Polarimetric SAR Imaging of Earth’s Surface Processes and Geophysical Applications

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Remote Sensing” - is the small or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that is not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship).

Remote sensing techniques are in fact same as “Geophysical Surveying Techniques” in broad sense.
Remote Sensing Platforms

- Balloon
- Airplane and UAV (Uninhabited Aerial Vehicle)
- Space Shuttle
- (Artificial) Satellite
Earth Observation

- Passive remote sensing
  - (Signal energy is supplied naturally)
    - Optical remote sensing
    - Radiometry, and etc.
  - Landsat series satellites, SPOT, IKONOS, ...

- Active remote sensing
  - Microwave Remote Sensing
    - Scatterometers, Radar Altimeter, etc.
    - Synthetic Aperture Radar (SAR)
    - SEASAT, ERS-1/2, JERS-1, RADARSAT-1/2, ...
  - Laser Ranging
EM Spectrum & SAR Frequency

Earth Observation

Astronomy

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Does the “Wavelength” matter? YES

- **Optical Remote Sensing**
  - Visible light (4 μm – 8 μm)
  - Sensors cannot practically resolve the “phase” information from the reflected or scattered light because the wavelength is too short.

- **Microwave Remote Sensing (e.g. SAR)**
  - Microwave used in imaging radar (1cm – 1 m)
  - Wavelength is long enough so that one can resolve the “Phase” from the received signal.
Advantages of Microwave in Remote Sensing

- The longer wavelength allows us to resolve the phase information, which in turn makes diverse “interferometric techniques” possible.

- The longer wavelength makes the atmospheric particles (e.g. rain drops, snow flakes, and space dusts) transparent, which in turn makes the SAR an all weather imaging system.
Synthetic Aperture Radar (SAR)

Active Imaging Radar

(Microwave chirp signals)

All weather Imaging Capability without Sun light!

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ESI^3L Planet Earth
Active Sensor: SAR & Instrumentation

Space Segment

Ground Target

Scattering

Ground Station

User Segment

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ESI^3 L Planet Earth
Interferometry is the technique of superimposing (interfering) two or more waves, to detect differences between them. Interferometry is applied in a wide variety of fields, including astronomy, fiber optics, oceanography, seismology, quantum mechanics, volcanology and plasma physics.
SAR Interferogram - Interferometry

\[ R = \text{Time delay} \times \text{Light Vel.} \]
3D-Mapping with Interferometry: step by step

- Raw SAR Data
- SAR SLC Data
- Interferogram
- Phase unwrapping
- Digital Elevation Model
- Thematic Mapping
- 3-D Animation
Space-borne SAR Interferometry

- Airborne SAR Interferometry
  - Repeat pass interferometry
  - Tandem interferometry with two fixed antennae

- Space-borne SAR Interferometry
  - Repeat orbit interferometry
  - Two satellite tandem interferometry
  - One satellite two antennae interferometry
  - Bistatic SAR interferometry

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Polarity of Signal matters?  YES
**Definition:** A fully-polarized EM wave in which the polarization ellipse reduces to a straight line.

**Explanation:** For a linearly polarized EM wave, the tip of the electric field vector traces a straight line on a plane that is perpendicular to the wave propagation direction. Only the orientation angle $\psi$ is needed to describe the polarization of the wave. Horizontal ($\psi = 0$ and 180) and vertical ($\psi = 90$) are the most common examples of linearly polarized waves.
- **Co-Pol** signal: The polarization of which the transmitted signal and the received ‘backscattered” signal is same.
- **Cross-Pol** signal: The polarization of the transmitted and received signal is different.
Single Pol SAR → Full Pol SAR

Fully Pol SAR

ALOS/PALSAR
JAXA (Japan)
L-band
2006

Terra SAR
DLR (Germany)
X and L-band
2007

RADARSAT-2
CSA (Canada)
C-band
2007

ERS-1/2 SAR
ESA (Europe)
C-band

JERS-1 SAR
NASDA (Japan)
L-band

RADARSAT-1
CSA (Canada)
C-band

ENVISAT/ASAR
ESA (Europe)
C-band

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Controlled Source

KCRUST

Study Sites to be presented in this talk

YeonCheon

Gang-gu-Wha

Survey in 2008

Portable Seismometers to be deployed:
- Ko-Heung-100 Taurus (GSC - Canada) - 1000 Texan (IRIS UTEP – USA)

OBS to be deployed:
- 100 (Canada & JAMSTEC Japan)
- Korea (K_CRUST) (?)
- 20 Taurus

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20 Taurus
Topics to be discussed …

- Topographic mapping of Earth – SRTM
- Earthquakes
- Volcano - D-InSAR (Differential InSAR)
- Land Subsidence - PS-InSAR
- Soil Moisture
- Coastal Tidal Flats
- Ocean Waves and Currents
- Internal Waves in Ocean
SRTM (Shuttle Radar Topographic Mission)

(Mapping of the Earth between 60°S – 60°N in 10 days, February, 2000)

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Schematics of SRTM in “cross-track interferometric Mode”
SRTM (Shuttle Radar Topographic Mission)

- Launched in February 2000 for 10 days
- SRTM mapped the whole Earth from -600 (S) to +600 (N)
- SAR has now become the main tool making precise topographic maps (DEM).
SRTM Image sample

Location: 50 to 52 degrees North latitude, 68 to 70 degrees West longitude
Orientation: North toward the “Left”
Image Data: Shaded and colored SRTM elevation model
Date Acquired: February 2000
Earthquake
Deformation Imaging with D-InSAR
(Differential SAR Interferometry)
Earthquake (地震) Monitoring - Remote Sensing Techniques

- Visual (or qualitative) monitoring of earthquake related deformation – surface “faults”
- Quantitative monitoring of earthquake deformation using D-InSAR
  - Pre-cursors
  - Co-seismic deformation
  - Post-seismic deformation
  - Inter-seismic deformation
Ground Deformation (Interferometric) Imaging of Earthquakes from Space

- Earthquake pre-cursors . . . ( ? )
- Co-seismic deformation imaging
  - Hector Mine Earthquake, California (Mw=7.1)
- Post-seismic deformation imaging
  - Landers Earthquake, California (Mw=7.3)
- Inter-seismic deformation imaging
  - Black water little lake fault system
- Sichuan Earthquake (May 12th 2008), (M=7.9) China

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Hector Mine Earthquake (Oct. 16, 1999, Mw 7.1)
ERS-2 data: Sep. 15 - Oct. 20, 1999

Co-Seismic Deformation Imaging
Hector Mine Earthquake (Mw=7.1) With ERS-1 SAR Interferometry
(Peltzer et al. 2001)
Hector Mine earthquake, Mw7.1, Oct. 16, 1999
2-component surface displacement field from ERS SAR data

(c-band ERS-1/2 SAR data)

Technique
Using Space-borne Differential SAR Interferometric or D-InSAR

Analysis of Co-seismic Deformation

(Peltzer, Crampe, & Rosen, 2000)
Post-Seismic Deformation Imaging
LANDERS Earthquake
(Mw=\sim 7.3)
With ERS-\sim SAR Interferometry

(Peltzer et al., 1996)
Inter-seismic deformation is usually slow and difficult to monitor or image using space-borne SAR systems

(Peltzer et al., 2001)
Shear along Blackwater fault and other surface deformation features in northern Mojave
Earthquake Application Examples with ALOS (PALSAR)

- Sichuan (Chengdu) Earthquake
  - Magnitude = 7.9 (8.1)
  - May 12th 2008
Sichuan (Chengdu) China Earthquake

May 12th 2008

Eqk China

AOGS’08 ESI3L Planet Earth
ALOS
(Lunched in Jan. 2006)

L-BAND
Space-borne
Fully
Polarimetric
SAR system

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ESI^3 L  Planet Earth
Fault line

北川县城 (Beichan City)

绵竹 (Mianzhu)

德阳 (Deyang)

红油 (Jiangyou)

Fault line

Azimuth direction
Range direction

Range Displacement

0
11.8 cm

Patterns of longer wavelength is tentative due to small size of area analyzed in the present stage.

ALOS PALSAR
Includes material Copyright
METI and JAXA [2008]
L1.1 product produced by ERSDAC, Japan
DInSAR processing by CRC-SI/UNSW, Australia

17 Feb 2008 ~ 19 May 2008
Bperp = 252 m
Btemp = 92 days
Notes on Earthquake Application

- Interseismic precursory deformation can be effectively monitored.
- Tectonic displacements can be accurately imaged.
- Post seismic deformation can be most effectively imaged and mapped.
Monitoring Volcanoes …
D-InSAR
(Differential SAR Interferometry)
Volcanoes around the World and ...
The summary of forming Mt. Baekdu volcanic cone

1. Shield formation
   - late Pliocene ~ early Pleistocene (2.77~1.58 Ma), basalt

2. Composite cone formation
   - continuously erupted through Pleistocene

3. Composite sheet formation
   - Holocene, 4 times volcanic explosion, volcanoclastic material

Historical Activity

- 968±20 A.D. One of the largest eruptions ever since the human history (Horn and Schmincke, 2000)
- Four historical records describe varying eruptive activities since the 15th century (1413, 1597, 1668, and 1702 A.D.)
- Mt. Baekdu has been dormant (resting?) since the last eruption in 1702
Objectives of Study

- Recently, continuing signs of volcanic activity
  - A series of significant micro-seismic events
  - Increasing trend of temperature of hot spring
  - Gas (CO$_2$, He, H$_2$, CH$_4$) emissions (Wunderman et al., 1994)

- Increasingly available and reliable source of satellite SAR data (ERS–1/2, JERS–1 and now ALOS) are available.

  The object of this research is to measure surface displacement by using SAR Interferometry.

  - Problems:
    - No high resolution DEM in Mt. Baekdu area
      - now, SRTM–3 (3 arcsec) DEM are available
    - Poor climate conditions (Natural and Logistic problems!)
      - surface covered with snow during almost throughout the year
      - cloudy weather caused by evaporation of Cheonji lake water
    - No permanent GPS station (Political Problem!)
      - difficulty in removing atmospheric effect independently with SAR data
3-D Animation of Baekdu-san Volcano
## JERS-1 & ERS-1/2 SAR Data sets

### 41 JERS-1 SAR data
(1992/09 ~ 1998/10)

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### 10 ERS-1/2 SAR
(1992/09 ~ 2002/09)

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**23 scenes**  
**18 scenes**
26/59 JERS-1 interferometric pairs.
Differential Interferograms (88/230)

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Atmospheric Effects?

- **Differential Phase** =
  1) Surface displacement (actual displacements of volcano) +
  2) DEM error +
  3) Atmospheric effects:
     - turbulence
     - stratified troposphere (related with topography)

- In the study of volcano (especially stratovolcano like Mt. Baekdu), the estimation of atmospheric phase related with topography is very important.
Tropospheric Phase Delay

- Tropospheric delay for each season estimated by using meteorological data

- Phase difference on differential interferograms among seasonal phase delay.

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Tropospheric Phase Delay

- Tropospheric delay in differential interferogram

L-band

Jan. – Apr.  
Apr. – Jul.

C-band

Jan. – Apr.  
Apr. – Jul.
Analysis of Deformation

- Network adjustment
  - There are closures among the different interferograms.
  - Therefore, it is possible to compensate each observed phase delay by means of the network adjustment.

\[ A(m \times n)X(n \times 1) = Y(m \times 1) + E(m \times 1) \]

\[ X = (A^T V^{-1} A)^{-1} A^T V^{-1} Y \]

\[ \Delta X = \sqrt{(A^T V^{-1} A)^{-1} Y^T (V^{-1} - V^{-1} A(A^T V^{-1} A)^{-1} A^T V^{-1}) Y} \]

\[ m - n \]

- From above equation,
  - residual phase estimated in each interferogram
  - residual phase in each SAR image with respect to first SAR data
  ⇒ Time series analysis

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Deformation Rate of Baekdu-san Volcano

\[ P_{\text{Baekdu}}^{\text{cal}} \]: residual phase in Mt. Baekdu (deformation + atmospheric effect)

\[ P_{\text{Sobaek}}^{\text{cal}} \]: residual phase in Mt. Sobaek (≈ atmospheric effect)

\[ P_{\text{Baekdu}}^{\text{cal}} - P_{\text{Sobaek}}^{\text{cal}} \]: deformation

2.4 mm/yr inflation (?)

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Volcano and Volcanic hazards can be effectively monitored

- Scientific and dynamic parameters of active volcanoes can be precisely and effectively monitored as a function of time.
Monitoring Land Subsidence ... with PS-InSAR (Persistent Scatter SAR Interferometry) technique
Landscape of Study Area
PSInSAR Technique

- PSInSAR technique is a deformation estimating method using SAR data.
- All images acquired can be exploited. (Requiring more than 20 SAR images.)
- Small displacement of stable target (permanent scatterers, PS) is observed.
- Highly precise result can be acquired. (Less than few millimeter per year)
PSInSAR Technique

$$\Delta \Phi = \alpha \vec{1}^T + \vec{p}_\xi \vec{\xi}^T + \vec{p}_\eta \vec{\eta}^T$$

For each interferogram

$$+ \vec{B} \Delta \vec{q}^T + \vec{T} \vec{v}^T$$

For each PS

$$+ \text{APS} + \mathbf{E}_{\text{dec}}$$

APS and decorrelation noise phases

Separation of phase contributions form different factors

- Linear phase gradient
  (For each scene)
- DEM error (For each PS)
- LOS velocity of scatterer
  (For each PS)
- Atmospheric phase screen
  (APS) (For each scene)

(Ferretti et al., 2001)

More than 20 images

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SAR Data Used

- 27 JERS-1 SAR scenes (Path 238/ Row 89)
- Eleventh scene (acquired on March. 24, 1996) was set to be master image.
- 24 interferograms were exploited.

JERS-1 SAR System Parameters

- Wave length: 0.235 meter (L-band)
- Slant range: 730 kilometer
- Nominal incidence angle: 35 degree

(http://www.eoc.jaxa.jp/satellite/satdata/jers_e.html)
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Results (Deformation)
Perspective View of Displacement Field

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ESI³L  Planet Earth
Soil Moisture mapping using PolSAR data
Soil Moisture Mapping with Pol SAR

- Empirical relations
- Microwave images
- Surface soil moisture
- Theoretical Scattering model
- Precision farming
- Assimilation to model
- Root zone Soil moisture profile
- Discharge predictions
- etc.
Fully polarimetric AirSAR data at L- and P-band frequencies

- Soil moisture content, $m_v$
- Surface RMS height, $s$
- Surface correlation length, $l$
Study Area

L-band HH
L-band HV
L-band VV

Description of data
ESI3 L Planet Earth
Soil
- high porosity (48.7% ~ 60.2%)
- high permeability
- Sand of 15.9% and clay of 28.2%

The weather
- temperature of 23°C
- cloudy
- rainy intermittently
Roughness Measurement
Soil Moisture Measurement
Theoretical background (1)

- The IEM model
  - A theoretical scattering model by Fung (1994)
  - A criteria
    
    \[(ks) \cdot (kl) < 1.2 \sqrt{\varepsilon_r}\]

    \(k\) is the wave number, \(s\) is the surface RMS height, \(l\) is the surface correlation length, and \(\varepsilon_r\) is a relative dielectric constant of the soil.

  - The main equation
    
    \[
    \sigma_{pq}^0 = \frac{k^2}{2} e^{2k^2s^2} \sum_{j=1}^{\infty} \frac{1}{j!} \frac{W^{(j)}(-2k_x,0)}{j!} \]

    where \(W^{(j)}\) is the Whittaker function.
Conversion of volumetric soil moisture to dielectric constant

- Semi-empirical model by Dobson et al. (1.4~18 GHz)
- Semi-empirical model by Peplinski et al. (0.3~1.3 GHz)
Soil Moisture Inversion

\[ \bar{\theta} = \{s, l, m_v\} \]

Surface Parameters

The IEM model

- Multi-dimensional regression
- Inversion using artificial neural networks

\[ \tilde{Z} = \{\sigma_{HH}^L, \sigma_{VV}^L, \sigma_{HH}^P, \sigma_{VV}^P, \phi\} \]

Backscatter Coefficients & incidence angle
Maps of surface parameters estimated from the ANNs2 inversion model

Surface RMS height

Surface correlation length

Volumetric soil moisture content

Black color represents the masked pixels
Soil Moisture measurement with PolSAR

- Polarimetric SAR technology makes it possible to estimate the soil moisture remotely.
- Soil moisture estimation requires careful ground truth data and complicated inversion.
- Global agricultural objectives can however met and space-borne “soil moisture missions” are being planned.
Study of Intertidal Flats with NASA JPL AIRSAR and RADARSAT-1 data
Intertidal Zones or Tidal Flat

- Form a transition zone between geosphere and hydrosphere (Ocean)
- Are important for fisheries and cleansing zones of pollutants from land
Objectives of Research

✓ Which are the most sensitive parameters to describe and investigate the intertidal zones with SAR technology?

✓ How the radar backscattering characteristics can vary according to the different geologies of intertidal zones?

✓ How can we define the polarimetric characteristics on mud flat with respect to the polarimetric SAR signal?
Intertidal Zones – An Example

**East Sea**

- Yellow Sea: 1,980 km², 83%
- South Sea: 688.45 km², 17%
- 2668.45 km²

**Sand Flat**
- Sand > 90%

**Mixed Flat**
- Mud < 90%

**Mud Flat**
- Mud > 90%

**Locations**
- Daebudo
- Jebudo
- Yeoja Bay

[DHONG, 2001]

ESI³ Seoul National University
SAR Backscattering/Reflectivity (Amplitude)

Function of SAR Configuration & Geophysical parameters

- Polarization
- Wavelength
- Incidence angle
- Surface roughness
- Surface dielectric constant
- Environmental factors

Wavelength
Incidence angle
Polarization
Surface roughness
Surface dielectric constant

X-Band and L-Band radar reflection from surfaces of varying roughness. (After Lillesand and Kiefer, 1994.)

Smooth: no return
Slightly Rough: slightly diffuse
Moderately Rough: moderately diffuse
Very Rough: very diffuse

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Radar Backscattering from Intertidal Zones

\[ \sigma^0(i,j) = \sigma(i,j) / dA \]

RADARSAT

\[ \sigma_N^0 = 10 \times \log_{10} [(DN_N^2 + A_3) / A_{2N}] + 10 \times \log_{10} (\sin I_N) \ (dB) \]

NASA/JPL AIRSAR

\[ \sigma_{ij}^0 = |S_{ij}|^2 \quad \text{with} \ i, j = H,V \]

SAR Reflectivity (Amplitude)
Ground Truthing - Surface Roughness

RMS Height: $s$

$$RMS_{height} = \sqrt{\frac{\sum_{i=1}^{N} (z_i - \bar{z})}{N-1}}$$

Surface Correlation Length: $l$

$$\rho(l) = \frac{\sum_{i=1}^{N} z_i z_{i+j-1}}{\sum_{i=1}^{N} z_i^2} = \frac{1}{e} \quad \text{(Euler's value} \approx 2.72)$$

Photogrammetry 3-D analysis

(AOGS’08)
Dielectric Property of Bare Soil Surface

Complex Dielectric Constant

\[ \varepsilon = \varepsilon' - i\varepsilon'' \]

[Stratton, 1941; Von Hippel, 1954]

Topp et al. (1980)

\[ \varepsilon' \]

Dobson et al. (1984)

\[ \varepsilon' (0\% \text{ mud}) \]

\[ \varepsilon' (80\% \text{ mud}) \]

\[ \varepsilon'' (0\% \text{ mud}) \]

\[ \varepsilon'' (80\% \text{ mud}) \]

Soil Moisture

\[ m_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon' - 5.5 \times 10^{-4} \varepsilon'^2 + 4.3 \times 10^{-6} \varepsilon'^3 \]

[Topp et al. 1980]
Microwave Scattering Models on Rough Dielectric Surfaces

**Theoretical Scattering Models**
- Kirchhoff Approach
- Geometric Optics (GO) Solution
- Physical Optics (PO) Solution
- Small Perturbation Method (SPM)
- Depolarization Effects due to Surface Roughness [Mattia et al., 1997]
- Integration Equation Model (IEM) [Fung, 1994]
- The Extended Bragg Model [Hajnsek et al., 2003]
- [Schuler et al., 2002]

**Empirical Models**
- Oh et al., 1992
- Dubois et al., 1995 etc.

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Field Verification in Yeoja Bay

Geophysical Parameter Acquisition

Ground Control Points (GCPs) Selections
**IEM Simulation Results (1)**

**C-band HH polarization**

- **RMS height (s) = 2.2 cm**
- **RMS height (s) = 0.1 cm**

Sensitive to RMS height, $s$!!
IEM Simulation Results(2)

L-band HH polarization

Sensitive to RMS height, s !!

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IEM Results for HH- and VV-polarization

HH-polarization is more Sensitive to Incidence Angle

Lack of adequate Theoretical Scattering Models for HV-polarization

L-band
$E_r=80, k l=2.63556$

HH polarization

VV polarization

Backscattering Coefficient (dB)

Incidence angle (deg)

$ks = 0.5798$ (VV)
$ks = 0.5798$ (HH)
$ks = 0.2846$ (VV)
$ks = 0.2846$ (HH)
Sigma Nought Images depending on the Different Surface Sediment Types

Yeoja Bay

Nov. 7, 2001 low tide

Sand: 0.42%, Silt: 46.22%, Clay: 53.36%
$\sigma$ = -24 to -26 dB

Jebudo

Jul. 11, 2004 low tide

Sand: 82.09%, Silt: 5.6%, Clay: 12.32%
$\sigma$ = -10 to -12 dB

Sand: 82.09%, Silt: 5.6%, Clay: 12.32%

Mud contents in percentage vary from 48% to 70%

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Radar Backscatter

The graph shows the relationship between the mud content in percentage (%) and the backscattering coefficient (dB) for RADARSAT-I (C-band, HH-polarization) at Yeoja Bay and Jebu-do. The data points are represented as follows:

- Green circles: Yeoja Bay
- Blue circles: Jebu-do

The regression equation is:

\[ y = -11.680 + 0.059x - 0.002x^2 \]

The coefficient of determination, \( R^2 \), is 0.944113.
Retrieve Surface Parameters from SAR?

\[ \sigma_{ij}^0 \sim f(k_s, k_l, \varepsilon', \lambda, \theta) \]

Single Polarization (RADARSAT-1)

SAR Image

 Orbit Information

\[ \sigma_{ij} \]

IEM

Extended Bragg model

Surface parameters ???!

Fully Polarimetric SAR Data (NASA/JPL AIRSAR)

\[ k_s, k_l, m_v \]

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Three Linear Radar Backscattering Results

[Diagram showing radar backscatter results with labels for different areas such as land, bamboo poles, shore line, waterline, mud flat, ocean, and a fishery area.]

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IEM Estimation and Radar Backscattering Estimation Results

HH polarization

VV polarization

Incidence angle

Backscattering Coefficient (dB)

IEM Results of study sites

Ocean

Mud flat

$k_s=0.580$

$k_s=0.285$
Evaluation of Inversion Results

Measured $k_s$ vs. Estimated $k_s$

<table>
<thead>
<tr>
<th>Site</th>
<th>measured $k_s$</th>
<th>estimated $k_s$</th>
<th>RMS errors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gaussian X-Bragg</td>
<td>Uniform X-Bragg</td>
</tr>
<tr>
<td>Site A</td>
<td>0.580</td>
<td>0.429</td>
<td>0.703</td>
</tr>
<tr>
<td>Site B</td>
<td>0.438</td>
<td>0.373</td>
<td>0.554</td>
</tr>
<tr>
<td>Site C</td>
<td>0.285</td>
<td>0.339</td>
<td>0.285</td>
</tr>
<tr>
<td>Site D</td>
<td>No exposed soil surface</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Both airborne and space-borne polarimetric SAR provides an excellent tool for the investigation of intertidal zones.

Both C-band and L-band frequencies are adequate for this type of studies.
Waves and Currents
in Ocean
with ATI
(Along Track Interferometry ) SAR
\[ \Delta \phi_{ATI} = \frac{4 \pi \tau}{\lambda} U_r \]
# NASA/JPL AIRSAR Parameters for Korean ATI Campaign

<table>
<thead>
<tr>
<th></th>
<th>L-band</th>
<th>C-band</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATI Mode</strong></td>
<td>Common- Transmitter mode (ATI2)</td>
<td></td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>0.242257 m</td>
<td>0.056698 m</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>VV</td>
<td></td>
</tr>
<tr>
<td><strong>Pulse Bandwidth</strong></td>
<td>40 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>Pulse duration</strong></td>
<td>10 μs</td>
<td></td>
</tr>
<tr>
<td><strong>Sampling Frequency</strong></td>
<td>90 MHz (2× complex sampling frequency)</td>
<td>1108 Hz</td>
</tr>
<tr>
<td><strong>PRF</strong></td>
<td>1108 Hz</td>
<td></td>
</tr>
<tr>
<td><strong>Aircraft Speed</strong></td>
<td>216 m/s (197-1), 219 m/s (107-1)</td>
<td>8007 m (197-1), 8005 m (107-1)</td>
</tr>
<tr>
<td><strong>Altitude</strong></td>
<td>19.8 m</td>
<td>1.93 m</td>
</tr>
<tr>
<td><strong>Physical Baseline</strong></td>
<td>~48 s (at 40° Incidence angle)</td>
<td></td>
</tr>
<tr>
<td><strong>R/V</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Pre-Processing of ATI SAR Data

- **Phase Calibration**
  - Flat earth correction, Phase bias removal
  - Subtracting the non-zero phase difference over the land at the sea level

- **ATI phase to velocity conversion**
  - Platform velocity, Baseline, Radar wavelength

- **Registration of the L- & C-band ATI data and Geometric Correction**
  - Re-gridding processing (SCH-coordinate) and Land information
ATI SAR & Velocity Image

Flight direction

197-1 Line

ESI³L  Planet Earth
$U_r = \frac{\lambda V}{2\pi B}$

Calibrated Interferogram
Ocean Surface Waves

\[ P_{\nu_o}(k) = [H(k)]^2 E(k) \]

\(<\text{Velocity bunching nonlinearity}>\)

\[ \frac{R}{4V} k_m^{3/2} \cos \phi_m \cdot g^{1/2} G(\theta, \phi_m) H_s \quad G(\theta, \phi) = (\sin^2 \theta \sin^2 \phi + \cos^2 \theta)^{1/2} \]

When \(R/V < 80\), and range traveling waves

\[ \text{Quasilinear transform} \]

\[ H(k) = \left( \frac{k_i B}{V} \right) \omega G(\theta, \phi) \left[ 1 - 3 \frac{k_x^2 R^2}{V^2} f^u(0) \right]^{1/2} \]

Significant waveheight \[ H_s = 2\left[ \int E(k) dk \right]^{1/2} \]
Ocean Surface Waves

LAF-LAA AT1 Data

107-1 Line
Ocean Surface Waves

LAF-LAA ATI Data

197-1 Line

AOGS’08 Planet Earth
### Dominant Ocean Wave (Swell) System

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Image Size</strong></td>
<td>1024m×1024m</td>
<td>2048m×2048m</td>
<td>2048m×2048m</td>
</tr>
<tr>
<td><strong>Incidence Angle</strong></td>
<td>27.0°</td>
<td>38.7°</td>
<td>38.8°</td>
</tr>
<tr>
<td><strong>Mean Depth</strong></td>
<td>-38m</td>
<td>-65m</td>
<td>-92m</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>98m</td>
<td>100m</td>
<td>101m</td>
</tr>
<tr>
<td><strong>Wave Direction</strong></td>
<td>237°</td>
<td>208°</td>
<td>196°</td>
</tr>
<tr>
<td><strong>Wave Period</strong></td>
<td>7.99s</td>
<td>8.01s</td>
<td>8.05s</td>
</tr>
<tr>
<td><strong>Significant Waveheight</strong></td>
<td>0.21m</td>
<td>0.30m</td>
<td>0.32m</td>
</tr>
</tbody>
</table>

**Wave Refraction**

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Surface Current Estimation

From Multiple-frequency (L- & C-band) ATI data

1) Conversion of radial velocity into horizontal velocity

\[ U_H = U_r / \sin \theta_i \]

\( \theta_i \) : Incidence angle

2) Spatial averaging

To remove spatial varying components
(Swell, orbital motions of long ocean waves in the low wind sea states and at the moderate incidence angle)

3) Current velocity estimation

\[ \alpha(\theta) = \frac{1}{2} \left[ \frac{\langle U \rangle_s^L - \langle U \rangle_s^C}{c_p^L - c_p^C} + 1 \right] \]

\[ v_c = \langle U \rangle_s^{L(C)} - [2\alpha(\theta) - 1]c_p^{L(C)} \]
Ocean Surface Current Vectors

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**Comparison and Validation**

### ATI SAR vs. RCM 7

<table>
<thead>
<tr>
<th></th>
<th>ATI SAR</th>
<th>RCM 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>107-line</td>
<td>197-line</td>
</tr>
<tr>
<td>R-1</td>
<td>-0.41</td>
<td>-0.14</td>
</tr>
<tr>
<td>(35°19' 09&quot;N, 129°22' 41&quot;E)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-2</td>
<td>-0.18</td>
<td>-0.07</td>
</tr>
<tr>
<td>(35°17' 35&quot;N, 129°21' 26&quot;E)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-3</td>
<td>-0.08</td>
<td>- -</td>
</tr>
<tr>
<td>(35°16' 20&quot;N, 126°18' 45&quot;E)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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SAR ATI Observation of Ocean

- ATI SAR provides us with one of the most unique and effective observation tools for ocean waves and currents
- Requires C-band and L-band SAR systems
Study of Internal Waves in Ocean

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Internal Wave

- Internal Wave exists in the deep stratified water
- Vertical and Horizontal mixing of water
  - → Plankton movements
  - → Fisheries are affected by Internal Wave phenomenon
- Acoustic wave propagation in water
  - → Detection of submarines, etc.
- Generation (formation ?) and general characteristics of Internal Wave is still being investigated.
  - → Newly identified research field in Physical Oceanography
- Conventional Ocean cruising is no good !
  - → space-borne observation is essential
Internatl Wave Observation Facilities

Satellite image

Ship Observation
CTD: Hydrography

U(z,t) 10 sec

T(z,t) 10 sec

U(z,t) 10 sec

T(z,t) 1 minute

Barney / ADCP (B01)

Thermistor Chain1 (R01)

ESROB4 ADCP/CTD

Barney / ADCP (B02)

Thermistor Chain2 (R02)

Workhorse ADCP
Current U (z,t) minute

Real-time (10 minutes) Communication (CDMA)

Weather station
Wind direction and speed 
Air temperature 
Air pressure

Surface wave
Measure wave height, Significant wave height, 
Wave period, Wave period

ESIESI

ESI^3 L Planet Earth
Satellite Observation of Internal Waves

Landsat, SPOT, ERS-1/2, RADARSAT, ENVISAT Satellite Data

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Analysis of Internal Wave in the Sea of Japan

Ko-sung

Dong-Hae (Sea of Japan)

Kang-Neung

RADARSAT

Landsat ETM+

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Korteveg-de Vries (KdV) Eq. for Internal Wave

\[
\frac{\partial \eta(x,t)}{\partial t} + c_0(x) \frac{\partial \eta(x,t)}{\partial x} + \alpha(x) \eta(x,t) \frac{\partial \eta(x,t)}{\partial x} + \beta(x) \frac{\partial^3 \eta(x,t)}{\partial x^3} = 0
\]

Two-layer model

\[\eta(x,t) = \eta_0 \text{sech}^2 \left( \frac{x - c_i t}{L} \right)\]

\[c_0 = \sqrt{\frac{g(\rho_2 - \rho_1)h_1 h_2}{\rho_2 h_1 + \rho_1 h_2}}\]

\[\alpha = \frac{3c_0}{2h_1 h_2} \frac{\rho_2 h_1^2 - \rho_1 h_2^2}{\rho_2 h_1 + \rho_1 h_2}\]

\[\beta = \frac{c_0 h_1 h_2}{6} \frac{\rho_1 h_1 + \rho_2 h_2}{\rho_2 h_1 + \rho_1 h_2}\]

\[\eta_0 = \frac{12\beta}{\alpha L^2} \quad c_i = c_0 + \frac{4\beta}{L^2}\]
Optical Image of Internal Wave

Peak-to-peak method

\[
D = 1.32l \\
I = 2h_1h_2 / \sqrt{3\eta_0 | h_2 - h_1 |} \\
h_1 = \frac{g'h \pm (g'2h^2 - 4g'hC_p^2)^{1/2}}{2g'} \\
\eta_0 = \frac{4h^2C_p^4}{3g' \left( \frac{D}{1.32} \right)^2 \left( g'2h^2 - 4g'hC_p^2 \right)^{1/2}}
\]

\[
\rho_1 = 1026.0 \text{ (kg m}^{-3}) \\
\rho_2 = 1029.5 \text{ (kg m}^{-3}) \\
h_1 = 20.0 \text{ (m)} \\
h_2 = 1480.0 \text{ (m)} \\
\eta_0 = 16.5 \text{ (m)}
\]

LANDSAT ETM
2001.07.07

276m
Internal Wave in SAR Image

Incidence Angle: 27 °
Total Water Depth: 1000 m

Curve fitting method

RADARSAT
2004. 06. 04  09:14 (UTC)

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EOIII L  Planet Earth
KdV Eq. Simulation of Internal Wave (SAR)

Look-up Table

\[ \rho_1 = 1020.0 \ (kg/m^3) \]
\[ \rho_2 = 1020.5 \ (kg/m^3) \]
\[ h_1 = 10.0 \ (m) \]

\[ \rho_1 = 1025.0 \ (kg/m^3) \]
\[ \rho_2 = 1027.5 \ (kg/m^3) \]
\[ h_1 = 40.0 \ (m) \]

\[ \rho_1 = 1027.0 \ (kg/m^3) \]
\[ \rho_2 = 1032.5 \ (kg/m^3) \]
\[ h_1 = 70.0 \ (m) \]

\( \rho_1 = 1025.0 \ (kg/m^3) \)
\( \rho_2 = 1027.5 \ (kg/m^3) \)
\( h_1 = 40.0 \ (m) \)
\( h_2 = 960.0 \ (m) \)
\( \eta_0 = 38.5 \ (m) \)

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Field Verification of Internal Wave

<table>
<thead>
<tr>
<th>SAR Model Estimations</th>
<th>In-situ Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ₁ 1025.0 (kg/m³)</td>
<td>1025.5 (kg/m³)</td>
</tr>
<tr>
<td>ρ₂ 1027.5 (kg/m³)</td>
<td>1027.2 (kg/m³)</td>
</tr>
<tr>
<td>h₁ 40 (m)</td>
<td>35 (m)</td>
</tr>
</tbody>
</table>

CTD Measurement
Dong-hae (East Sea)

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Prediction of Internal Wave Arrival

- Predictor-corrector scheme
- Finite difference

AOGS’08
\[ \rho_1 = 1025.0 \text{ (kg/m}^3\text{)} \]
\[ \rho_2 = 1027.5 \text{ (kg/m}^3\text{)} \]
\[ h_1 = 40.0 \text{ (m)} \]
\[ h_2 = 960.0 \text{ (m)} \]
\[ \eta_0 = 38.5 \text{ (m)} \]
Internal Waves and SAR

- Space-borne Remote Sensing platforms are probably the most effective way of observing internal waves because of it’s spatial dimension.
- Both optical and microwave imaging system provides adequate observation data but SAR is preferred because of it’s all weather capability.
Summary on SAR Applications

- The imaging radar SAR (Synthetic Aperture Radar) can observe and monitor the planetary surface changes or deformation with spatial resolution in the range of several mm to tens of km.
- All currently available frequency ranges of X-, C-, S-, L-, and P-band can be or should be utilized.
- Airborne / space-borne SAR system provides us with one of the most powerful “new” all weather research tool in Planetary (Earth) system science.
Update on SAR Programs in Korea

KOMPSAT-5

- X-band SAR
- Orbit altitude ~ 550 km
- Top resolution ~ 1 m
- Planned for launching in 2010 – 2012
- Operation life time ~ 5 yr

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Future - Earth System Missions

- **DESDynI** (NASA, JPL, USA) (2010 – 2016)
  - Includes L-band SAR and multi-beam Lidar
  - Solid Earth/Deformation
  - Biosphere/Eco-systems/Forestry
  - Hydrosphere/Cryosphere

- **L-Band TanDEM Mission** (DLR, Germany) (2012-2020)
  - Biosphere
  - Geosphere
  - Hydrosphere/Cryosphere
Future Lunar Missions

- Current Lunar Missions
  - Selene (Japan): Sept. 2007
  - Chen le (China): Oct. 2007

- Future Lunar Missions
  - Chandra (India): later this year in 2008
  - LEO (Lunar Exploration Orbiter, Germany): 2014
We are now living in
Golden Age
of studying Planetary (Earth) System with
all weather Synthetic Aperture Radar !

Thank you !