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Satellite radar remote sensing: applications to the study of Earth sciences and natural resources

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Outline

- The very basics of radar remote sensing and InSAR
- Radar remote sensing of Earth sciences & natural resources
  - Earthquake
  - Landslide
  - Volcano
  - Aquifer
  - Surface Water and Wetland
  - Soil Moisture
  - Land Cover
  - Agriculture
- Emerging SAR/InSAR technologies
- Emerging L-Band Capabilities
- A Road Map
In its simplest form, a radar operates by broadcasting a pulse of electromagnetic energy into space— if that pulse encounters an object then some of that energy is redirected back to the radar antenna.

Precise timing of the echo delays allows determination of the distance, or “range”, while measuring the Doppler frequency tells the velocity of the target.

The electromagnetic wave is transmitted from the satellite. The wave propagates through the atmosphere, interacts with the Earth surface. Part of the energy is returned back and recorded by the satellite.

By sophisticated image processing technique, both the intensity and phase of the reflected (or backscattered) signal can be calculated. So, essentially, a complex-valued SAR image represents the reflectivity of the ground surface.

The amplitude or intensity of the SAR image is primarily controlled by terrain slope, surface roughness, and dielectric constants, while the phase of the SAR image is primarily controlled by the distance from satellite antenna to ground targets and partially controlled by the atmospheric delays as well as the interaction of microwave with ground surface.

Interferometric synthetic aperture radar (InSAR) combines phase information from two or more radar images of the same area acquired from similar vantage points at different times to produce an interferogram.

The interferogram, depicting range changes between the radar and the ground, can be further processed with a digital elevation model (DEM) to image ground deformation at a horizontal resolution of tens of meters over areas of ~100 km x 100 km with centimeter to sub-centimeter precision under favorable conditions.
2. Interferometric coherence analysis

- A measure of changes in backscattering characteristics

10/25/95-10/26/95
07/17/97-09/25/97

Lu et al., 2000

3. Polarimetric SAR image analysis

C-HV data will offer better potential for detection and delineation of clearcuts than C-HH and C-VV data

4. SAR polarimetric phase analysis

Different types of targets show different PPD behaviours

PPD: ~0° for odd refl. #
~180° for even refl. #
PPD distributed between 0° and 180°

Van Zyl, 1989

5. Analysis of SAR images at different frequencies

X-band
L-band
P-band
Synthetic Aperture Radar Satellites

• Current and Past Sensors
  • European ERS-1, 1991-2000, C-band, 35-day repeat cycle
  • European ERS-2, 1995-now, C-band, 35-day repeat cycle (experiencing malfunctions since early 2001)
  • Japanese JERS-1, 1992-1998, L-band, 44-day repeat cycle
  • Canadian Radarsat-1, 1995-now, C-band, 24-day repeat cycle
  • European Envisat, 2002-now, C-band, 35-day repeat cycle
  • U.S. SIR-C Mission, April (10 days) and Oct (10 days), 1994 X/C/L-band, Fully Polarized

• Future Sensors
  • Japanese ALOS, 2006, L-band, 46-day repeat cycle
  • Canadian Radarsat-2, 2006(?), C-band
  • German TerraSAR-X, 2006(?), X-band
  • U.S. DOD Space-based Radar Constellations
  • U.S. ECHO+, forever?
  • …

Wavelength ($\lambda$)
• X-band: $\lambda = \sim 3$ cm
• C-band: $\lambda = \sim 5.7$ cm
• L-band: $\lambda = \sim 24$ cm

InSAR study of Earthquakes

• Measuring spatial and temporal patterns of surface deformation in seismically active regions are extraordinarily useful for estimating seismic risks and improving earthquake predictions.

Oct. 23 and Nov 3, 2002 Denali Earthquakes

2002 Denali Fault Earthquakes

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2002 Denali Fault Earthquakes

Wavelength ($\lambda$)
• $\lambda = \sim 3$ cm
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• $\lambda = \sim 24$ cm

2002 Denali Fault Earthquakes

2002 Denali Fault Earthquakes

2002 Denali Fault Earthquakes

2002 Denali Fault Earthquakes
Observed and Modeled InSAR images for the Oct. 23, 2002 Earthquake:

- Lu, Wright, Wicks, EOS, 2003

Slip Distribution of the Oct. 23, 2002 Earthquake:

- Wright, Lu, Wicks, GRL, 2003

InSAR + GIS analysis for the Nov. 3, 2002 Earthquake:

- Lu, Wright, Wicks, EOS, 2003

Right-lateral Displacement (cm) vs. Distance from Fault (km) for the Nov. 3, 2002 Earthquake:

- Lu, Wright and Wicks, EOS 84 (41), p.429-431, 2003
InSAR monitoring of landslides

- Measuring and documenting how landslides develop and are activated are prerequisites to minimize the hazards they pose in areas of rapid urban growth.

Slumgullion Landslide, CO

- Wright, Lu, Wicks, BSSA, 2004

InSAR image of Slumgullion landslide

- Lu and Coe, in prep, 2005
Radar remote sensing of volcanic processes

- Measuring how a volcano’s surface deforms before, during, and after eruptions, provides the essential information about magma dynamics and a basis for mitigating volcanic hazards.
InSAR images can characterize transient deformation of Westdahl volcano before, during, and after the 1991 eruption.

Pre-eruption InSAR image

Post-eruption InSAR images (several examples)

1 color cycle = 2.8 cm deformation

Lu et al., GRL, 2000
Lu et al., JGR, 2003

Deformation history of Westdahl Volcano

Magma plumbing system for Westdahl volcano, inferred from InSAR and modeling

Lu et al., JGR, 2003
Land Subsidence Mapping – radar remote sensing of aquifer and hydrogeology

- Mapping surface subsidence and uplift related to extraction and injection of fluids in groundwater aquifers and petroleum reservoirs provides fundamental data on reservoir/aquifer properties and processes and improves our ability to assess and mitigate undesired consequences.

Subsidence of Al Ain, United Arab Emirates, from InSAR, 1993-1999

InSAR + GIS

A coastal area over southeastern China

Landsat-7 image, Oct 2000

10 km

L-band JERS-1 InSAR

InSAR Deformation Map

10 km

Subsidence

0 8 cm/year

Lu et al., in prep., 2005
Subsidence was up to 8 cm/year

Land subsidence + GIS data layers over cities provide critical information for decision making: *Is my house sinking?*

Satellite Radar Image of San Bernardino, CA


Mapping of Land Surface Deformation by InSAR

Radar remote sensing of hydrology

- Monitoring dynamic water-level changes beneath wetlands can improve hydrological modeling predictions and enhance the assessment of future flood events over wetlands.
Water extents over Po Yang Lake, China

Water in April 1998

Water increment in June 1998

Water increment in July 1998

Flood mapping over Po Yang Lake, using JERS-1 SAR

Hurricane Katrina
Radarsat-1 SAR image
Sept 2, 2005

Inundation and oil slicks mapped from SAR image

Rykhus, Lu, & Jones, 2005

Inundation, oil slicks, floating debris Mapped from SAR image
Sept 5, 2005

Rykhus, Lu, & Jones, 2005
When radar waves interact with flooded vegetation

![Diagram of radar waves interacting with vegetation](image)

- **Radar Signal**
- **Double-bounce Radar signal**

Water-level changes imaged by L-band InSAR

![Map showing water-level changes](image)

- **Range Change**

Flood depth estimated from 30-m elevation data derived from 5-m lidar data collected in 2002.

Water-level changes imaged by L-band InSAR

![Graph showing water-level change](image)

- **Water-level change from 1993/11/29 to 1994/01/02**
- **Water-level change from 1996/01/20 to 1996/03/04**

A B

1993/11/29 – 1994/01/02
1996/01/20 – 1996/03/04
Water-level changes imaged by L-band InSAR

1993/11/29 – 1994/01/02

1996/01/20 – 1996/03/04

A B

Swamp forests near coastal New Orleans

Sugar Cane Fields

Swamp Forest

Lake canal

Water-level changes imaged by C-band InSAR

Louisiana

Study Area

C-band Radar Can See Water-level Changes in Swamp Forests

* Lu et al., EOS, April 5, 2005

Swamp forests near coastal New Orleans

• Lu, Crane, and other, EOS, April 5, 2005

• Lu et al., EOS, April 5, 2005
Future Data and Technology Needs for Hydrology

- Rapid repeat times for interferometry. Daily imagery would be ideal for flood and other hazard assessments.
- Full polarization to exploit the water-vegetation interface.
- C- and L-band imagery would provide the necessary control to map surface water elevation changes in a wide range of location.

Radar remote sensing of Soil science

- Mapping soil moisture will provide an environmental descriptor that integrates much of the land surface hydrology and is the interface for interaction between the solid Earth surface and life.

Basic Principles

- Retrieval of land surface parameters
  - Formulate a radar backscattering model
  - Apply an inversion procedure
- Ideally, we would like to start from Maxwell’s equations

Synthetic Aperture Radar (SAR) images over Carlsbad, New Mexico
Mapping of change in soil moisture, Carlsbad, New Mexico

Lu and Meyer, IJRS, 2002

Backscattering properties of soil

A Radar backscattering model (i.e., Integral Equation Model)

\[
\sigma_{\text{ss}}(s) = \frac{k^2}{2} \exp(-2k^2s^2) \sum_{n=0}^{\infty} \frac{s^{2n}}{n!} W^n(-2k^2s, 0)
\]

The surface backscattering components \(\sigma_{\text{hh}}, \sigma_{\text{vv}}\), and \(\sigma_{\text{hv}}\) can be simulated for a wide range of incidence angle, surface dielectric and roughness properties, corresponding to a range of soil moisture values.

By comparing simulated backscattering values with those observed, soil moisture can be inferred (Intense computation \(\Rightarrow\) ARSC)

The Semi-Empirical SAR Soil Moisture Retrieval Scheme

Mauser et al., 2004

Mapping soil moisture with SIR-C SAR images. The horizontal resolution (several meters) of soil moisture imagery derived from fully polarimetric SAR data is not attainable otherwise.

Dubois et al., 1995
Inferring soil moisture with InSAR images

Drying (blue) and moistening (yellow/red) between two SAR acquisitions in an arid region of Colorado inferred from InSAR. Range change was interpreted as being due to changes in penetration depth that results from change in soil moisture.

Nolan & Fatland, 2003

Future Data and Technology Needs for Soil Moisture Science

• Rapid repeat times for interferometry. Daily imagery would be ideal to map dynamic changes in the surface water content. A minimum requirement would be weekly coverage.

• Multi-wavelength capabilities for imaging soil moisture content at varied penetration depths. Ideally, a multi-wavelength mission(s) could image soil moisture at depths of about a few cm and tens of cm. The depth penetration would produce true 4-dimensionsal soil moisture maps that would provide the basis for hydrology and ecology studies.

• Full polarization.

Radar remote sensing of land-cover characterization
Assessment of the use of radar data to improve land cover mapping accuracy

B. Wylie, R. Rykhus, L. Yang, and Z. Lu

Preliminary Results:
overall accuracy improvement of 1%.
Large improvement over water, evergreen forest, and forested wetland

Landsat TM
JERS-1 SAR
Envisat ASAR images: 10/03, 11/03, 03/04 (RGB)

C-Band multi-polarization SAR detects marshes and distinguishes between different marsh species.

Envisat ASAR images: 10/03, 11/03, 03/04 (RGB)

SAR images are used to map biomass burning and to monitor fires on a continuing basis (Kasischke et al., 1995)

ERS-1 SAR
1991 Fire Scar
Tok, Alaska

Lava flow mapping using SAR and Landsat TM images at Westdahl Volcano


Radar remote sensing of Agriculture

SAR Backscattering from Agricultural Fields

- Soil surface roughness
- Soil surface moisture
- Soil type
- Crop species
- Vegetation biomass
- Vegetation moisture
- Land slope
- Seed row direction
- others

Challenges: All of agriculture parameters are a function of
- Acquisition mode (geometry, frequency, polarisation)
- Acquisition time and interval
- Temporal signature

Analysis Approach

- SAR image(s)
- multi-looking (optional)
- coregistration
- radiometric calibration
- multi-data filtering or segmentation
- geometric calibration
- geocoded σ₀ data

Digital Elevation Model

Agriculture Figure

Crop classification derived from multi-temporal C-band ERS-1 SAR images over Flevoland, the Netherlands (Schotten et al., 1995). For regions with persistent clouds, SAR imagery allows frequent monitoring of crop growth.
HH/VV and biomass temporal variation over wheat fields

Crop Height Estimation

\[ \text{Log(Measured crop height)} = a_0 + a_1 \times VV + a_2 \times VH + a_3 \times VV/VH \]

Rice - Philippines, Multi-temporal ENVISAT ASAR AP data

Rice - Philippines, ENVISAT ASAR AP & Radarsat-1 data
Future Data and Technology Needs for Land Cover/Vegetation/Agriculture Sciences

- Zero baseline L-HH InSAR for estimating temporal decorrelation, which empirical models relate to vegetation characteristics.
- Short repeat period that minimizes temporal decorrelation, useful for both vegetation and deformation.
- Fully polarimetric capability.
- Polarimetric InSAR for improved vertical structure accuracy and land-cover type discrimination.
- Multiple frequency for providing two height estimates used to expand observation.

Future Trends in Radar Remote Sensing

- From single image to multi-temporal images
- From single polarization to dual/full polarization
- 4-D spatial-temporal analysis
- Intense computation and parallel processing
Emerging SAR/InSAR technologies

- **Permanent Scatterer InSAR** – Improve deformation measurement accuracy of conventional InSAR
- **Cross-Platform InSAR** – Generate high-resolution DEM by manipulating radar signals from different platform/sensors
- **Operational InSAR Processing System** – Improve InSAR processing throughput and lay the foundation for routine monitoring seismic/volcanic/landslide deformation
- **ScanSAR InSAR** – Improve spatial coverage of conventional InSAR to image large-scale deformation
- **Polarimetric InSAR** – Mapping vegetation height through InSAR analysis of polarimetric SAR signal
- **Multi-temporal, polarimetric SAR** – Improve land cover mapping and characterization over regions where weather conditions plague optical remote sensing

**Differential Phase Equation**

For pixel $n$ in interferogram $i$:

$$\phi_{n,i} = \phi_{e,n,i} + \phi_{\text{defo},n,i} + \phi_{\text{APS},n,i} + \phi_{\text{orbit},n,i} + \sigma_{n,i}$$

- **DEM Error Term**
- **Atmospheric Phase Term**
- **Deformation in LOS**
- **Orbit Error Term**
- **Noise**

**Improve InSAR technique**

- **Permanent Scatterer InSAR**
Improve InSAR technique
- Permanent Scatterer InSAR

Permanent Scatterer InSAR – Improve deformation measurement accuracy of conventional InSAR

Cross-Platform InSAR – Generate high-resolution DEM by manipulating radar signals from different platform/sensors

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Technique development of Cross-Platform InSAR (CPInSAR)

- ENVISAT SAR sensor (ASAR) uses a slightly different radar frequency when compared to the ERS-2 SAR sensor.
- Accordingly ASAR data can not be combined with ERS-2 data via conventional InSAR technique.
- A technique, called cross-platform InSAR (CPInSAR) is being developed to manipulate SAR signals from two different sensors to generate a DEM.
- Under favorable imaging geometry conditions and terrain types, the accuracy of the CPInSAR-derived DEM can reach tens of centimeters - better than SRTM and comparable to Lidar.

CPInSAR DEM
30-minute Repeat-Pass InSAR
Preliminary CPInSAR DEM; baseline = 1.8 km
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InSAR Future: from research to operation

InSAR Processing & Monitoring System

Processing Queue

DPM, PPM

DCAM

GUI

InSAR Database

On-Line Disk

Off-Line Disk

InSAR Products

InSAR Processing

Volcano/Earthquake/Landslide Observatories

Processing Parameters

Models

DPM: Data Processing Module

FPM: Fault SAR Processing Module

PSMM: PsInSAR Processing Module

GUI: Graphic User Interface

DCAM: Data Cataloging and Archiving Module

InSAR Future: from research to operation

ScanSAR InSAR

SARMAP, 2004
Emerging SAR/InSAR technologies

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Polarimetric InSAR for Canopy Height Mapping

1. Develop an optimization procedure to maximize the interferometric coherence between two polarimetric radar images to reduce the effect of baseline and temporal decorrelation on the interferogram.
2. Develop a coherent target decomposition approach that separates radar backscattering returns coming from the canopy top, the bulk volume of the forest, and the ground surface. The difference of interferometric phase measurements then leads to the height difference between the physical scatterers possessing these mechanisms.
3. Develop a physical radar scattering model over different vegetation types to calculate the canopy height, the bare-earth topography, the mean volume extinction coefficient that is related to canopy density, and other canopy structural parameters based on measurements from a polarimetric InSAR image.

Biomass Estimation from fully polarized SIR-C Data

- **Mapping biomass at Yellowstone Park using SIR-C (C- and L-bands) SAR images taken in Oct. 1994.** The biomass ranges from no biomass (blue) to non-forest areas with crown biomass of less than 4 tons per hectare (brown) to areas of canopy burn with biomass of between 4 and 12 tons per hectare (light brown). (Courtesy of JPL.)

Dobson et al., 1995
Comparison between LIDAR and Radar Height Estimates

- SLICER tree height (blue line)
- GeoSAR X-minus P-band height (red line)
- GeoSAR X-band interferometric estimate of tree height (green circles)

Crop Type from fully polarized images

The availability of multiple polarizations will greatly improve the potential for crop type mapping.

Hydrology

Snow

Polarimetric data provide information on snow state (wet/dry) and structure within the snow pack, offering increased capability for snow-water equivalent (SWE) measurements.

Traffic monitoring over ocean (water body)

Fully polarimetric data offer increased potential for ship detection.
Finally, …

The L-band ALOS PALSAR

is coming to life in January 2006!

Emerging L-Band Capabilities

- L-band penetrates into vegetation
  - Land cover classification
  - Biomass estimation
  - Wetland monitoring
- Interacts with mechanically more stable parts of vegetation canopies
  - Increased interferometric coherence
  - Differential interferometry on global scale
  - Also better coherence over snow and ice
- Sea surface returns less sensitive to wind
  - Shallow Water Bathymetry

Emerging L-Band Capabilities

- L-band PALSAR provides capabilities unobtainable from existing C-band SARs
- L-band PALSAR avoids much of the temporal decorrelation that plagues C-band systems over vegetated regions
- Can measure water levels in wetlands to a couple centimeters (everglades etc.)
- Fully polarized PALSAR improves biomass mapping
- Fully polarized PALSAR maps soil moisture at a spatial resolution not achievable from optical imagery

A Road Map - New SAR Era at UAF

Volcano
Earthquake
Landslide/Mining subsidence
Permafrost
Ice/Glacier/Snow
Geomorphology
Geological mapping
GL, AVO, AEIC, Dept of Geol. & Geophy.

Dept of Geography: GIS
ASRF: SAR data & Emerging SAR algorithms
ARSC: Parallel computing

School of Natural Resources & Agriculture Sciences

Land cover mapping
Radar RS of Forestry (fire science)
Radar RS of Agriculture
Radar RS of Soil sciences
Radar RS of Hydrology
In the past decade, InSAR/SAR was in the hands of solid Earth sciences!

In the next decade, InSAR belongs to sciences of natural resources!

Let's work hand-by-hand, to face the challenges, and to have fun!