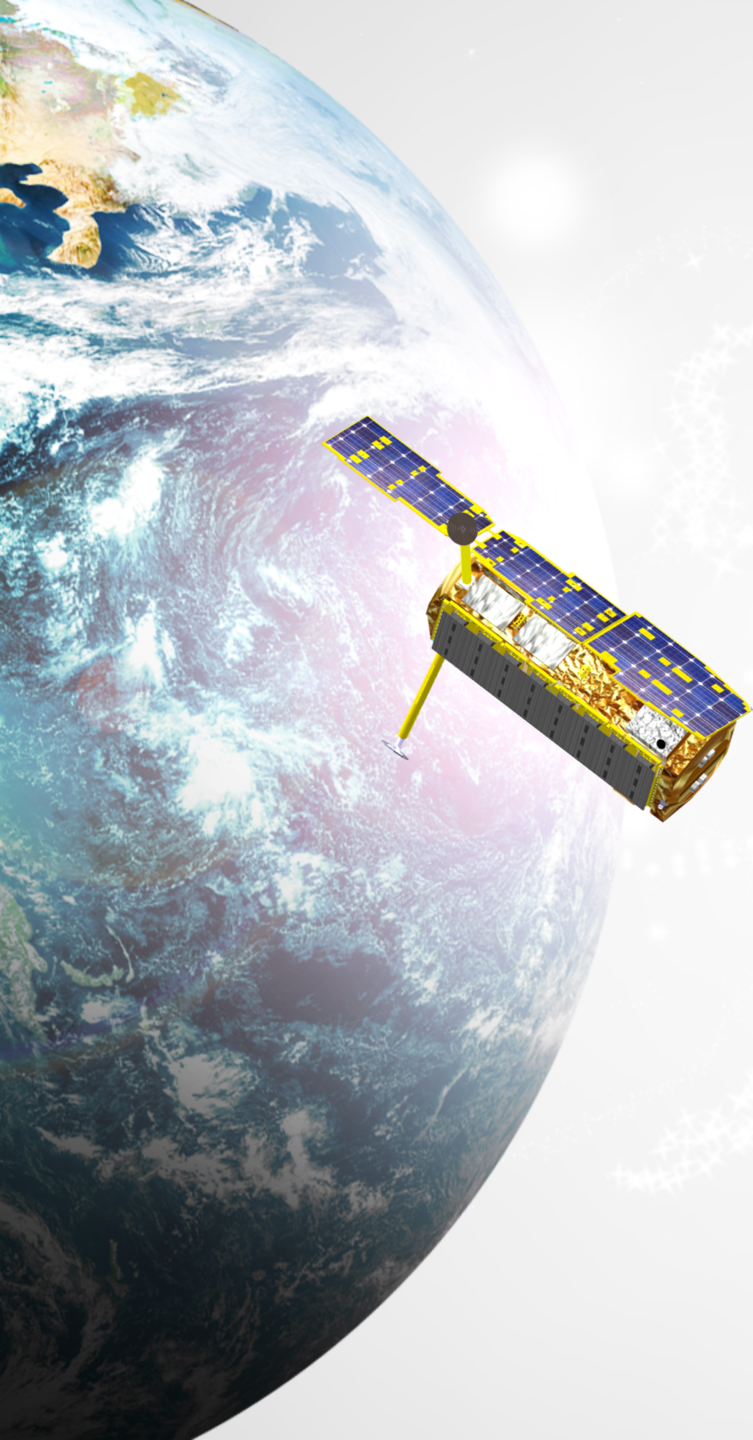
Image Name	DC Image (Hz)	LEOP DC Geometry (Hz) after (ΔY=0, ΔP=-0.012)	New DC Geometry (Hz) after (ΔY=0.017, ΔP=-0.014)	LEOP ΔDC (Hz)	New ΔDC (Hz)
ES_01_HH	-395.4	-394.7	-396	-0.7	0.6
ES_01_VV	-710.6	-709.5	-710.8	-1.1	0.2
ES_09_HH	188.4	174.1	154.3	14.3	34.1
ST_03_HH	221.1	202.8	196.5	18.3	24.6
ES_05_HH	405.6	422.1	411.4	-16.5	-5.8
ST_16_HH	-9.9	32.4	3.1	-42.3	-13
ES_19_HH	-23.7	0.3	-31.8	-24	8.1
ST_08_HH	-491.5	-480.2	-497.5	-11.3	6
ES_16_HH	29.8	39	9.7	-9.2	20.1
RMSE				**19.4 Hz**	**16.6 Hz**

- ΔDC with offset from LEOP: $19.4\ Hz\ (RMSE)$, ΔDC with new offset: $16.6\ Hz\ (RMSE)$
- ΔDC accuracy with newly estimated offset is increased by $15\ \%$

➡ K6 satellite attitude estimation algorithm works very precisely with K5 data

Conclusions

- Satellite attitude offset estimation algorithm and procedure are developed for K6 SAR processing and calibration
- The validity of suggested algorithm is tested using K6 simulated data and K5 data
- The intentionally applied satellite offset to simulated data was able to be precisely estimated, and ΔDC after offset correction is reduced from 117.5 to $4.5\ Hz$ (RMSE)
- The satellite attitude offset was estimated from Kompsat-5 Amazon data, and it was compared to the value from K5 LEOP calibration activity
  - ✓ Attitude offset from K5 LEOP calibration: $\Delta Y = 0°, \Delta P = -0.012°$
  - ✓ Newly estimated attitude offset: $\Delta Y = 0.007°, \Delta P = -0.014°$
- ΔDCs after offset correction are compared
  - ✓ ΔDC with offset from LEOP: $19.4\ Hz\ (RMSE)$, ΔDC with new offset: $16.6\ Hz\ (RMSE)$
  - ✓ ΔDC accuracy with newly estimated offset is increased by $15\ \%$
- K6 satellite attitude offset estimation algorithm and procedure were performed very accurately with K6 simulated data and K5 data



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THANKS FOR YOUR ATTENTIONS

KOMPSAT-6