Design and Performance Simulation of a Ku-Band Rotating Fan-Beam Scatterometer

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Outline of the presentation

- Mission background
- Requirement for the scatterometer
- Design of key system parameters
- Simulation of system performances
- Summary
Mission background - Objectives & Payloads

Mission Objectives:
- monitoring the wind and waves at the ocean surface at the global scale in order to improve:
  - The wind and wave forecast for marine meteorology (including severe events)
  - the ocean dynamics modeling and prediction,
  - our knowledge of climate variability
  - fundamental knowledge on surface processes linked to wind and waves

Payloads:
- SWIM (Sea Wave Investigation and Monitoring by satellite)
  - A Ku-band real aperture radar for measurement of directional ocean wave spectra;
- SCAT (SCATterometer)
  - A Ku-band rotating fan-beam radar scatterometer for measurement of ocean surface wind vector.
Mission background
–platform, orbit and schedule at satellite level

- **Platform**
  - Small sat less than 1000kg

- **Orbit**
  - ~500km
  - Sun synchronous polar orbit
  - Local descending time: 7:00am

- **Ground station**
  - 3 or 4 stations in China
  - 2 stations in arctic area

- **Preliminary schedule**
  - 2009.05 Mission definition
  - 2010.05 System design
  - 2011.12 Engineering model
  - 2013.06 Flight model
  - 1st half, 2014 Launch
Requirements for the scatterometer

- Objectives:
  - Measurement of global $\sigma^\circ$
  - Retrieval of global ocean surface wind vector

- Data requirements
  - Swath width: $>1000\text{km}$
  - Surface resolution: 50km (standard); 25km (goal)
  - Data quality (at 50km resolution)
  - $\sigma^\circ$ precision:
    - 1.0dB for wind speed 4~6m/s
    - 0.5dB for wind speed 6~24m/s
  - Wind speed: 2m/s or 10% @ 4~25m/s
  - Wind direction: 20deg @ 360deg for most part of the swath

- Life time: 3yrs
Design of key system parameters

- Key design principles
- Choice of system type
- System configuration
- Key system parameters
- Design of antenna
Key design principles

- Ku-band rotating fan-beam scatterometer
  - Platform dimension, available GMFs
- Long LMF pulse with de-ramp pulse compression
- Digital I-Q receiver with on-board pulse compression processing and resolution cell regrouping
- TX/RX channel except antenna and switch matrix identical primary/backup design to ensure liability
Choice of system type
- Why rotating fan beam?

Why rotating beam?
- Overlap of surface coverage with SWIM is requirement, nadir gap should be avoided.
- Deployment of multiple fan-beam antenna is not allowed due to platform capability.
- Large swath at a relatively low orbit (~500km) requires scanning.

Why rotating fan beam?
- Lower rotating speed to ensure lifetime of rotating mechanism;
- Multiple incident angles for better wind direction retrieval;
- Large incident angle ranges (20~46°) for research of ocean surface scattering characteristics, by compensating with SWIM (0~10°)
System configuration

- **Antenna subsystem**
  - Antenna and feeding network;
  - Scanning mechanism;
  - Servo controller;

- **RF subsystem**
  - Switch matrix;
  - RF receiver;

- **RX/TX electronics subsystem**
  - IF receiver;
  - Frequency synthesizer;
  - TX up-converter

- **Power amplifier subsystem**
  - TWT and EPC

- **Digital subsystem**
  - Signal generator;
  - System controller;
  - DSP module;
  - Data communication controller;

- **Secondary power supply subsystem**
  - DC-DC power converter;
  - TC/TM module

- **WG & cable assembly**
Key system parameters

- Basic radar parameters
- Optimization of radar parameters
- Antenna parameters
# Basic radar parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>13.256GHz</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>0.5MHz</td>
</tr>
<tr>
<td>Internal calibration precision</td>
<td>Better than 0.15dB</td>
</tr>
<tr>
<td>Receiver NF</td>
<td>≤2.0dB</td>
</tr>
<tr>
<td>Insertion loss of TX channel</td>
<td>≤1.5dB</td>
</tr>
<tr>
<td>Insertion loss of RX channel</td>
<td>≤3.0dB</td>
</tr>
<tr>
<td>Transmitting power (peak)</td>
<td>120W</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1.35ms</td>
</tr>
<tr>
<td>PRF</td>
<td>2 × 75 = 150Hz</td>
</tr>
</tbody>
</table>
Optimization of radar parameters

- Optimization:
  - trade-off between SNR and measurement samples and number of looks.
  - maximization of wind vector retrieval performance
    - Surface resolution
    - Signal bandwidth
    - Rotating speed
Observation geometrical relationship

\[ \alpha = \sin^{-1} \left[ \left( 1 + \frac{H}{a} \right) \sin \theta \right] \]

\[ R = a \cdot \frac{\sin(\alpha - \theta)}{\sin \theta} \]

Half swathwidth: \( D = a \sin(\alpha_1 - \theta_1) \)

Resolution in azimuth direction: \( \Delta D_a = R \cdot \Delta \theta_a \)

Resolution in elevation direction: \( \Delta D_e = \frac{\Delta R}{\sin \alpha} = \frac{c \tau}{2 \sin \alpha} = \frac{c}{2B \sin \alpha} \)
Resolution in azimuth direction & azimuth beam-width

- Fan beam → lower gain → antenna as long as possible
- Decided by antenna beamwidth
- Limited by satellite dimension: ≤ 1.2m
- Beamwidth ~1.1 deg → resolution in azimuth direction: 10.5~14.5km
Design of rotating speed

- Trade-off between independent $\sigma$° measurement samples for single look and number of looks
- Optimization of 3.4rpm
Optimization of PRF and pulse width by observation geometry

<table>
<thead>
<tr>
<th></th>
<th>PRF (Hz)</th>
<th>Pulse width (ms)</th>
<th>Duty ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal result</td>
<td>$55 \times 2 = 110$</td>
<td>3.0</td>
<td>33.00%</td>
</tr>
<tr>
<td>Best available TWTA</td>
<td>$75 \times 2 = 150$</td>
<td>1.35</td>
<td>20.25%</td>
</tr>
</tbody>
</table>
Resolution in elevation direction & signal bandwidth

- Low SNR due to low antenna gain
- Bandwidth 0.5MHz
  - resolution: 380~650m
- On-board non-coherent re-grouping to improve $\sigma_\theta$ precision
  - resolution of 5km
Swath width and incident angle

- 1000km $\Rightarrow \theta \sim 44^\circ$
- 50km margin $\Rightarrow \theta \sim 46^\circ$
- $\sigma^\circ$ vs incident angle

Bragg scattering: $\theta = 20^\circ \sim 70^\circ$

$\theta \uparrow \Rightarrow R \uparrow \sigma^\circ \downarrow$
$\Rightarrow$ SNR $\downarrow$

$\Delta \theta_e \downarrow$
$\Rightarrow$ smaller incident angle
# Optimization of antenna

<table>
<thead>
<tr>
<th>Symmetrical sinc beam pattern</th>
<th>Non symmetrical beam pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Azimuth BW (-3dB):</strong> ≤1.1°</td>
<td><strong>Azimuth BW (-3dB):</strong> ≤1.1° (symmetrical)</td>
</tr>
<tr>
<td><strong>Elevation BW (-3dB):</strong> ≥15°</td>
<td><strong>Elevation beam pattern:</strong></td>
</tr>
<tr>
<td><strong>Peak alignment:</strong> 40° off nadir</td>
<td><strong>Near end gain:</strong> ≥25dB@26°</td>
</tr>
<tr>
<td><strong>Peak gain:</strong> ≥30dB@40°</td>
<td><strong>Far end gain:</strong> ≥28dB@46°</td>
</tr>
<tr>
<td><strong>Gain for 1000km swath outer boundary:</strong></td>
<td><strong>Peak gain:</strong> ≥30dB@40°</td>
</tr>
<tr>
<td>≥29dB@44°</td>
<td></td>
</tr>
</tbody>
</table>
天线安装板
扫描机构
天线
卫星舱板

![图表1](image1)
![图表2](image2)
Simulations of system performances

- Simulation of $\sigma^\circ$ precision
- Simulation of wind vector retrieval performance
Simulation of $\sigma^\circ$ precision

**Modeling**
- Radar equation
- SNR
- $\sigma^\circ$ precision

$$P_r = P_t \frac{\lambda^2}{(4\pi)^3} L \int \frac{G^2 \sigma^\circ}{R^4} dA$$

where:

$$P_t = 120W = 50.8dBm$$

$$\lambda = 2.263cm = -16.5dB$$

$$L = 3.5dB \text{ (instrument loss)}$$

$$SNR = SNR' \cdot \sigma^\circ$$

$$SNR = \frac{P_r}{N} = \frac{1}{kBT} \cdot P_t \frac{\lambda^2}{(4\pi)^3} L \int \frac{G^2 \sigma^\circ}{R^4} dA$$

$$K_p = \frac{\delta P}{P} = \frac{\delta\sigma^\circ_{true}}{\sigma^\circ_{true}} = \sqrt{\frac{1}{N_{\text{eff}}} \left(1 + \frac{1}{SNR' \cdot \sigma^\circ_{true}}\right)^2 + \frac{1}{N_{\text{noise}}} \left(1 + \frac{1}{SNR' \cdot \sigma^\circ_{true}}\right)^2}$$

$$K_p(dB) = 10 \log \left(1 + K_p\right)$$

**OVWST2010, May 18-20, 2010**
**Barcelona, Spain**
Number of looks and number of independent samples
Distribution of SNR
σ° Precision (compared with Seawinds)
Analysis:

- Except for wind cells in the outer part within the swath, identical Kp can be obtained within the swath;

- For wind speed of 4~6 m/s, $\sigma^\circ$ measurement with precision better than 1.0 dB can be obtained within most part of the swath, which will have positive contributions for wind vector retrieval;

- For wind speed of 6~24 m/s, $\sigma^\circ$ measurement with precision better than 1.0 dB can be obtained within most part of the swath;

- Compared with Seawinds, Ku-RFSCAT can obtain $\sigma^\circ$ precision for wind speed of 4 m/s similar to the $\sigma^\circ$ precision obtained by seawinds with wind speed of 3 m/s; but wind direction retrieval can be better due to the increased number of incident azimuth angles.
Wind vector retrieval performance

- Only $\sigma^0$ data with precision better than 1.0dB will be used for wind retrieval;
- Standard MLE method and NSCAT GMF are used for simulation;
- Median filter algorithm for wind direction ambiguity removal

$$\text{MLE} = \sum_{\text{views}} \frac{(\sigma^0_m - \sigma^0_c)^2}{(K_p \cdot \sigma^0_m)^2}$$
Wind retrieval for resolution of 25km

[Graphs showing wind speed distribution]
测试风速24m/s
Wind retrieval for resolution of 50km
25km resolution for statistical random wind field
25km resolution for statistical random wind field
Summary

- With 50km resolution, wind retrieval performance requirement can be satisfied for most part within the swath;
- When wind speed $\leq 12\text{m/s}$, 50km resolution data can have obvious better performance than the result with 25km resolution, which is due to the increase of number of independent samples;
- When wind speed $\geq 16\text{m/s}$, the difference of wind retrieval performance between 25 km and 50km resolutions will become neglectable, even for outer part of the swath;
- With increase of wind speed, performance for center part of the swath becomes worse, due to error of GMF for high speed;
- For scanning fan-beam scatterometer, it is expected to improve the wind retrieval performance by developing wind retrieval algorithms for low SNR, multiple incident angle $\sigma^\circ$ measurements.
Thanks!