Development of SAR system design and data processing software using MATLAB

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ISRO's MICROWAVE RS PAYLOADS (2010-2021)

EO TECHNOLOGY DEVELOPMENT

2012
RISAT-1

2015
RISAT-1A & 1B

2018
SCATSAT-1

2019
CHANDRAYAAN-2
DUAL FREQUENCY SAR
KA BAND RADAR ALTIMETER

2021 & BEYOND
RISAT 2B SERIES
3 X-BAND SARS

RISAT 1A & 1B
RISAT 2A
NISAR
OCEANSAT-3

• FULL-POL
• InSAR
• SWEEPSAR
Introduction to SAR

- Imaging radars use antennas that have elongated gain patterns that are pointed to the side of radar flight track.
- The pulse sweeps across the antenna beam spot, creating an echo.
- The resolution in both range and azimuth direction is independent of the distance between antenna and target.
- Range resolution is dependent on the signal bandwidth, while azimuth resolution is dependent on the Doppler bandwidth generated due to the motion of the spacecraft.

![Fig. Doppler shift history of the echo as the sensor passes over it.](image)

Lines of Equi-Doppler

Lines of Equidistance.
Without pulse compression, range resolution is directly proportional to pulse width creating a trade-off between resolution and mean transmitted power.

To take care of this, SAR sensors employ modulation techniques like linear frequency modulation (chirp, most-often used) or Barker codes during transmission.

After reception, the echoes are compressed using matched-filtering technique, so that the resolution is improved. This is pulse/range compression.

\[ \Delta R = \frac{C\tau}{2} \]

\[ \Delta R_{\text{comp}} = \frac{C}{2 BW} \]

With this resolution is improved in range direction, but what about azimuth??
Enhancement of Range Resolution by SYNTHESIS OF LONGER APERTURE

- Makes use of Doppler variation between sensor and target
- Periodic pulse transmission simulates phased-array
- Length of the simulated antenna limited by the azimuth beam footprint

\[ L_{SYN} = \frac{R\lambda}{L} \]

Synthesized beamwidth: \( \frac{\lambda}{2L_{SYN}} \)

Resolution: \( \frac{R\lambda}{2L_{SYN}} = \frac{L}{2} \)

SAR resolution independent of range

AZIMUTH RESOLUTION FOR C-BAND FREQ (\( \lambda \approx 6\text{cm} \)), L OF 6m AND R OF 600KM ?
User Requirements, Imaging Geometry and Platform Parameters

Satellite Orbital Geometry

- $H$: Height
- $R_E$: Radius of Earth
- $R_n$: Near Range
- $R_f$: Far Range
- $\alpha_n$: Near Earth Centre Angle
- $\alpha_f$: Far Earth Centre Angle
- $\Theta_n$: Near Look Angle
- $\Theta_f$: Far Look Angle

Impact of surface height

Antenna pattern gain variation shown in Red (ht = 0 m) and Green (ht = h m)
TYPICAL SAR SYSTEM DESIGN FLOW

User Requirements

RESOLUTION

Swath $\propto \frac{1}{\text{Antenna width}}$

Antenna width

SIGMA-NAUGHT (TARGET DETECTABILITY)

• Antenna Gain
• Avg. Power
• Range Resolution

Antenna area

Signal BW

Trade-off studies

• Peak Power
• Pulse width
• PRF

Data Rate

Basic Stripmap Mode Parameters

• Custom scripts
• Antenna systems toolbox
• Phased array toolbox
• MATLAB toolbox
• Symbolic math toolbox
• Signal processing toolbox

Rng Res. $\propto \frac{1}{\text{Signal BW}}$

Az. Res. = $\frac{\text{Antenna length}}{2}$

Signal BW & Antenna length

Signal BW

Signal BW & Antenna length

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Requirements

- **HIGHER RESOLUTION THAN IN STRIPMAP**
  - SPOTLIGHT MODE
  - BETTER RESOLUTION AT THE COST OF SWATH/ AZIMUTH COVERAGE

- **LARGER SWATH THAN IN STRIPMAP**
  - SCANSAR MODE
  - LARGER SWATH AT THE COST OF RESOLUTION

- **LARGER SWATH ALONG WITH HIGH RESOLUTION**
  - SWEEPSAR MODE
  - LARGER SWATH ALONG WITH HIGH RESOLUTION IS POSSIBLE BUT REQUIRES HIGH DATA RATE AND ADVANCED TECHNOLOGIES LIKE DIGITAL BEAM FORMING

... TYPICAL SAR SYSTEM DESIGN FLOW
Antenna pattern generation

- Antenna peak gain ($G_0$)
- Antenna width ($W_{eff}$)
- Pointing angle of peak antenna gain ($\alpha_0$)
- Wavelength ($\lambda$)

\[
G = G_0 \frac{\sin \left( \frac{\pi W_{eff} \sin(\alpha - \alpha_0)}{\lambda} \right)}{\pi W_{eff} \sin(\alpha - \alpha_0)}
\]
Noise equivalent sigma naught (NES0) or minimum sensitivity level

\[
\sigma_0 = \frac{(4\pi)^3 R^3 (KT_0 LF) 2V \sin \theta}{P_{\text{avg}} G^2 \lambda^3 \delta_r}
\]

where, 
- \( P_{\text{avg}} \) is the average transmitted power given by \( P_T \times \text{PRF} \),
- \( P_T \) is the transmitted peak power,
- \( \text{PRF} \) is the optimum PRF determined earlier,
- \( \tau \) is the pulse width,
- \( G \) is the antenna gain at the point of evaluation (depending on off-nadir distance)
- \( \delta_r \) is the slant range resolution
- \( \theta \) is the incidence angle
- \( R \) is the slant range
- \( V \) is the satellite velocity
- \( F \) is the receiver noise factor
- \( T_0 \) is the system temperature, assumed to be 290 K.
- \( K \) is the Boltzmann’s constant = 1.38 x 10^{-23} \text{ J/K}
- \( L \) is the system losses which includes Transmitter, Receiver and mismatch losses
PRF OPERATION RANGE

- PRF has to be selected to avoid eclipsing between:
  i. Data Window and Pulse Width
  ii. Nadir Return and Data Window

- The selected PRF will be a function of:
  i. Look Angle
  ii. Incidence Angle
  iii. Swath
  iv. Pulse Width

- Selected PRF needs to satisfy the ambiguity levels.
  - Azimuth ambiguity defines the lower limit of PRF.
  - Range Ambiguity defines the upper limit of the PRF.

\[
\begin{align*}
\text{Data window from 1}\text{st pulse} & = (\frac{2R_{\text{near}}}{c}) + \text{PW} \\
\text{M}\text{th Nadir Echo} & = (\frac{(M-1)}{PRF}) + (\frac{2H}{c}) \\
\text{N}\text{th Pulse} & = (\frac{N-1}{PRF}) + (\frac{2R_{\text{far}}}{c}) + \text{PW}
\end{align*}
\]
AMBIGUITY CALCULATIONS

AZIMUTH AMBIGUITY

- Azimuth ambiguity defines the lower limit of PRF.
- PRF > Doppler Bandwidth to avoid azimuth ambiguities.

RANGE AMBIGUITY

- Range Ambiguity defines the upper limit of the PRF.

Ambiguity Ratio = Total Ambiguous Power / Unambiguous Power
TRADE OFF ANALYSIS TO SELECT THE PRF

**PRF VS LOOK ANGLE**

- Nadir Return & DW Eclipsing
- PW & DW Eclipsing

**PRF VS PULSEWIDTH**

- Nadir Return & DW Eclipsing
- PW & DW Eclipsing

**PRF VS SWATH**

- SWATH vs PRF

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System Design Results

- custom scripts
- Antenna toolbox
- Phased array toolbox
- Radar toolbox
Data processing Software requirement and overview

- Software was required to process and verify the payload data as a part of Ground Checkout activity of the payload.

1. Requirement for verification of payload configuration parameters in the payload data.

2. Requirement for Verification of derived processing parameters from payload data w.r.t. accepted specifications.

- Requirement for scope of Automation of software to reduce data processing and verification time and to minimize human interference.

- **MATLAB toolbox**
  - Symbolic Math Toolbox
  - Signal processing toolbox
  - MATLAB report generator toolbox
Payload data constituents and derived processing parameters

Payload data file(.bin)

Auxiliary data
• Contains payload configuration information like pulse width, Bandwidth, Imaging duration, Sampling frequency etc.

Video data
• Contains payload internal calibration and return signal (Chirp) information.
• Derivation of chirp characterization and radar performance parameters after the video data processing.
• Chirp characterization parameters are Pulse width, Bandwidth, Amplitude Droop, Amplitude and Phase imbalance between I and Q, RMS phase error of unwrapped phase of chirp signal, Chirp rate.
• Radar performance parameters are PSLR (peak side lobe ratio), ISLR (integrated side lobe ratio), Resolution.

Configuration file(.csv)

• Contains payload configuration information like Pulse width, Bandwidth, Imaging duration, Sampling frequency etc.
Conventional data processing software flow diagram

- More time consumption due to manual verification
- Chances of error in verification due to human interference
- Scope for Atomization
Automated data processing software flow diagram

- Time saving
- Less chances of error due to automatic verification
- Consolidation of results in single pdf

**Payload Ground check out unit**

1. Configuration parameters provided during payload operation
2. BMU Simulator
3. Payload Telemetry and Tele-command
4. Supply control
5. Payload data recorder
6. Payload data file (.bin)
7. Data storage
8. Searching for bin file
9. Searching for config file
10. File found
11. Aux data processing software
12. Commanded parameters Extraction from config file
13. Aux field Extraction for every PRF
14. Error flags Generation w.r.t. commanded parameters
15. Required Commanded Aux parameters
16. Accepted Specifications of parameters
17. Error flags Generation w.r.t. Accept values of the parameters
18. Video data Analysis software
19. Chirp data Extraction
20. Processing parameters derivation and chirp characterization plot generation
21. Payload data format
22. Error messages and flag value, figures (.png), processing parameters values table
23. PDF Error report generation
24. PDF report generation software

**PDF ERROR REPORT**

- Extracted Aux(left) and chirp characterization parameters (right) error (deviation) with respect to commanded parameters/accepted specifications

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Summary

• SAR payload data was processed and verified using automated data processing software.
• Usage of automated data processing software was found to be *time saving* and *verification error free* as compared to conventional data processing software.

Future scope

• Integrating terrain information and Earth oblateness for imaging geometry simulations
• Raw data generation for different SAR modes
• MATLAB based processing to generate Quick Look SAR Image
• Designing a digital twin SAR sensor by integration with physics-based engines

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Thank you