USGS
science for a changing world

Introduction to SAR and Water Resource Applications

September 9, 10, and 11, 2008

Workshop Manual

EROS Training and Education

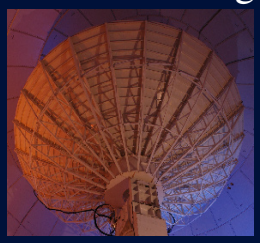
U.S. Department of the Interior
U.S. Geological Survey

About The Workshop

Introduction to SAR and Water Resource Applications

The Introduction to Synthetic-aperture radar (SAR) and Water Resource Applications Workshop , held September 9-11, 2008 at the Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD, is supported by USGS Land Remote Sensing program and the Canada Centre for Remote Sensing. The workshop was planned in response to the needs of the Department of Interior, the Integrated Landscape Monitoring (ILM) Prairie Pothole Thrust, and the Yukon River Basin (YRB) node of the Climate Effects Network. Attendees include USGS staff from multiple sites and disciplines, as well as Canadian, Federal, and State agencies. This workshop is also offered as a WebEx session with an audio bridge to provide an opportunity for off-site participation.

EROS Training



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Day 1

1230 Registration opens
1300 Welcome - Tom Holm, USGS
1320 Workshop Objectives & Introductions - Jennifer Rover, USGS
1330 Introduction to RADAR - Kevin Murnaghan, CCRS
1500 Break
1520 Introduction to RADAR cont'd
1600 RADARSAT-2 Overview and Update - Brian Brisco, CCRS
1630 Potential Wetland Applications with RADARSAT-2 - Jennifer Rover, USGS; Alisa Gallant, USGS; Bruce Wylie, ARTS
1700 Ajourn
1745 Optional evening social at Old Chicago, near hotel (Dutch Treat)

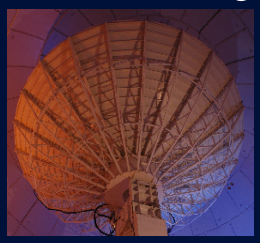
Day 2

0830 Interferometry - Zhong Lu, USGS
1015 Break
1035 Interferometry con't- Zhong Lu, USGS
1200 Catered lunch provided
1300 Polarimetry - Joost van der Sanden, CCRS
1500 Break
1520 Polarimetry con't - Joost van der Sanden, CCRS
1700 Ajourn

Day 3

0830 Software Demonstrations - Kevin Murnaghan, CCRS; Brian Brisco, CCRS
1030 Break
1050 Radar Applications at EROS - Russell Rykhus, SGT
1130 Radar Intelligence for Carp and Critters - Brian Huberty, USFWS
1200 Catered lunch provided
1230 Tour of EROS and the Archive (optional) - Wayne Miller, USGS; Charlie Trautwein, USGS
1315 Hybrid Multi-Sensor SAR-Optical Approach to Mapping and Monitoring Wetlands - Laura Bourgeau-Chavez, MTRI
1345 Overview of Lidar and Its Applications - Dean Gesch, USGS
1415 Hydrologic Derivatives from Lidar - Sandra Poppenga, USGS
1445 Break
1500 Additional presentations or an informal discussion
1600 Workshop Adjourns

EROS Training



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Day 1

- Welcome and Introductions
- Introduction to RADAR
- RADARSAT-2 Update
- Potential RADARSAT-2 Appications

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Presentation Overview

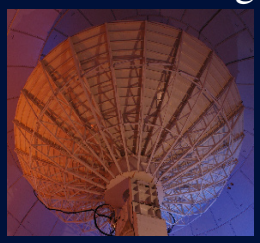
Welcome - Tom Holm, USGS

Welcome to U.S. Geological Survey's. Remote Sensing Education and Training: Introduction to SAR and Water Resource Applications.

Workshop Objectives & Introductions - Jennifer Rover, USGS

Workshop logistics, EROS Tour, Evening Social, Instructor and Participant Introductions.

EROS Training



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EROS Overview

Tom Holm
USGS Earth Resources Observation and Science (EROS) Center
September 9, 2008

U.S. Department of the Interior
U.S. Geological Survey

Center for Earth Resources Observation and Science

"Project EROS"

"…the time is now right and urgent to apply space technology towards the solution of many pressing natural resource problems being compounded by population and industrial growth."

Secretary of the Interior
Stewart L. Udall –1966

Center for Earth Resources Observation and Science

Data Acquisition/Archives:
To expand and safeguard the national archive of remotely sensed land data

Data Access:
To ensure that scientists, businesses, decision makers and the public have ready access to land information

Science:
To promote applications, knowledge and use of land information to better understand our planet

Center for
Earth Resources Observation and Science

Instrument Suite: **AERONET**: Aerosol Robotic network
SCAN: Soil Climate Analysis Network - USDA
ANSS: Advanced National Seismic Station - USGS
CORS/GSOS: Constantly Operating Reference Station / GPS Surface Observing System
RCS: Reference Climate Station – Canada – Future Site
CRN: US Climate Reference Network
SURFRAD: Surface Radiation Network

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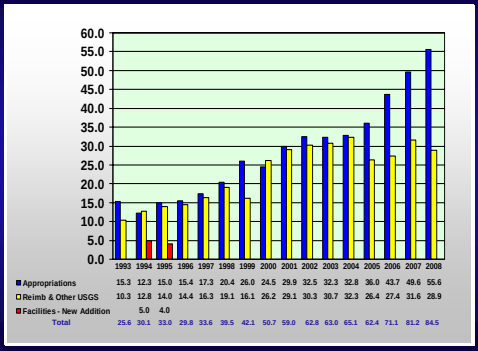
Budget



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Appropriations	15.3	12.3	15.0	15.4	17.3	20.4	26.0	24.5	29.9	32.5	32.3	32.8	36.0	43.7	49.6	55.6
Reimb & Other USGS	10.3	12.8	14.0	14.4	16.3	19.1	16.1	26.2	29.1	30.3	30.7	32.3	26.4	27.4	31.6	28.9
Facilities - New Addition		5.0	4.0													
Total	25.6	30.1	33.0	29.8	33.6	39.5	42.1	50.7	59.0	62.8	63.0	65.1	62.4	71.1	81.2	84.5

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Contracts

- Technical Services Support Contract
  - Stinger Ghaffarian Technologies (SGT)
    - Subcontractors - ADNET Systems, Inc., Information Dynamics, NCDC Imaging, Riverside Technology, Inc.
- Scientific Support Services Contract
  - Arctic Slope Regional Corporation Research and Technology Solutions (ARTS)
- Landsat Data Continuity Contract
  - Science Application International Cooperation (SAIC)

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Landsat Data at No-Charge

- **Began as Pilot to LDCM Distribution Policy**
- **Distribution of Landsat 7 ETM+ SLC-off over the U.S began June 4, 2007**
- **First month distributed more than 2,500 scenes – equivalent to 3 months of normal distribution**
- **Over 13,158 scenes distributed in 348 days between June 4, 2007 and May 16, 2008**

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Landsat Standard Product

- Dataset currently processing
  - L7 ETM+ SLC-off only; newly acquired
  - ≤ 20% cloud cover, high quality

Pixel size:	15m/30m/60m
Media type:	Download (web-enabled), CD/DVD ($50)
Product type:	L1T (terrain-corrected)
Output format:	GeoTIFF
Map projection:	UTM (Polar Stereographic for Antarctica)
Orientation:	North up
Resampling:	Cubic convolution
DEM:	GLS DEM (SRTM, NED, CDED, DTED, GTOPO 30)

USGS

Secretary Kempthorne Showcases Free Public Availability of Landsat Satellite Image Archive at ESRI Conference

SAN DIEGO, CA -- Secretary of the Interior Dirk Kempthorne announced at the ESRI Conference that his direction to the U.S. Geological Survey (USGS) to make its 35-year Landsat satellite image archive available over the Internet for free marks the commitment of the department to breaking down information barriers.

"With the click of a mouse, scientists, government officials and land managers will be able to see the changes in the earth's landscape at any point in the past three and a half decades," he told the conference on Saturday.

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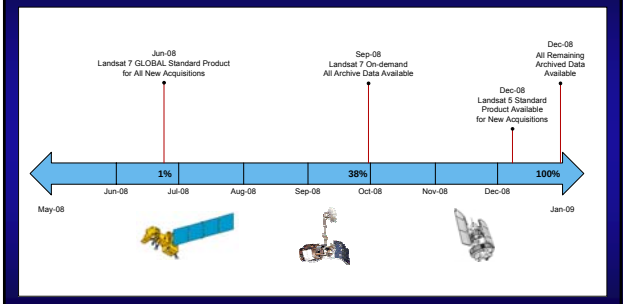
Timeline for all Landsat at No-Charge



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Remote Sensing Education and Training at EROS -- The Early Years

- From 1973 to the mid-1980's, EROS was recognized by many as the world's premier remote sensing education & training center.
  - Averaged 18 domestic and 3 international training courses per year.
  - Courses ranged from introductory to advanced and crossed disciplines.
  - Domestic courses often were organized with other federal agencies.
  - International courses were organized in cooperation with the USGS Office of International Geology and the U.S. Dept. of State.
  - The program was very successful and resulted in important benefits not only to the attendees and their organizations, but also to the USGS, as well as to DOI.
- Regrettably, EROS' formal remote sensing education and training activities were terminated in the mid-1980's.

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Remote Sensing Education and Training at EROS -- Renewed Goals

- Develop and offer a variety of ongoing functional capabilities and resources that together provide remotely sensed data users, and especially potential users, with opportunities to become more informed and educated about all aspects of the science and technology of land remote sensing.
- Program Elements
  - Remote Sensing Curriculum
  - Remote Sensing Instruction
  - Target Audience

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Remote Sensing Education and Training at EROS – Curriculum Development

- Well-conceived and comprehensive set of courses.
- Based on high-quality and relevant instructional material.
- Rooted in existing and anticipated future needs.
- Avoid competing with other remote sensing education providers by focusing on unmet needs.
- Development will require the efforts of many people with diverse talents and abilities.
- Yet, we do not have to start from "scratch," because significant amounts of high-quality material exist upon which to build future workshops and courses.

USGS

Remote Sensing Education and Training at EROS -- Curriculum - Examples

- Remote Sensing Fundamentals
- Role of Remote Sensing in Scientific Studies
- Characteristics of Remotely Sensed Data
- Sensors and Platforms - Radar, Lidar, Hyperspectral, etc
- Data Availability and Access
- Data Analysis, Interpretation, and Integration
- Multidisciplinary Scientific Applications of Remotely Sensed Data

USGS

Remote Sensing Education and Training at EROS -- Proposed Instruction

- Short Courses
  - One day to four days in duration
  - Cover the full scope of the curriculum or focus on specific parts
  - Tailored to the needs of the audience
  - Presented at EROS Center or at "host" locations
- Topical Workshops
  - Focus on topics of interest to a particular segment of users
    - Emerging technologies
    - Important applications
    - Urgent policy issues
  - Promote community engagement and interaction
- Web-Based Technologies
- Printed Material

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Remote Sensing Education and Training at EROS: Radar – our first workshop offering

- The Introduction to Synthetic-aperture radar (SAR) and Water Resource Applications Workshop is a joint effort between the USGS EROS Center and the Canada Centre for Remote Sensing.

USGS
Bruce Quirk
Zhong Lu
Larry Tieszen
Jennifer Rover

CCRS
Brian Brisco
Kevin Murnaghan
Joost van der Sanden

USGS

Presentation Overview

Introduction to RADAR - Kevin Murnaghan, CCRS

- Background
- Synthetic Aperture Radar principles
- SAR Image processing
- Calibration
- Speckle filtering
- Geometric corrections
- Information extraction

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Introduction to RADAR

Kevin Murnaghan
Kevin.Murnaghan@nrcan.gc.ca
Canada Centre for Remote Sensing

CANADA'S NATURAL RESOURCES: NOW AND FOR THE FUTURE
www.nrcan.gc.ca
Natural Resources Canada
Ressources naturelles Canada
Canada

General

- Please ask questions during presentation
- Watch out for RADAR terms

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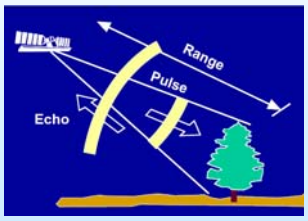
Radio Detection And Ranging

A Radar system has three primary functions:

- Transmit microwave (radio) signals towards a scene
- Receive the portion of the transmitted energy backscattered from the scene
- Measures the return signals:
  - Strength (detection)
  - Time delay (ranging)



RADAR provides its own energy source and, therefore, can operate both day or night.

This type of system is known as an active remote sensing system.

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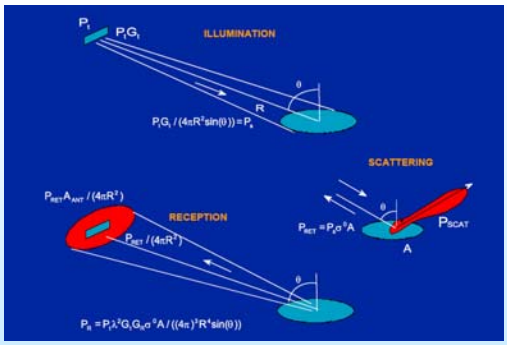
Radar Equation



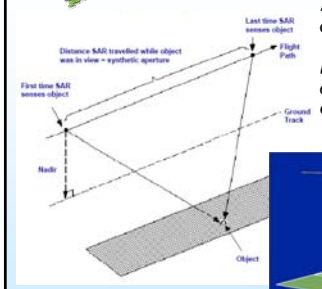
Why Use RADAR for Remote Sensing?

- Controllable source of illumination
  - Sees through cloud, fog and rain
  - Acquisitions day and night
- Images can be high resolution (3 - 10 m)
- Different features are better portrayed or discriminated compared to visible sensors
  - Ice, ocean waves
  - Soil moisture, vegetation mass
  - Man-made objects, e.g. Buildings
  - Geological structures

What is Synthetic Aperture (SAR)?

- A side-looking radar system which makes a high-resolution image of the Earth's surface (for remote sensing applications)
- Continuous strips of the ground surface are "illuminated" parallel and to one side of the flight direction.
- Digital signal processing is used to focus the image and obtain a higher resolution than achieved by conventional radar

Concept of Synthetic Aperture



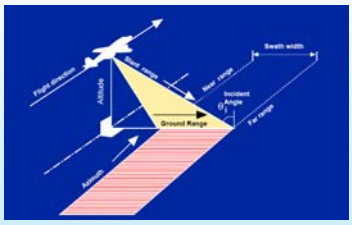
As the SAR moves along its path, it accumulates data.

Many observations of each target are made as the aperture moves over it.

SAR Geometry

- The along-track dimension is referred to as "azimuth"
- The across-track dimension is referred to as "range"
  - Slant range
  - Ground range

- Nadir is the point directly below the RADAR
- Near range edge is closest to nadir and far range edge is farthest from the radar.



Source: Adapted from K. Raney

SAR Resolution

Resolution should not be confused with pixel spacing which results from sampling done by the SAR image processor.

Range Resolution

- Determined by built-in radar and processor constraints which act in the slant range domain.
- Range resolution is dependent on the length of the processed pulse; shorter pulses result in "higher" resolution.
- Radar data are created in the slant range domain, but usually are projected onto the ground range plane when processed into an image.

Azimuth Resolution

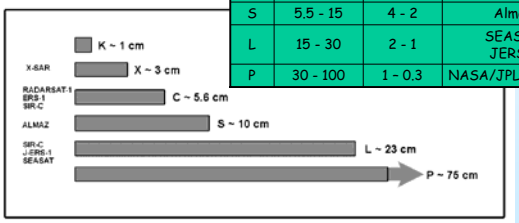
- Real aperture RADAR
  - determined by the azimuth angular beamwidth
- Synthetic Aperture RADAR
  - Azimuth processing increases resolution.
  - Hundreds of times smaller than the transmitted antenna beam width, less than the antenna length.
  - Constant with range.

Microwaves

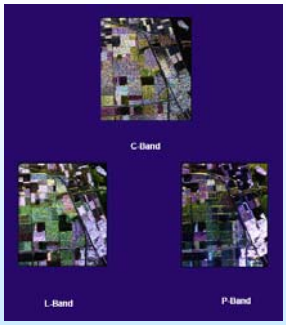
- Most remote sensing radars operate at wavelengths between .5 cm to 75 cm.
- Wavelength should be matched to feature
  - Examples
    - Ice – small features – X-band
    - Geology – Large features – L-band
- Longer wavelengths ⇨ more penetration
  - precipitation or surface layer
- Wavelengths > 2 cm are not significantly affected by cloud cover
- Rain is a factor at wavelengths < 4 cm.

Relative Size of Microwaves

Band	Wavelength (cm)	Frequency (GHz)	Example
X	2.4 – 3.75	12.5 - 8	Military SAR580
C	3.75 – 7.5	8 - 4	ERS-1 RADARSAT-1
S	5.5 - 15	4 - 2	Almaz
L	15 - 30	2 - 1	SEASAT JERS-1
P	30 - 100	1 – 0.3	NASA/JPL AIRSAR



Frequency Comparison



Multipolarization colour composites courtesy of JPL

Flevoland, Netherlands

Agricultural Scene

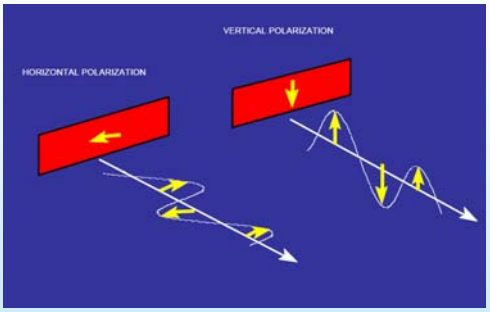
Choice of Radar frequency

- System factors
  - Low frequencies:
    - More difficult processing
    - Need larger antennas and feeds
    - Simpler electronics
  - High frequencies:
    - More difficult electronics
    - Need more power
    - Good component availability at X-band
- Note that many research SARs have multiple frequency bands
  - *e.g.* JPL AIRSAR, SIR-C, Convair-580

Polarization

- Orientation of the electric vector of an electromagnetic wave.
- Antennas usually transmit and receive either horizontally or vertically polarized electromagnetic radiation.
- Like or co-polarized
  - Transmit and receive polarizations are the same directions
  - HH – Horizontal transmission and reception
  - VV – Vertical transmission and reception
- Cross-polarized
  - Transmit and receive polarizations are orthogonal
  - HV - Horizontal transmission and vertical reception
  - VH - Vertical transmission and horizontal reception.

EM Wave Polarization Electrical Wave



Polarimetric Scattering

- When the radar wave interacts with a surface and is scattered from it, the polarization can be modified, depending upon the properties of the surface.
- This modification affects the way the scene appears in polarimetric radar imagery, and the type of surface can often be deduced from the image.

Choice of Polarization

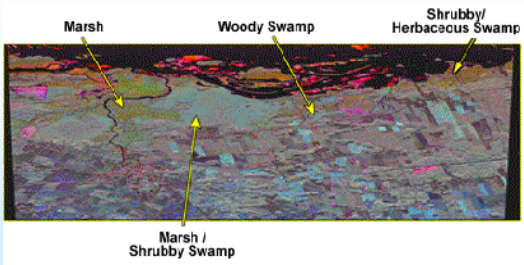
❖ Basic or operational SARs usually have only one polarization for economy, *e.g.* HH or VV

❖ Advanced systems tend to have multiple polarizations, *e.g.* all of: HH, HV, VV, VH (quad pol)

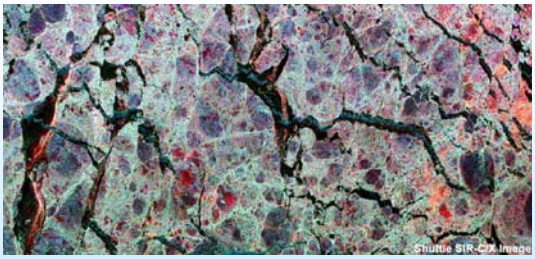
❖ Multiple polarizations help to distinguish the physical structure of the scattering surfaces:

- the alignment with respect to the radar (HH *vs.* VV)
- the randomness of scattering (*e.g.* vegetation - HV)
- the corner structures (*e.g.* HH VV phase angle)
- Bragg scattering (*e.g.* oceans - VV)

SAR 580 Example

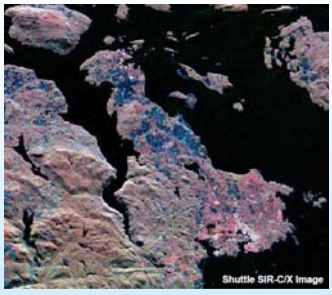


Weddell Sea Ice, Antarctica



C-band, HH L-band, HV L-band, HH

Victoria and Sannich Peninsula, Canada



Urban
Suburban
Forest
Agriculture / Clear-cut

C-band, HH L-band, HV L-band, HH

Benefits of Polarimetry

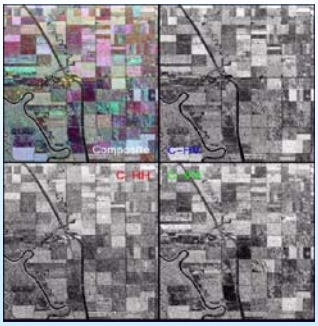
❖ the scattering matrix, Stokes matrix and polarization signature can be computed for each pixel

- can be a powerful classification tool
- for both visual and machine classification

❖the scattering matrix can be used

- to synthesize the return with any transmit/receive polarizations
- to investigate the scattering properties of different surfaces
- to optimize polarization for optimum detectability

Benefits of Multipolarimetric Imagery

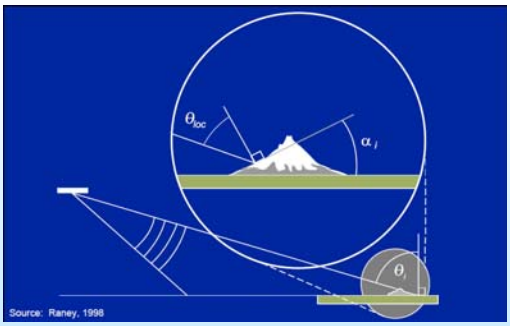


Angles

•**Incident Angle**
- •The angle between the radar illumination and vertical.
- •changes from the near range to the far range affecting the viewing geometry.

•**Local Incident Angle**
- •The angle between the radar illumination and the local surface normal
- •Partially determines the image brightness or tone for each pixel.

Local Incident Angle



Relief Displacement

Side looking radars are subject to one-dimensional relief displacement analogous to that inherent in aerial photography.

Air Photos
- Tall objects are displaced radially away from nadir

SAR
- Displacement in range direction only
- Tall objects displaced toward the sensor.

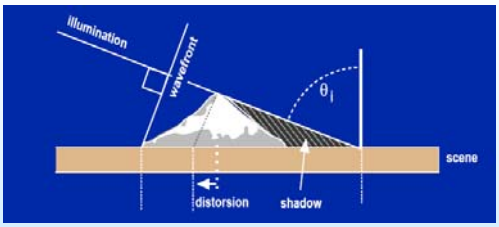
Relief Displacement

The type and degree of relief displacement in the radar image is a function of the difference between the local incidence angle and the incidence angle .

Shadow

- Areas not illuminated by the radar because of viewing geometry and scene relief.
- Since no return signal is received, radar shadow appears very dark in tone in the imagery.
- Radar shadow is most common in steep terrain imaged at large incident angles.
- The height of an object (building, bridge, etc.) can be obtained from its radar shadow.
- Can be used to determine range direction if scene is not labeled
- More prominent at far-range with larger incidence angles

Radar Shadow



Source: Raney, 1998

Radar Shadow in Airborne SAR

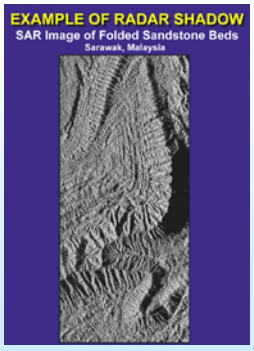
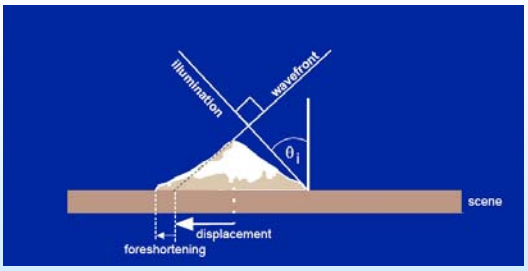


Image courtesy of CCRS and MACRES

Foreshortening

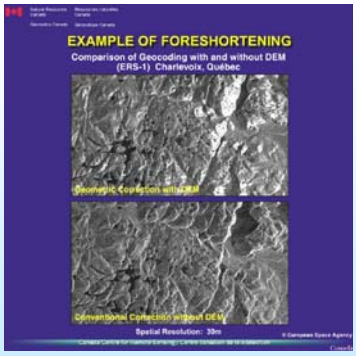
- Foreshortening is the appearance of compression in topographic features in the scene.
- Foreshortened areas are brightened
- The horizontal displacement resulting from the small incident angles causes foreshortening of the slope facing the radar.
- The features appear to be tilted toward the radar
- Foreshortening is at a maximum when a steep slope is orthogonal to the radar beam.
- Larger incidence angles reduce foreshortening in the scene but increases shadowing

Foreshortening



Source: Raney, 1998

Foreshortening

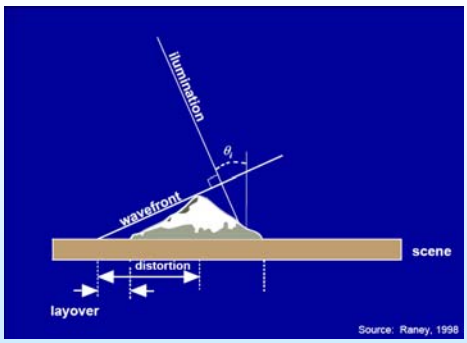


Layover

- Layover is an extreme case of foreshortening
  - Occurs when the incident angle is smaller than the local topographic slope.
  - The reflected energy from the upper portion of a feature is received before the return from the lower portion of the feature.
- The top of the feature will be displaced, or "laid over" relative to its base.
- Difficult for interpretation since each pixel may contain scatter from more than one area.
- More prevalent with small incident angles

Canada Centre for Remote Sensing - ESS

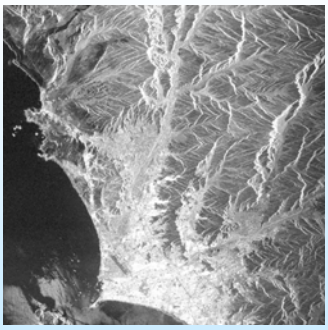
Layover



Natural Resources Canada Ressources naturelles Canada Canada

Canada Centre for Remote Sensing - ESS

Layover Effects on SAR Imagery (Lima, Peru)



Natural Resources Canada Ressources naturelles Canada Canada

Diffuse and Specular Reflectance

- Surface roughness
  - relative to wavelength
  - influences the reflectivity
  - Changes brightness or tone in radar imagery.
- Specular
  - Smooth surface
  - Reflect nearly all incident energy away from the radar
  - Appear dark on radar imagery
  - Calm water or paved highways
- Diffuse
  - Rough surface
  - Scattered in many directions.
  - Brighter tone in radar imagery
  - Vegetation surfaces

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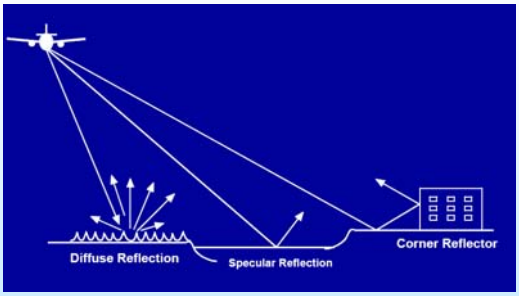
Diffuse and Specular Reflectance



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Scatter

- Two types of reflecting surfaces
  - distributed scatterers
  - discrete scatterers.

- A radar measures that component of the scattered energy which returns along the same path as the incident beam.

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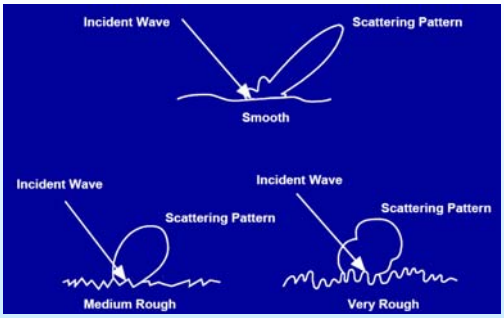
Scatter Types

- Discrete scatterers
  - Relatively simple geometric shape
  - Example - a building
  - Corner reflector
    - sides intersect at (nearly) right angles
- Distributed scatterers
  - multiple small areas or surfaces
  - scatter in many different directions.
  - Example
    - forest canopy
    - cultivated fields.

Surface Roughness

- Surface roughness of a scattering surface is determined relative to radar wavelength and incident angle.
- In general a rough surface is defined as having a height variation of about half the radar wavelength.
- In terms of a single wavelength, a given surface appears rougher as incident angle increases.
- Rough surfaces will usually appear brighter on radar imagery than smoother surfaces composed of the same material.

Surface Roughness
Surface Scattering Patterns



Reflectors

- Small objects may appear extremely bright in radar imagery.
- Dependent on the geometric configuration of the object.
- Dihedral reflector
  - Two surfaces at right angles and open to the radar
  - Narrow beamwidth
  - Example – ground and the side of a building or a bridge.
- Trihedral corner reflector
  - Three mutually perpendicular plane surfaces open to the radar.
  - Wide beamwidth
- Transponder
  - Active reflector with known cross section
  - Polarization adjustable
- Corner reflectors used as reference points in the radar imagery.

Reflectors

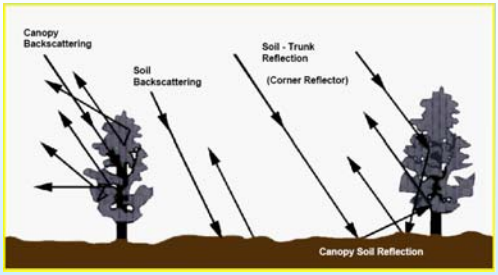
RADARSAT-1 Precision Transponder

Trihedral Reflector

Volume Scattering

- Multiple scattering processes within a medium
- Examples
  - Vegetation canopy of a corn field or a forest.
  - layers of very dry soil, sand, or ice.
- Volume scattering influences the backscatter.
- Radar will receive backscatter from both the surface and the volume.
- The intensity of volume scattering depends on
  - physical properties of the volume (variations in dielectric constant, in particular)
  - characteristics of the radar (wavelength, polarization and incident angle).

Reflections



Applications of SAR

- Mapping and monitoring of Sea Ice
- Measuring motion of the Earth's surface, to help us better understand landslides, earthquakes and volcanoes and support emergency management efforts.
- Studying the movements and changing size of glaciers and ice floes to help better understand long-term climate variability.
- Developing highly detailed and accurate elevation maps.
- Monitoring floods and where they are likely to occur.
- Assessing terrain for the likelihood of finding oil or other natural resources.
- Early recognition and monitoring of oil spills.
- Assessing the health of crops and forests.
- Planning urban development and likely effects.
- Studying land cover and land use change.

Information Extraction

- Image interpretation
- Supervised/Unsupervised classification
- Change detection
- Modelling
- Fusion

And Etc.

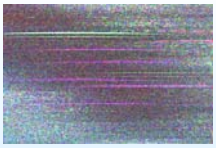
Classes of Radar Product

- Signal Data
- Georeferenced Products
  - complex or detected
  - slant or ground range.
- Geocoded Products
  - detected
  - ground range.

Signal Data

- Raw radar echo data in in-phase and quadrature (I/Q) format
- In slant range
- Stripped of telemetry format information reassembled into contiguous radar range lines
- Not an image, must be processed using a SAR processor to generate an image product

SAR 580 Product Progression



Range Compressed Signal Data

Processed Image

Georeferenced vs. Geocoded Products

- **Georeferenced products:**
  - geographic location of image recorded in file header
  - not corrected to a map projection and should not be used for mapping purposes.
- **Geocoded products:**
  - geometrically corrected to conform to a map projection.
  - often use ground control points and DEM to increase the geocoding accuracy.
  - Usually resampled to a standard square pixel size.

Geocoded SAR 580

Geocoded Products

- Systematically Geocoded or Map Image (RADARSAT-SSG)
  - Product is processed to "North Up" and corrected to a map projection.
  - Image may be converted to one of a large number of map projections.
  - Sample spacing remains as in original data.

Geocoded Products

- Precision Geocoded or Precision Map Image (RADARSAT - SPG)
  - Additional processing inputs
    - Digital Elevation Terrain Model
    - Precisely surveyed ground control points
  - Data format and map projections same as for SSG.
  - Sample spacings remain as in original data.
  - Variety of terminology used for different satellites

Spaceborne SARs

- Less incidence angle variation within a scene that airborne
- Depending on the orbital parameters, a spaceborne SAR can collect data more quickly over larger areas than airborne systems.
- Frequency of coverage is set by orbit constraints and imaging modes of the radar.
- Revisit for typical spaceborne SAR is between 3-35 days.
- Corrections must be made in processing for the effects of earth curvature, earth rotation and orbital variations.

Satellite SAR Missions

- SEASAT (USA) 1978
- Almaz (USSR/Russia)
- SIR-A 1981
- SIR-B 1984
- ERS-1 (Europe) 1991
- J-ERS-1 (Japan) 1992
- SIR-C / X-SAR 1994
- RADARSAT-1 (Canada) 1995
- ERS-2 (Europe) 1995
- Shuttle SRTM 2000
- ENVISAT (Europe) 2002
- ALOS (Japan) 2006
- TerraSAR-X (Germany) 2007
- RADARSAT-2 (Canada) 2007
- Cosmo-Skymed (Italy) 2008

Future Missions

- ALOS 2 (Japan)
- TanDEM-X (Germany)
- Sentinel (Europe)
- SMAP (USA)
- Radarsat-C (Canada)

SAR Interpretation

❖ Two major types of brightness variations observable in a radar image:

- variations in tone
- variations in texture

❖ Though uncommon, radar artifacts are a potential source of unwanted brightness variation as well

❖ Computers are used to supplement and/or extend our visual interpretation of these brightness variations

Elements of Interpretation

Interpretation Element		Example of computer interpretation technique
❖ tone	→	density slicing
❖ colour	→	multispectral classification
❖ texture	→	texture analysis
❖ pattern	→	spatial transforms / classification
❖ size	→	size feature classification
❖ shape	→	syntactic classification
❖ association	→	contextual classification

Image Tone

❖ Refers to each distinguishable grey level from black to white

❖ Proportional to strength of radar backscatter

❖ Relatively smooth targets like calm water appear as dark tones

❖ Diffuse targets like some vegetation appear as intermediate tones

❖ Man-made targets (buildings, ships) may produce bright tones, depending on their shape, orientation and/or constituent materials

Image Texture

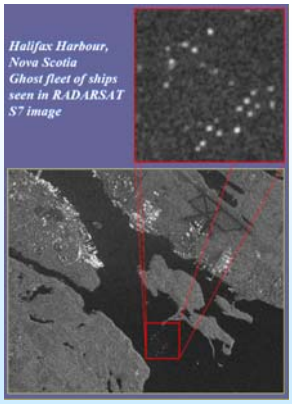
- Refers to the pattern of spatial tone variations
- Function of spatial uniformity of scene targets
- For radar images texture consists of scene texture multiplied by speckle
- Texture may be described as fine, medium, or coarse

SAR Image Artifacts

- SAR image artifacts can occur due to platform, sensor, and/or processing problems
  - Ambiguities
    - Azimuth Ambiguity
    - Range Ambiguity
    - Nadir Ambiguity
  - Scalloping
  - Automatic Gain Control effects for RSAT-1
- Image radiometrics & geometrics can be affected
- Sometimes reprocessing can improve
- Sometimes incorrigible

Ambiguities

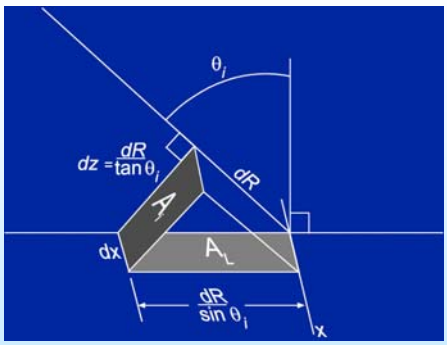
- Azimuth Ambiguity
  - too slow sampling of returned Signals
- Range Ambiguity
  - simultaneous returns from desired illuminated region and of a previously or successively transmitted pulse
    - Nadir Return
    - return from "under the satellite" accompanies return from imaged swath



β_0, σ_0, γ_0 and RADARSAT Data

- Backscatter
  - $\beta 0$ per unit area in slant range
  - $\sigma 0$ per unit area in ground range
  - $\gamma 0$ per unit area of the incident wavefront (perpendicular to slant range)

β_0, σ_0, γ_0 and RADARSAT Data



β_0, σ_0, γ_0 and RADARSAT Data

$$\sigma^0{}_{jk} = \beta^0{}_{jk} + 10 * \log_{10}\left(\sin\left(\theta_j\right)\right)$$

and

$$\gamma^0{}_{jk} = \beta^0{}_{jk} + 10 * \log_{10}\left(\tan\left(\theta_j\right)\right)$$

where j = range sample
k = azimuth sample
Θj = incident angle

$\sigma_0\ jk$ = RADAR BACKSCATTER COEFFICIENT ([dB])

$\beta_0\ jk$ = RADAR BRIGHTNESS ([dB])

- Most natural radiometric observable of a RADAR
  Requires no knowledge of local incident angle

$\gamma_0\ jk$ = GAMMA ([dB])

β_0, σ_0, γ_0 and RADARSAT Data

- Incident angle (θ_j)
  - should be ***local*** incident angle
  - often use **model geoid at sea level** to define θ_j
    - approximate
    - may be significant radiometric approximation
    - may lead to significant error in backscatter coefficient

Wetlands and Agriculture are flat minimizing problems

Geometric Location Accuracy

- Based on Processor Accuracy in determination of geometry of lines at zero-Doppler (output product)
- ***Assumes all targets and imagery at zero height ASL***
  - will be significantly different in "real cases"

Radiometric Calibration

- Dependent on imaging system and processor
- Account for imaging and processing parameters of system and microwave propagation
- Calculations performed during the processing

Radiometric Calibration

$$\beta^0 \alpha \left(\frac{1}{P_T}\right)\left(\frac{1}{g^2(\theta_j)}\right)\left(\frac{1}{G_{SYS}}\right)(R^3)$$

- where:

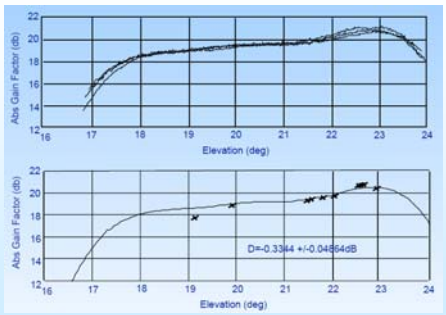
  PT = transmitter power

  g (θ*j*) = one way antenna gain pattern

  GSYS = system gains

  R = slant range

Antenna Gain Pattern for Standard Beam S1



Reference:
T. I. Lukowski, R.K. Hawkins, C. Cloutier, J. Wolfe, L.D. Teany, S.K. Srivastava, B. Banik, R. Jha and M. Adamovic, "RADARSAT Antenna Pattern Determination, " Proceedings of GER'97, Ottawa, May 27-29, 1997.

Use of Radiometrically Calibrated Products

- Goal of radiometric calibration
  - to account for all the contributions in the radiometric values not due to the target characteristics, so that the backscatter values of targets can be compared to one another or a reference
- Radar data and calculations are not "perfect"
  - Uncertainities in the radiometric values may be increased by further processing by the user
  - When relating radiometric values to ground measurements, uncertainties in both must be considered

RADARSAT Relative Radiometric Accuracy

Design Goals for Standard Beam Modes:

100 km * 100 km scene	1.0 dB
one orbit	1.5 dB
three days	2.0 dB
mission lifetime	3.0 dB

Radiometric Corrections

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Introduction to Speckle

- Granular noise that inherently exists in SAR imagery.
- Single look image looks grainy, salt and pepper appearance and is the dominating factor in radar imagery.
- Speckle noise occupies a wider dynamic range than the scene content itself.
- Images processed with a small number of 'looks' will have distribution intensities which are quite asymmetric due to speckle noise.
- Creating a symmetrical histogram may not be the optimum procedure. Instead, pixels are set to the extreme limits of the data intensity distribution (e.g. DN values of 0 and 255 for 8-bit data).

What is Speckle

Speckle is caused by the coherent addition of backscatter from multiple scatterers within each resolution cell. It produces random constructive and destructive interference

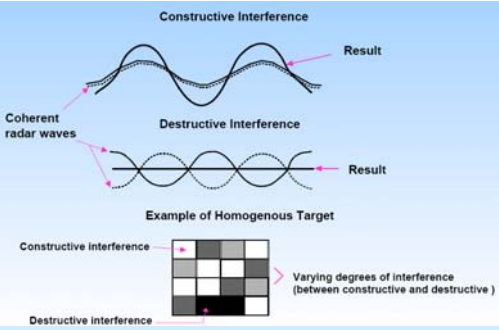
❖ An incident radar wave interacts with each element of the surface and surface cover to generate scattered waves propagating in all directions.

❖ Those scattered waves that reach the receiving antenna are summed in direction and phase to make the received signal. The relative phase components contain the differential propagation paths.

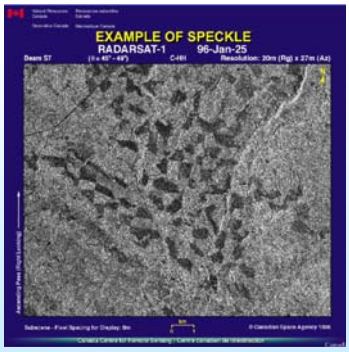
❖ The SAR focusing operation coherently combines the received signals to form the image.

❖ The scattered wave phase addition results in both constructive and destructive interference of individual scattered returns and randomly modulates the strength of the signal in each resolution cell.

Speckle



Example of Speckle



Fading and Speckle

Fading and speckle are the inherent "noise-like" processes which degrade image quality in a coherent imaging system. Fading is due to variation in the echo phase delay caused by multiple targets in a resolution cell with range variations differing by less than a wavelength. Local constructive and destructive interference appears in the image as bright and dark speckles, respectively.

Using independent data sets to estimate the same ground patch, by average independent samples, can effectively reduce the effects of fading and speckle. This can be done by:

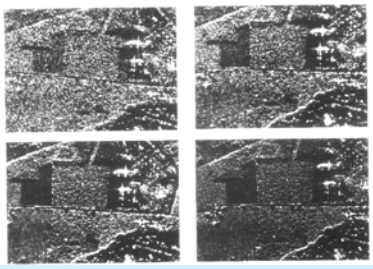
- ❖ Multiple-look filtering, separates the maximum synthetic aperture into smaller sub-apertures generating independent looks at target areas based on the angular position of the targets. Therefore, looks are different Doppler frequency bands.
- ❖ Averaging (incoherently) adjacent pixels.

Reducing these effects enhances radiometric resolution at the expense of spatial resolution.

Speckle Suppression

- ❖Speckle can be reduced by incoherent (amplitude or power) processes.
- ❖ Speckle reduction (or smoothing) necessarily reduces the resolution of single channel SAR data.
- ❖ Two basic linear processes:
  - • Multi-look - divides the signal into minimally overlapped frequency bands, processes each to a reduced resolution image, registers these, detects and adds the detected images.
  - • Averaging - detects the full resolution image, performs local averaging and resampling processes to create reduced resolution, reduced speckle images.
  - • For distributed targets both processes are equivalent.

Multi-look Processing



A 6.1 m x 6.1 m N = 1 Q_{SAR} = 0.027

B 6.1 m x 6.1 m N = 4 Q_{SAR} = 0.11

C 6.1 m x 6.1 m N = 16 Q_{SAR} = 0.43

D 1.5 m x 2.13 m N = 1 Q_{SAR} = 0.31

Courtesy R. Shuchman and E. Kasischke, ERIM

Examples of multi-look processing. Note that image chips A, B, and C all have the same resolution, but that image chips C and D have comparable image quality factors (data from an X-band airborne SAR, 1972, optically processed). (In Principles & Applications of Imaging Radar, Manual of Remote Sensing, 1998, Chapter 2 - Raney, pg. 75)

Why Speckle Filtering

❖ The presence of speckle noise must be considered when selecting analysis methodologies.

❖ Speckle filtering will permit:

- better discrimination of scene targets.
- easier automatic image segmentation.
- the application of the classical enhancement tools developed for imagery from optical sensors such as; edge detectors, per-pixel and textural classifiers.

The Ideal Speckle Reduction Filter

❖ **Reduce speckle with minimum loss of information**

In homogeneous areas, the filter should preserve:

- radiometric information
- edges between different areas

In textured areas, the filter should preserve:

- radiometric information
- spatial signal variability: textural information

Families of Speckle Reduction Filters

❖ Non-adaptive filters
- The parameters of the whole image signal are considered.
- Do not take into consideration the local properties of the terrain backscatter or the nature of the sensor.
- Not appropriate for filtering of non-stationary scene signal.
- Examples are the FFT filters.

❖ Adaptive filters
- Accommodate changes in local properties of the terrain backscatter.
  - The speckle noise is modelled as being stationary
  - The target signal is not stationary since the mean backscatter changes with the type of target
- Examples are the Frost, Lee, Map Gamma, local mean and local median filters

Kernel Size

- Examples are Mean, Median and Mode filter kernels (or windows).
- Filters are a sub-array of X by Y pixels that moves through the image.
- All three filters are square box filters, with a kernel size of 3 by 3 pixels
- Degree of smoothing is a function of the size of the kernel.
- As filter kernel size increases, smoothing increases.

Adaptive Filtering

- Adaptive filters (e.g. Map Gamma) reduce speckle while preserving the edges (sharp contrast variation).
- Adaptive filters modify the image based on statistics extracted from the local environment of each pixel.
- Larger kernel size (e.g. 11x11) result in an important increased smoothing effect.

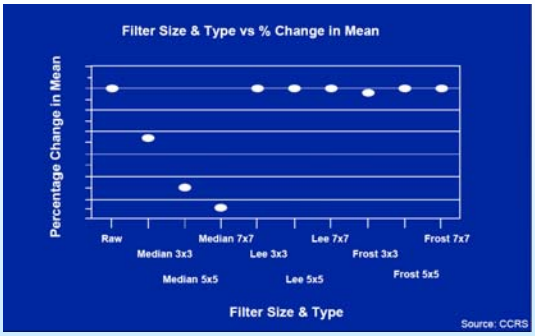
Advantages of Adaptive Filters

- Most of the well known adaptative filters require the calculation of the local observed mean and normalized standard deviation (coefficient of variation).
- The adaptive filter produces an accurate estimate of the backscattering coefficient inside homogeneous (stationary) areas while preserving edge and texture structure in nonstationary scenes.

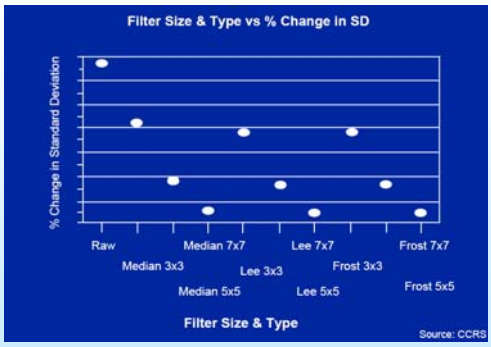
Effects of Filtering

- Whereas, adaptive filters (Lee, Frost and Gamma) preserve the mean value and are therefore preferable for SAR imagery.
- As the filter kernel size increases, so does the percent change in standard deviation.

Effects of Speckle Filtering



Effects of Speckle Filtering



Edge Detection in SAR Imagery

- Application : Segmentation of the image into separate entities, classification
- Types of Edge Detection Filters:
  - Directional, Gradient, Laplacian, Sobel, Prewitt, Ratio Edge Detector
- Warnings
  - The classical edge detectors (e.g. Gradient, Sobel) developed for imagery from optical sensors are not suitable for SAR images.
  - Because of the multiplicative nature of speckle, they detect more false edges within brighter areas.
  - Imagery must first be filtered (Gamma) prior to using the classical edge detectors.

Edge Detection in SAR Imagery (Cont'd)

- Potential alternatives

• The ratio edge detector (R. Touzi et al., IEEE TGRS, 1988) is suitable for SAR images and does not require pre-filtering.

• Performance of the ratio edge detector is better since information is lost during pre-filtering for the classical edge detectors.

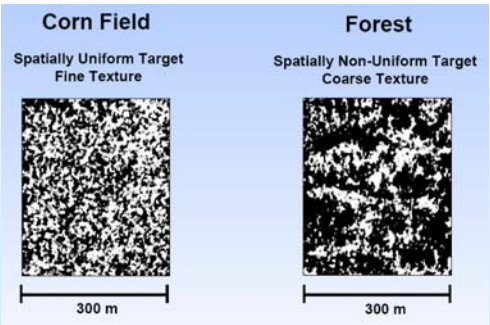
Introduction to Texture

•Texture is the spatial variation of tones in an image.

•Image texture may be qualitatively described as having properties like fineness, coarseness, smoothness, granulation, randomness, lineation, mottled, irregular, hummocky

•In a SAR image, texture has two components:
  •spatial variability in the scattering properties of the scene and speckle.

Image Texture



Texture Analysis

- Textural features contain information about the spatial distribution of tonal variations.
- Methods available:
  - Co-occurrence matrix (GLCM)
  - Grey level difference vector (GLDV)
  - Lacunarity (gap analysis)
  - Neighbouring grey level dependence matrix (NGLDM)
  - Spatial correlation function
  - Model-based approaches

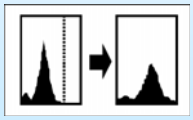
Texture Analysis (Cont'd)

Textural features statistics can be extracted using a grey level Co-Occurrence Matrix (GLCM).

- User specific neighborhood parameters.
- Examples of features from GLCM:
  - Homogeneity
  - Contrast
  - Dissimilarity
  - Angular second moment
  - Mean
  - Standard deviation
  - Entropy
  - Correlation
- Speckle suppression techniques may not preserve all scene texture details.

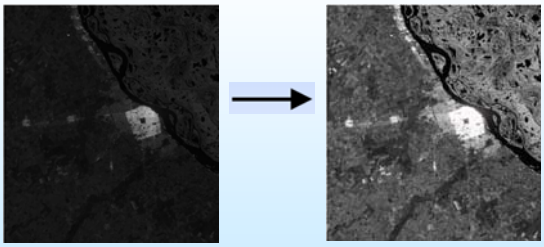
Contrast Stretch

- A contrast stretch enhances visual interpretation
- Matches data's dynamic range to dynamic range of display.
- Involves the construction of a look-up table (LUT).
- LUT is a graphical model of the mathematical function selected.



Contrast Stretch

Rosario, Argentina



Original image

Linear Stretch

Geometric Corrections

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Introduction

- SAR geometric characteristics are very different from optical
- Describe the geometric characteristics of SAR, including:
  - viewing geometry
  - target interaction
  - geometric correction
  - stereoscopy
  - interferometry
- Radar systems are side-looking distance measuring systems, thus key geometric parameters are the incident angle, local incident angle and look direction.
- The side-looking geometry of radar results in several geometric distortions, such as slant range scale distortions and relief distortions.

SAR Geometry

- ❖ What is it ?
  - Review of Platform - Target Geometry
  - Implications of SAR Geometry
    - displacement (foreshortening, layover, shadowing, Earth curvature)
    - Radiometry
- ❖ How to correct it ?
  - Geometric Correction Methods
  - Image Resampling Algorithms
- ❖ How to exploit it ?
  - Stereogrammetry
  - Interferometry

Geometry of Synthetic Aperture Radar (SAR)

❖ Incident angle (θ°) is the angle between the radar line-of-site and the local vertical with respect to the geoid. Incident angle is the most important parameter describing the relative geometry between the radar and the observed scene.
❖ System altitude alters incident angle and thus viewing geometry.
❖ Azimuth direction is the flight direction, or along-track direction.
❖ Range direction is the across-track direction.
❖ Slant range is the distance measured along a line between the antenna and the target.
❖ Ground range is the distance from the ground track to an object.
❖ Near range is the part of the radar image closest to the flight path or nadir, whereas far range is the part of the radar image farthest from the flight path.

Comparison of Imaging Geometries

- System altitude has a large effect on the imaging geometry of the SAR.
- Spaceborne systems operate between 600-800 km, whereas airborne systems between 3-12 km.
- Airborne systems would cover a larger range of incident angles (15°-60°) than spaceborne systems (37°-40°).
- Higher altitude of spaceborne systems means incident angles are usually steeper.

Geometric Distortions

- Slant range acquisition
- Relief displacement
  - layover
  - foreshortening
  - shadowing

NOTE: All these geometric distortions have effects on radiometry

Radar Slant Range / Ground Range

- Radar can be presented in either slant or ground range.
- Slant range is the natural radar range observation coordinate, defined as the line-of-sight from the radar to each reflecting object.
- Ground range is slant range projected onto the geoid of the Earth.
- Slant range data can be converted to ground range by resampling.

Slant Range vs. Ground Range

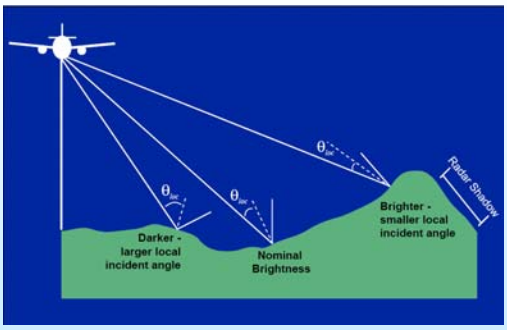
Look Direction

- Look direction is defined as the angle in the horizontal plane in which the radar antenna is pointing when transmitting a pulse and receiving the return signal from the ground or from an object.
- Unless perfectly symmetrical or perfectly random, targets have a preferred orientation.
- For example, opposing look directions for agricultural fields may produce different tones on the image due to row direction related to planting, tilling, or harvesting.
- In areas with high relief, opposing look directions are often necessary to fill in areas of radar shadow.
- On fixed looking systems, such as RADARSAT, two look directions can be acquired using ascending (east-looking) and descending (west-looking) passes.

Effect of Topography / Local Incident Angle on Image Brightness

- Local topographic slope can have a significant effect on image brightness.
- Local topographic slope causes changes in local incident angles.
- A small local incident angle results in brighter radar returns.
- A larger local incident angle results in darker radar returns.
- Slope-induced radiometric effects are useful for some applications such as geomorphology and geology.

Image Brightness as an Effect of Topography



Local Incident Angle Effects

Topographic Displacement

- Due to the different imaging geometries of radar and optical systems, topographic displacement differs between the systems.
- Horizontal displacement for a radar sensor is highest near nadir, and decreases with incident angle.
- Horizontal displacement can be severe at small incident angles.
- In contrast, topographic displacement for optical systems increases with incident angle.

Geometric Correction

- Geometric correction includes slant to ground range, registration, and local incident angle corrections (if topographic information is available).
- Allows a correspondence between the position of points on the final image and their location in a given cartographic projection.
- Consists of introducing spatial shifts on the original Image.

Geometric Correction (Cont'd)

- Algorithms are classified into three methods
  - Slant to ground method (zero relief)
  - Polynomial method (best fit approximations)
  - Radargrammetric method (known sensor geometry)
- The last method uses terrain elevation information.
- Elevation information (DEM) is required to correct the distortions caused by topographic displacements.
- All methods use a resampling kernel during the rectification of the images.

Geometric Correction (Cont'd)

- Radiometric distortions also exist in connection with terrain relief and cannot be completely corrected.
- Resampling of the image can introduce radiometric errors.
- A layover/shadowing mask and a local incident angles map are both helpful for many applications.
- Ground Control Points (GCPs) are used to establish and/or refine the transformation.

Slant / Ground Range Conversion

- SAR data are acquired in slant range.
- Slant to ground range conversion is used to project the acquired image to the ground system.
- Need to know (or assume) imaging geometry, platform altitude, range delay and terrain elevation.
- Resampling used to give uniform pixel spacing (in ground range) across the image swath.

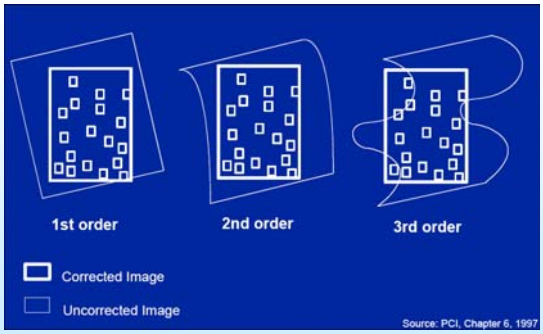
Slant / Ground Range Conversion

- Slant to ground range conversion can be done during signal processing or during image processing.
- Generally applied after radiometric correction.
- Approach and algorithms used are a function of analysis objectives.
- RADARSAT ground range products assume a sea level ellipsoid earth model with zero relief.

Image Registration Polynomial Transforms

- Polynomial transform uses a best-fit.
- Example shows how the uncorrected image changes to fit a map projection using various orders.
- Note the 1st order is a shift-rotation of the image, whereas the 3rd order is a complex warping of the image.
- 1st order polynomial transforms are adequate for images which only require a shift-rotation and a change of scale.
- 2nd order polynomials are used for images requiring nonlinear warping.
- 3rd and higher order polynomials create a more complex image transformation.

Image Registration Polynomial Transforms



Order of Polynomial Transformation

- Higher order transforms require a greater number of ground control points (GCPs) in order to produce the transform model.
- High order does not guarantee higher accuracy.
- Higher order usually ties the image down at the GCPs, but can increase errors between the GCPs.

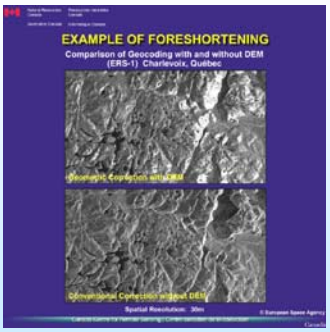
Radargrammetric Method

- Analytical formulation of the distortions during image formation.
  - relative to the platform (ephemeris and ancillary data)
  - relative to the sensor (integration time, pulse length, depression angle)
  - relative to the Earth (geoid, relief)
- Output is an "Ortho-image" corrected for all distortions, including relief.

Radargrammetric Method - Advantages

- Unified reference: cartographic system.
- Image to terrain correction.
- Only one resampling for an image(slant range to map projection directly, no intermediate conversion to ground required).
- Homogeneity in the ortho - image generation.
- Use of a DEM or a mean altitude.
- Better integration with GIS or digital maps.
- Comprehension and control of the full geometric process and of the resulting errors.

Comparison of Two Geocoding Methods



Radargrammetric Method

- In addition to GCPs, this method requires platform and sensor information and DEM or mean elevation data.
- Orbit and sensor information is usually available in radar product headers (e.g. RADARSAT CEOS Leader File).
- The planimetric accuracy of the final ortho-image is dependent on the accuracy of GCPs and the DEM.
- The curves representing the planimetric error of the RADARSAT ortho-image are a function of viewing angle (incidence) and DEM accuracy.

Geocoding Summary

- Geocoding is the geometric correction of image data to a map projection.
- Traditional method of geocoding is the polynomial transform. This method does not model the viewing geometry or use elevation data to correct for topography.
- The most accurate geocoding method is the radargrammetric method.
- The main advantages of the radargrammetric method are that it models the viewing geometry, uses satellite ephemeris data and elevation data to correct for topography.

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Resampling

- Nearest neighbour resampling should not be used for radar imagery.
- Sinx / x or Cubic Convolution is recommended for radar imagery.
- Multi-resampling degrades image radiometry and reduces interpretability.
- Filtering should be performed during the geometric correction step to avoid multiple resampling.

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Presentation Overview

RADARSAT-2 Update - Brian Brisco, CCRS

EROS Training

and Education

Earth Sciences Sector

RADARSAT-2 OVERVIEW & UPDATE

B. Brisco
Research Scientist
Canada Centre for Remote Sensing

Acknowledgments

Daniel De Lisle
CSA

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Earth Sciences Sector

Presentation outline

- **RADARSAT-1 Update**
- **RADARSAT-2 Mission**
  - Mission Objectives
  - Status Report
  - System Characteristics
  - Innovations
  - Image examples and applications
- **Concluding Remarks**

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Earth Sciences Sector

RADARSAT-1 Status

- Over 10 years of operations – twice planned lifetime
- 32 data receiving stations and 22 archive facilities worldwide
- Average system performance > 95% (product quality and calibration fully maintained)
- Total minutes of data: 404,174
- Total orbits completed: 54,255
- Total user requests: 230,730 (as of March 2006)
- Operations confirmed until March 2009

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RADARSAT-2 CSA-MDA Public-Private Partnership

MDA

- Design Authority
- Will own and operate RADARSAT-2
- MDA-GSI will sell and distribute RADARSAT-2 SAR imagery worldwide

Canadian Space Agency

- Technical expertise and Interface with other Canadian Government Departments
- CSA will manage the RADARSAT-2 data allocation within the Canadian Government
- All Canadian Government Departments and Agencies will be provided RADARSAT-2 data to support their mandate
- Data allocation can also be used for scientific, R&D and non-commercial institutional use

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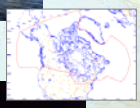
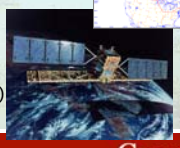
Key Priorities and Objectives

- **Responding to the challenges of:**
  - Monitoring the environment
  - Managing natural resources
  - Performing coastal surveillance



- Objectives:
  - Data continuity from RADARSAT-1
  - Maintain Canada's position in SAR capabilities for Earth observation, in partnership with the Private Sector – MacDonald Dettwiler and Associates (MDA)
  - New applications opportunities



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RADARSAT-2 Spacecraft

Successfully Launched on 14 December 2007 on a Soyuz Rocket from the Baikonur Cosmodrome, Kazakhstan, at 08:17 Eastern Standard Time

Reached nominal orbit 53 minutes later.

RADARSAT-2 Operational since April 25, 2008

LEOP complete	Deployments complete with spacecraft in Normal Pointing Mode.	Completed 15-Dec-08
Spacecraft commissioning review (SCR)	All subsystems transitioned to routine operations and redundancy checks complete.	Completed 28-Feb-08
First image	Standard Beam in dual polarization over a similar region to the first RADARSAT-1 image (ascending pass, Cape Breton). Additionally, strips of Quad-Pole and Ultrafine data will be collected as the Satellite passes North across the coast.	Completed 18-Dec-08
Operational orbit reached	Start of first repeat cycle	Completed 24-Jan-08
Ground Segment Commissioning Review (GSCR)	Ground Segment specific checks complete Performance assessed throughout Commissioning Phase	Completed 11-Mar-08
Ordering readiness review (OHRR)	Ready to start processing orders from major customer	Completed 11-Mar-08
Image Quality Assessment review (IQAR)	Commissioning Phase IQ complete	Completed 16-Apr-08

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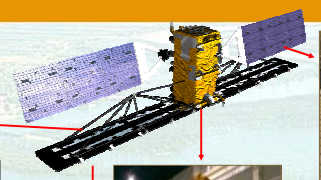
Spacecraft

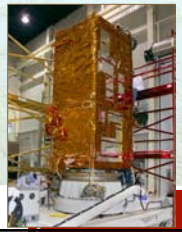


ABLE Engineering

Extensible Support Structure (ESS)

MDA

SAR Antenna and Sensor Electronics



Alenia Aerospazio Divisione Spazio

Bus and Solar Arrays

Canada

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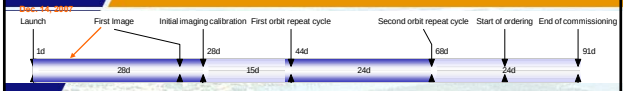
Commissioning Phase



Status:

Commissioning activities are completed. Images were collected in view of SAR characterization and calibration

R-2 Spacecraft orbit height within 400 meters of nominal. In the initial three weeks additional firings took place to achieve the nominal separation between the ground tracks of R-1 and R-2.

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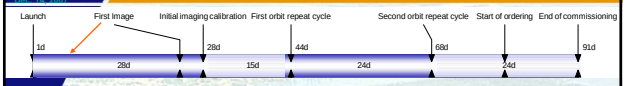
Commissioning Phase

Dec. 14, 2007



As of March 18, all beam modes are calibrated.

Key events:

Spacecraft Commissioning review	27 Feb 08
GS Commissioning Review (GSCR)	11 Mar 08
Ordering Readiness Review (ORR)	11 Mar 08
Commissioning Complete Review (CCR)	17 April 08

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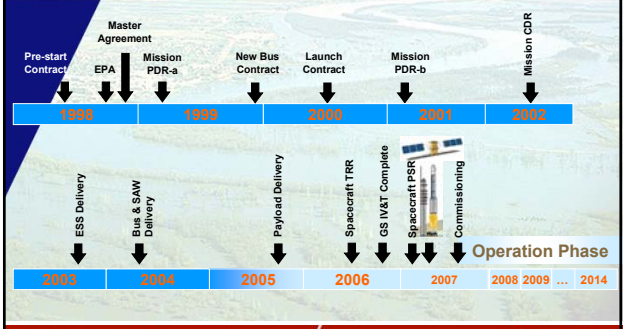
RADARSAT-2 Program Schedule



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System Characteristics

	Design Life	Imaging frequency	Spatial resolution	Polarization	Look direction	Status
RADARSAT-2	7 years	C-Band, 5.405 GHz	3 to 100 meters	Single (HH, VV, VH, HV) Dual (HH/ HV, VV/VH) Polarimetric	Left- and right-looking	Launch 2007
RADARSAT-1	5 years	C-Band, 5.3 GHz	10 to 100 m	Single HH	Right-looking	In operation (Since 95)
Envisat ASAR	5 years	C-Band, 5.331 GHz	30 to 1000 meters	Single (HH, VV) Alternating (VV/HH, VV/VH, HH/HV)	Right-looking	In operation (Since 02)
TerraSAR-X	5 years	X-Band, 9.650 GHz	1 to 15 meters	Single (HH, VV) Dual (VV/HH, VV/VH, HH/HV) Polarimetric (exp.)	Left- and right-looking	Launch 2007
ALOS PALSAR	5 years	L-Band, 1.27 GHz	10 to 100 meters	Single (HH, VV) Dual (HH/ HV, VV/VH) Polarimetric (exp.)	Right-looking	Launched in January 2006

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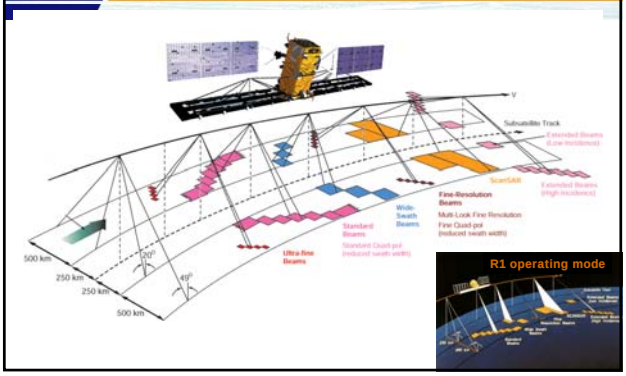
RADARSAT-2 Imaging Modes



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RADARSAT-2 Imaging Modes

	Beam Mode	Nominal Swath Width	Swath coverage to left or right of ground track	Approximate Resolution: Rng x Az
RADARSAT-1 modes with Selective Polarization Transmit H **or** V Receive H **or** V **or** (H **and** V)	Standard	100 km	250km - 750km	25m x 28m
	Wide	150 km	250km – 650km	25m x 28m
	Fine	50 km	525km – 750km	10m x 9m
	ScanSAR Wide	500 km	250km – 750km	100m x 100m
	ScanSAR Narrow	300 km	300km – 720km	50m x 50m
Single Polarization Transmit H and Receive H	Low Incidence	170 km	125km – 300km	40m x 28m
	High Incidence	70 km	750km – 1000km	20m x 28m
Polarimetry Transmit H **and** V on alternate pulses Receive H **and** V on every pulse	Standard QP	25 km	250km – 600km	25m x 28m
	Fine QP	25 km	400km – 600km	11m x 9m
Selective Single Polarization Transmit H **or** V Receive H **or** V	Multiple Fine	50 km	400km-750km	11m x 9 m
	Ultra-fine Wide	20 km	400km-550km	3m x 3m

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RADARSAT-2 Innovations

- **3-metre ultra-fine resolution**
  - highest resolution SAR available commercially
- **Routine left- or right-looking direction**
  - quicker re-visit time
  - more responsive to user requests
  - Antarctic mapping mission fully integrated
- **User-selectable polarization (mode-dependant)**
  - selective single polarization (HH or VV or HV or VH)
  - selective dual polarization (HH and HV or VV and VH)
  - quadruple polarization (HH, VV, HV, and VH)

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RADARSAT-2 Innovations

- **Onboard GPS receivers and star-trackers**
  - ensures a consistently high geometric & radiometric image quality
- **10 microsecond delay between imaging in different modes**
  - virtually no data gap when mode switching is required
- **Yaw-steering for zero-Doppler shift at beam centre**
  - facilitates processing
- **Solid-state data memory**
- **Higher downlink power**
  - 3-metre minimum size receiving antenna
  - lower "cost of entry" for new ground stations

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Increased Spatial Resolution

RADARSAT-2 ultra-fine mode data will provide the highest resolution commerical satellite SAR data available.

- **RADARSAT-2 will be capable of acquiring images with spatial (ground) resolutions as high as 3 m by 3 m (Ultra-Fine beam modes).**
- **Images acquired in the Ultra-fine beam modes will cover a nominal swath no more than 20 km wide and be single look as well as single polarization**

3 m

10 m

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Polarimetry provides...

$$E^S = \frac{e^{jk_0 r}}{r}\begin{pmatrix} S_{vv} & S_{vh} \\ S_{hv} & S_{hh} \end{pmatrix} E^i$$

Scattering matrix (complex)

$$\sigma^\circ \cong \sigma^\circ_{ground} + \sigma^\circ_{vegetation-ground} + \sigma^\circ_{vegetation}$$

5 independent measures

3 Backscatter coefficients σ°

amplitudes: *Svv, Shh, Shv*

2 Phases differences Δϕ

$$\phi_{like} = \phi_{hh} - \phi_{vv}$$

$$\phi_{cross} = \phi_{hh} - \phi_{hv}$$

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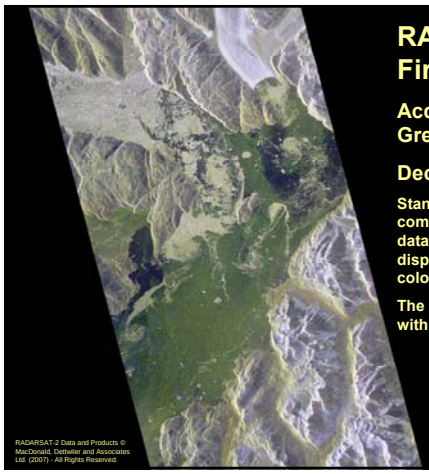

RADARSAT-2 First Image

Acquired over Greenland

December 18, 2007

Standard Quad-Pol composite of the three radar data channels (HH, VV, HV) displayed in a red-green-blue colour scheme.

The scene is ~ 25km x 50km, with 25m nominal resolution.

RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. (2007) - All Rights Reserved.

Fenrisgletscher glacier

A large, slow moving valley glacier that feeds into the Sermilik fjord - is visible in the upper right corner of the image.

Glaciers in this area produce large volumes of icebergs that flow out to sea.

In the fjord, variations in colour represent different types of sea ice and open water.

The use of polarimetric data greatly improves ice edge detection and the identification of ice types as well as increasing ice topography and structural information.

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Iqaluit, Nunavut, Canada

Fine Quad-Pol image acquired January 7, 2008

Composite of the three radar data channels (HH, VV, HV) displayed in a red-green-blue colour scheme.

The scene is ~25km x 28km, with 8m nominal resolution.

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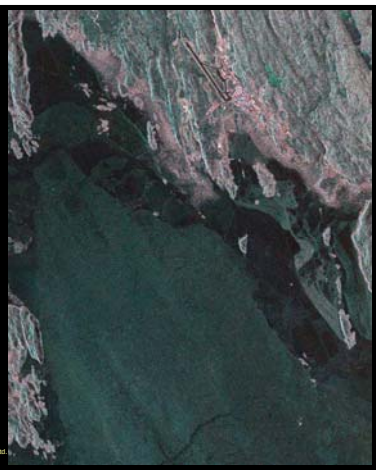
Iqaluit, Nunavut

The Iqaluit airport runway is the dark linear feature located beside the community.

For the most part, Frobisher Bay is ice-covered; however due to large tidal variations, areas of open water are visible along the shoreline as well as in the Bay.

The land clearly shows the striations typical of glaciated terrain. High-resolution and polarimetric responses provide information for the detailed mapping of terrain features, surface structure and variations in surface topology.



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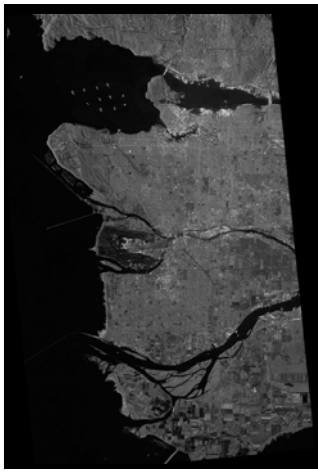

Vancouver

Acquired January 6, 2008 using the Ultra-Fine beam mode, in HH polarization.

The scene is ~ 20km x 36km, with 3m resolution.

The city of Vancouver is visible in the upper part of the image.

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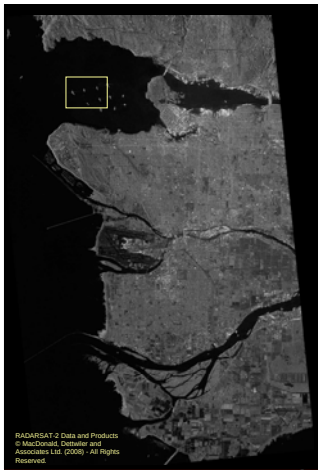
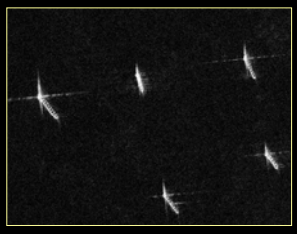


Vancouver

Five cargo ships in English Bay – structural detail of the cargo holds is evident. The bright return from the stern is due to the strong radar response from the superstructure of the ship.



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Vancouver
Vancouver Airport - The thin bright line feature coming in from the right hand side is the new rapid transit Canada Line currently under construction for the 2010 Olympics. More information can also be extracted from the airport terminal buildings and loading gates.
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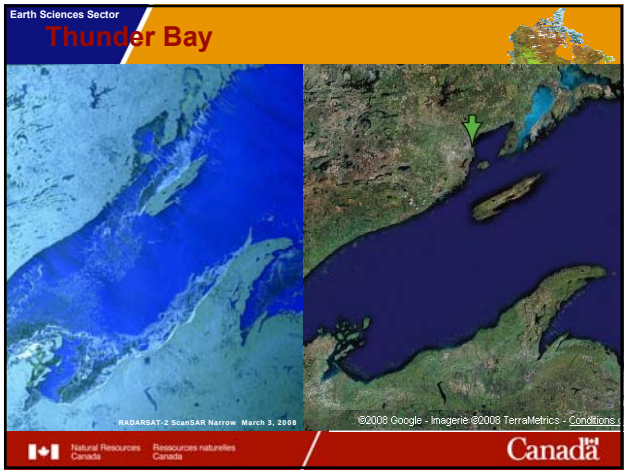
Earth Sciences Sector
Thunder Bay
RADARSAT-2 ScanSAR Narrow March 3, 2008
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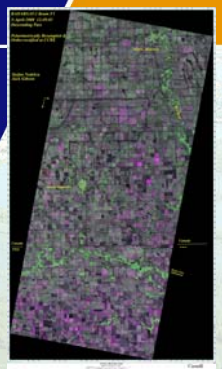
Earth Sciences Sector

Altona, Manitoba, April 5, 2008



- RS-2 Polarimetrically resampled & ortho-rectified
- HH, HV, VV = R, G, B
- RS-2 (beam F1)
- Processed by CCRS GEOCOR

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Canadian Space Agency / Agence spatiale canadienne

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Commitment to Continuity

- **RADARSAT Constellation program rooted in government decisions:**
  - Cabinet "approval-in-principle" December 2004
  - Budget 2005 announced funding of development phases
  - Treasury Board Preliminary Program Approval June 2005
- **Objective of program:**
  - "Provide C-band SAR data continuity to existing RADARSAT users" (not system continuity)
  - "Provide a System of three satellites to enhance operational use of C-band SAR data for: marine surveillance and sovereignty, environmental monitoring and disaster management

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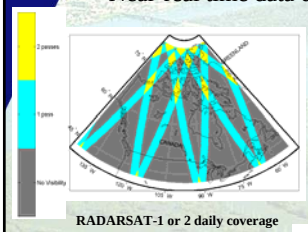
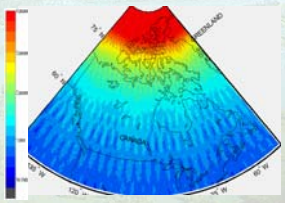
Increased revisit

- Daily Canadian coverage
- Daily near global access (95%)
- Near-real time data daily for operational applications



RADARSAT-1 or 2 daily coverage



RADARSAT Constellation daily coverage

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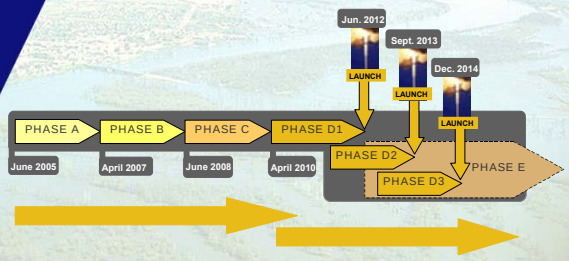
Constellation Timeline



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Concluding Remarks

- RADARSAT Programs key for GoC
- C-band continuity with innovative upgrades
- Key role in environmental monitoring, security and disaster support
- Agriculture (land cover), wetlands, and water resource applications are promising in addition to operational sea-ice, flooding and oil spill applications
- Collaborations encouraged

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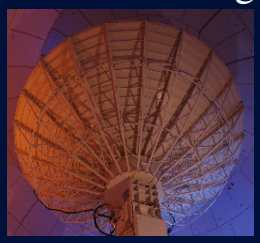
Presentation Overview

Potential Wetland Applications with RADARSAT-2 - Jennifer Rover, USGS; Alisa Gallant, USGS; Bruce Wylie, ARTS

- Integrated Landscape Monitoring - Prairie Potholes Pilot (Rover)
- The Terrestrial Wetland Global Change Research Network (Gallant)
- Yukon River Basin, Alaska - Wetlands…and Lakes (Wylie)

EROS Training



and Education

Potential Wetland Applications with RADARSAT-2

Jennifer Rover[1], Alisa Gallant[1], and Bruce K. Wylie[2]

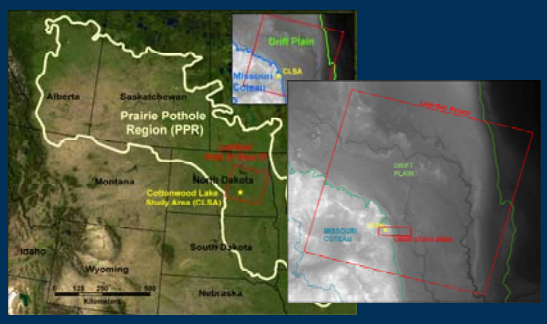
[1]US Geological Survey, Earth Resources Observation and Science Center, Mundt Federal Building, Sioux Falls, SD.
[2]ARTS, contractor to the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center. Work performed under USGS contract 08HQCN0007.

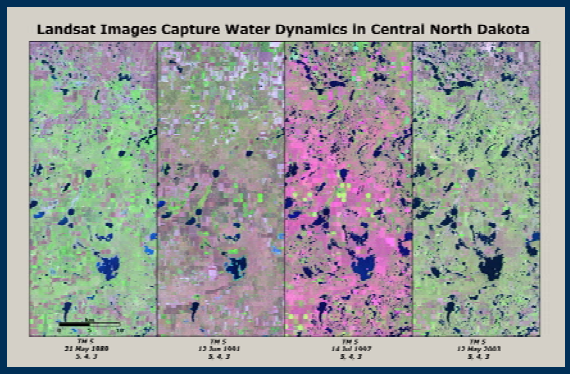
U.S. Department of the Interior
U.S. Geological Survey

RADARSAT-2 at EROS (Ultra Fine, 3m, VV)

- Integrated Landscape Monitoring - Prairie Potholes Pilot (Rover)
- The Terrestrial Wetland Global Change Research Network (Gallant)
- Yukon River Basin, Alaska - Wetlands…and Lakes (Wylie)

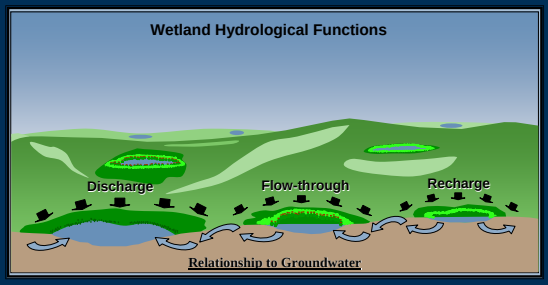
ILM study area





USGS

Types of Function

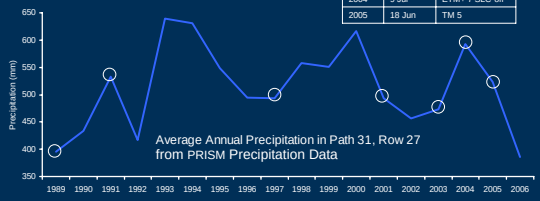


USGS

What does Landsat TM Data Provide?

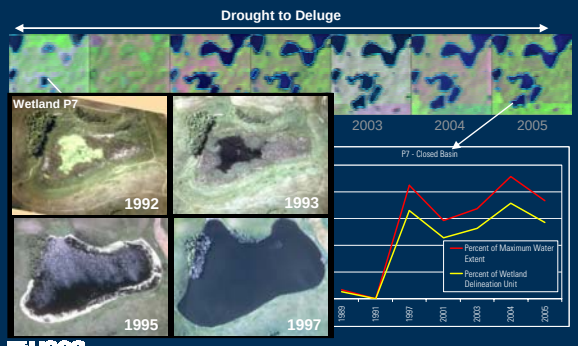
- Record of Surface Water…
  - Mapping water dynamics
  - Mapping response to climate

Acquisition Dates for TM Imagery		
Year	Date	Landsat
1989	21 May	TM 5
1991	12 Jun	TM 5
1997	14 Jul	TM 5
2001	1 Jul	ETM+ 7
2003	12 May	TM 5
2004	9 Jul	ETM+ 7 SLC-off
2005	18 Jun	TM 5



USGS

Mapping Hydrologic Function



USGS

What does RADARSAT-2 Data Provide?

- Water detection – Spring and deluge conditions, small wetlands (temp/recharge)
- Vegetation – Type and structure (groundwater influence)

USGS

USGS

USGS

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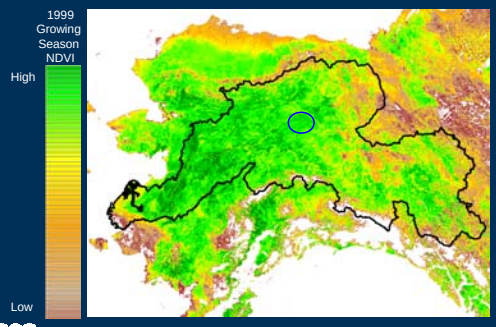
Arctic lakes: Canaries in the coal mine?

- Northern ecosystems responding to dramatic warming
- Lakes and wetlands both declining and expanding
- Identify and detect changes
- Identify mechanisms for change
- Understand and anticipate the effects of change

USGS

The Yukon River Basin



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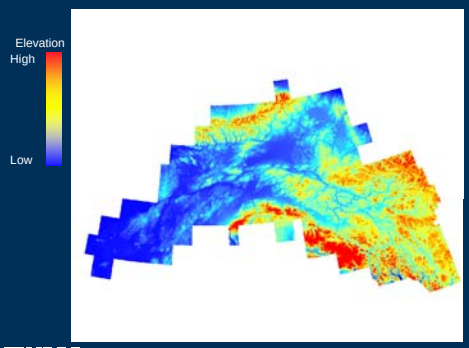
Yukon Flats



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Landsat 5,4,3 Aug 28, 2007

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Small wetlands important

- Downing et al. (2006)
  - New estimates of global abundances of surface water
  - Dominated by water bodies smaller than 1 km^2

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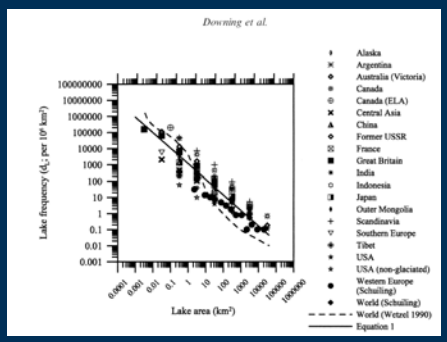
Scaling based on lake size and frequency



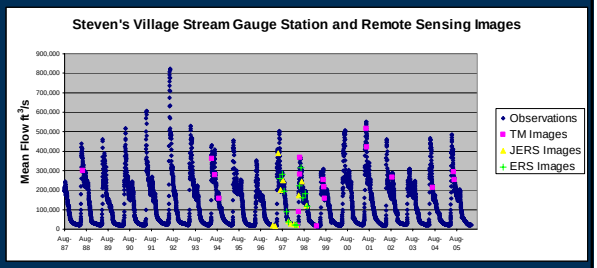
USGS

Goal: Quantify water intra-annual and inter-annual high resolution variation

- Use 5 m data sources
  - IKONOS, QuickBird
- Use RADARSAT-2 for
  - Consistent intra-annual monitoring (~9m detection)
  - Early season emphasis

USGS

Moderate resolution water dynamics to scale-up high resolution water dynamics to the Birch/Beaver Creek watersheds



(JERS and ERS images prior to 1997 and after 1998 not shown)

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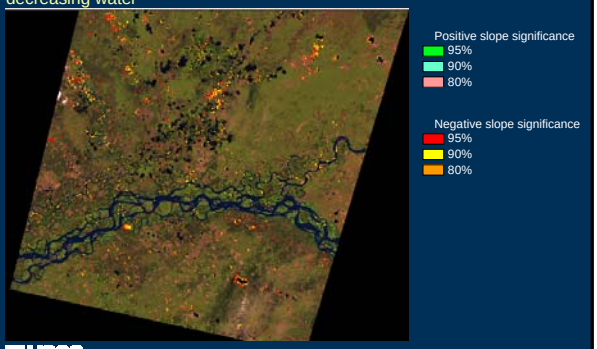
1988 June Landsat 5,4,3 with regression analysis of water change over years showing areas with significant (95 and 90%) increasing or decreasing water



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Soil moisture

- **Ground measurements of soil moisture across 30 m areas**
- **Investigate RADARSAT-2 (HH) amplitude and quad polarized imagery to remove terrain effects in conjunction with Landsat NDWI, tassel cap, and NDVI – Temperature analysis**

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Plans

- Water dynamics
- Soil moisture
- Vegetation mapping (forest, wetland)
- Land cover

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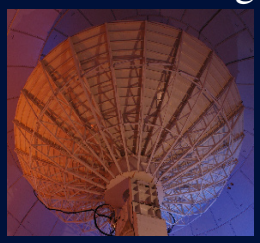
Day 2

- Interferometry
- Polarimetry

EROS Training



and Education

Presentation Overview

Interferometry - Zhong Lu, USGS

EROS Training

and Education

Introduction to Interferometric Synthetic Aperture Radar (InSAR)

- How InSAR works
- InSAR applications
- Hydrology & wetlands
- Future

U.S. Department of the Interior
U.S. Geological Survey

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1. InSAR : How It Works

- About InSAR
- InSAR processing steps
- InSAR artifacts
- Multi-interferogram processing

Terminology

- **Radar** (**Radio detection and ranging**) is a system that uses electromagnetic waves to identify the range, altitude, direction, or speed of both moving and fixed objects such as aircrafts, ships, motor vehicles, weather formations, and terrain.

- **SAR (Synthetic-aperture radar**) is a form of radar in which sophisticated processing of radar data is used to produce a very narrow effective beam (Note the resolution improvement of $\lambda H/A$, where λ - wavelength, H – sensor altitude, and A- aperture size).

- **Interferometry** is a technology which utilizes interference phenomena between two optical, acoustical, radar, or radio waves to determine wavelength, wave velocities, distances, and directions.

- **InSAR – Interferometric SAR**

USGS

Radar is an instrument for measuring distance

- **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.**

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Synthetic aperture radar is an active microwave sensor

- **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.**

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What Radar Can Tell Us

- Transmitted radar signals have known characteristics
  - Amplitude
  - Polarization
  - Phase and Time Reference
  - Wavelength, or Frequency
- A distant object that scatters the radar signal back toward the receiver alters the amplitude, polarization, and phase, differently for different wavelengths
- Comparison of the received signal characteristics to the transmitted signal allows us to understand the properties of the object.

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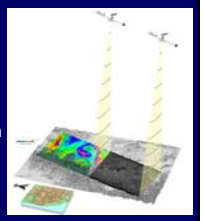
Interferometric SAR (InSAR)

- **InSAR** combines two or more SAR images of the same area acquired from similar vantage points at different times to produce an **interferogram**.

- The **interferogram**, depicting the changes in distance between the radar and the ground, can be further processed to
  - i) **image ground deformation** at a horizontal resolution of tens of meters over large areas with centimeter to sub-centimeter precision under favorable conditions.
  - or
  - ii) **generate DEM** at a horizontal resolution of tens of meters with a few meters accuracy.



Courtesy of C. Wicks

USGS

InSAR is all about interference fringes

Interferometric fringes are daily phenomena

Interferometric fringes on an oil film

USGS

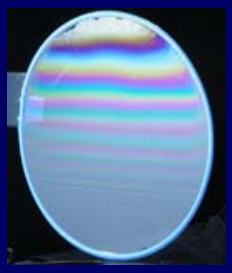
InSAR is all about interference fringes

Interferometric fringes are daily phenomena

Interferometric fringes on a CD

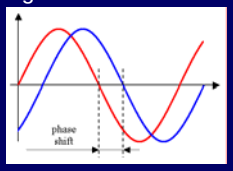
InSAR is all about interference fringes

Interferometric fringes are daily phenomena



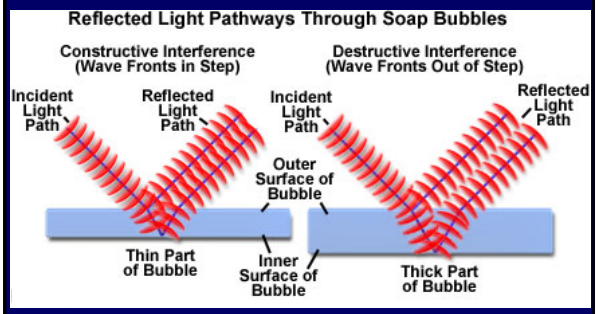
Interferometric fringes on a soap bubble

Thomas Young – Discovered interferometric phenomenon in 1801 and coined the term of "interference fringes" to describe the color bands



Two waves are said to be in phase when corresponding points of each reach maximum or minimum displacements at the same time. If the crests of two waves pass the same point at the same time, they are in phase for that position. If the crest of one and the trough of the other pass the same point at the same time, the phase angles differ by 180° and the waves are said to be of opposite phase.

InSAR is all about interference fringes



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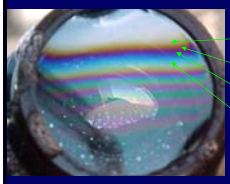
Interferometric fringes on soap bubbles

Interference colors on a soap bubble

White light is made up of all colors of different wavelengths. If one of these colors is subtracted from white light, the complementary color is seen.



- blue is cancelled, leaving yellow
- green is cancelled, leaving magenta
- yellow is cancelled, leaving blue
- red is cancelled, leaving a blue-green

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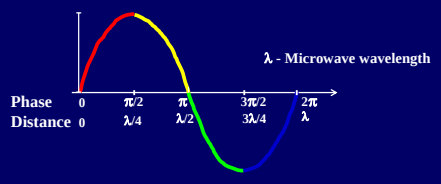
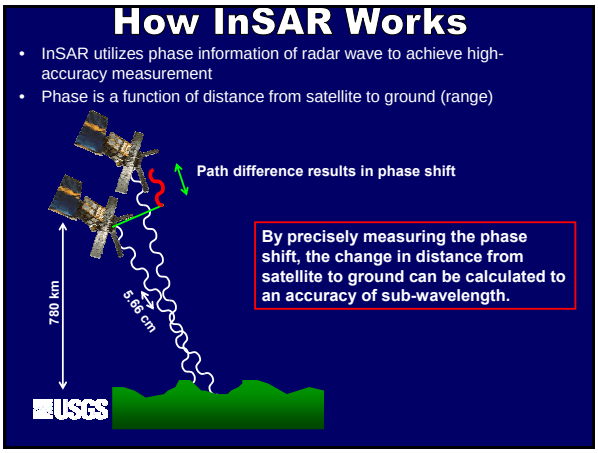
How Radar Interferometry Works

- Traditionally, distance measurement is done by precise timing.
- Accuracy is several meters for spaceborne sensors.



- In interferometry, the distance from the satellite to the ground is achieved by measuring the phase of the electromagnetic wave.
- Accuracy is centimeters to sub-centimeters.


How InSAR Works
• InSAR utilizes phase information of radar wave to achieve high-accuracy measurement
• Phase is a function of distance from satellite to ground (range)
Path difference results in phase shift
By precisely measuring the phase shift, the change in distance from satellite to ground can be calculated to an accuracy of sub-wavelength.
780 km
5.66 cm
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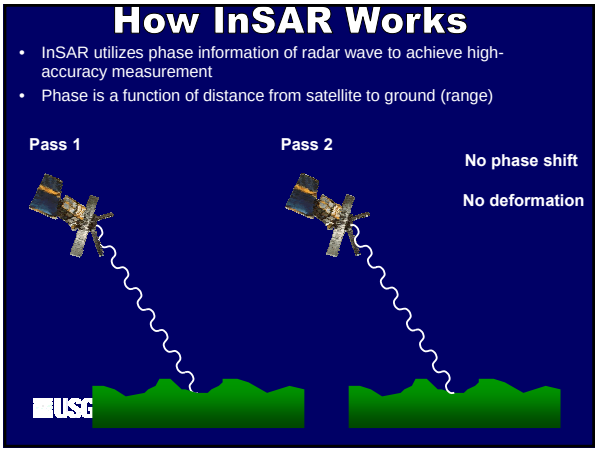
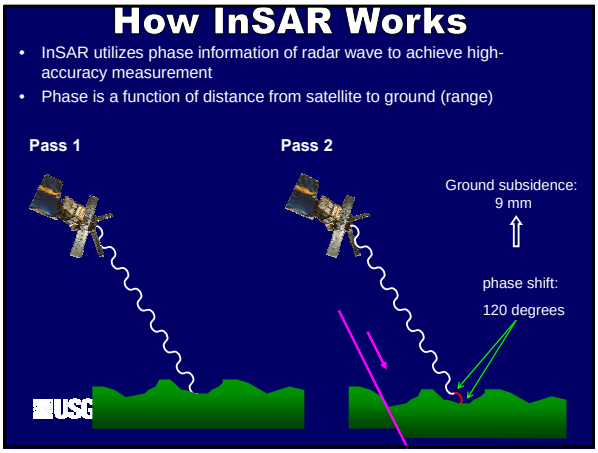
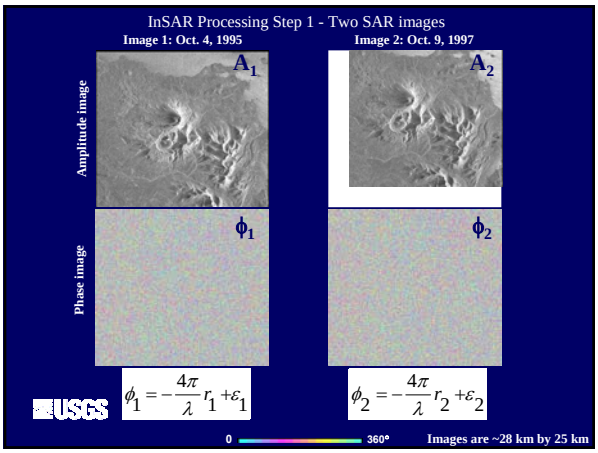

How InSAR Works
• InSAR utilizes phase information of radar wave to achieve high-accuracy measurement
• Phase is a function of distance from satellite to ground (range)
Pass 1
Pass 2
No phase shift
No deformation


How InSAR Works
• InSAR utilizes phase information of radar wave to achieve high-accuracy measurement
• Phase is a function of distance from satellite to ground (range)
Pass 1
Pass 2
Ground subsidence:
9 mm
phase shift:
120 degrees



InSAR Processing Step 1 - Two SAR images

Image 1: Oct. 4, 1995 **Image 2: Oct. 9, 1997**

$$\phi_1 = -\frac{4\pi}{\lambda} r_1 + \varepsilon_1 \qquad \phi_2 = -\frac{4\pi}{\lambda} r_2 + \varepsilon_2$$

- ε is the sum of phase shift due to the interaction between the incident radar wave and scatterers within the resolution cell.
- Because the backscattering phase (ε) is a randomly distributed (unknown) variable, the phase value (ϕ) in a single SAR image cannot be used to calculate the range (r) and is of no practical use

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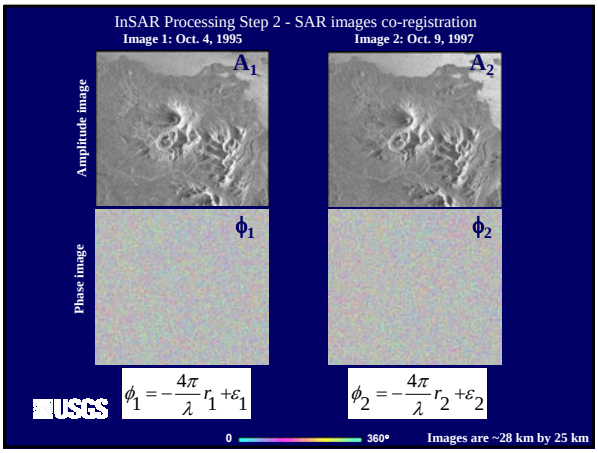
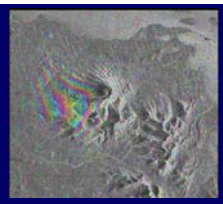


InSAR Processing Step 3 - Original interferogram: $\Delta\phi_{init} = \phi_1 - \phi_2$

$$\phi = \phi_1 - \phi_2 = -\frac{4\pi(r_1 - r_2)}{\lambda} + (\varepsilon_1 - \varepsilon_2)$$

Phase+amplitude images



0 — 360°

The fundamental assumption in repeat-pass InSAR is that the scattering characteristics of the ground surface remain undisturbed.

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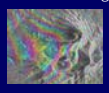
Assume $\varepsilon_1 \approx \varepsilon_2$

$$\phi = \phi_1 - \phi_2 = -\frac{4\pi(r_1 - r_2)}{\lambda}$$

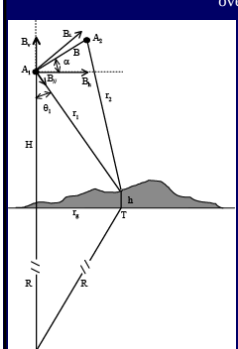
InSAR Processing Step 3 - Original interferogram: $\Delta\phi_{init} = \phi_1 - \phi_2$



$$\phi = \phi_1 - \phi_2 = -\frac{4\pi(r_1 - r_2)}{\lambda}$$

- Nominal values for the range difference, $(r_1 - r_2)$, extend from a few meters to several hundred meters.
- The SAR wavelength (λ) is of the order of several centimeters.
- Because the measured interferometric phase value (ϕ) is modulated by 2π, ranging from $-\pi$ to π, there is an ambiguity of many cycles (i.e., numerous 2π values) in the interferometric phase value. Therefore, the phase value of a single pixel in an interferogram is of no practical use.
- However, the change in range difference, $\delta(r_1 - r_2)$, between two neighboring pixels that are a few meters apart is normally much smaller than the SAR wavelength. So the phase difference between two nearby pixels, $\delta\phi$, can be used to infer the range distance difference ($r1 - r2$) to a sub-wavelength precision.
- This explains how InSAR uses the phase difference to infer the change in range distance to an accuracy of centimeters or millimeters.

InSAR Processing Step 4 - Phase difference caused by difference of satellite positions over a flat earth: $\phi_{flat\text{-}earth}$



$$r_1 = \sqrt{(H+R)^2 + (R+h)^2 - 2(H+R)(R+h)\cos\left(\frac{r_g}{R}\right)}$$

$$\theta_1 = \arccos\left[\frac{(H+R)^2 + r_1^2 - (R+h)^2}{2(H+R)r_1}\right]$$

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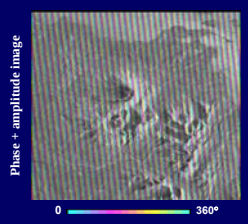
h = 0

$$\phi_{flat-earth} = -\frac{4\pi}{\lambda}(r_1 - r_2) = \frac{4\pi}{\lambda}\left(\sqrt{r_1^2 - 2(B_h \sin\theta_1 - B_v \cos\theta_1)r_1 + B^2} - r_1\right)$$

InSAR Processing Step 4 - Phase difference caused by difference of satellite positions over a flat earth: $\phi_{flat\text{-}earth}$



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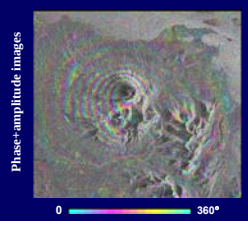
InSAR Processing Step 5 - Flattened interferogram: $\Delta\phi_{init} - \phi_{flat\text{-}earth}$



$$\Delta\phi_{init} - \phi_{flat-earth} = -\frac{4\pi}{\lambda}\frac{B\cos(\theta_1 - \alpha)}{r_1 \sin\theta_1}h + \phi_{def} = -\frac{4\pi}{\lambda}\frac{B_\perp}{H\tan\theta_1}h + \phi_{def}$$

For the ERS-1/-2 satellites, H is about 800 km, θ_1 is about 23° ±3°, λ is 5.66 cm, and $B_\perp$ should be less than 1,100 m for a coherent interferogram.

$$\Delta\phi_{init} - \phi_{flat-earth} \approx -\frac{2\pi}{9600}B_\perp h + \phi_{def}$$

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InSAR Processing Step 5 - Flattened interferogram: $\Delta\phi_{init} - \phi_{flat\text{-}earth}$

For the ERS-1/-2 satellites, H is about 800 km, θ_1 is about 23° ±3°, λ is 5.66 cm, and $B_\perp$ should be less than 1,100 m for a coherent interferogram.

$$\Delta\phi_{init} - \phi_{flat-earth} \approx -\frac{2\pi}{9600}B_\perp h + \phi_{def}$$

If ϕ_{def} is negligible in Equation 10, the phase value can be used to calculate height h. This explains how InSAR can be used to produce an accurate, high-resolution DEM over a large region.

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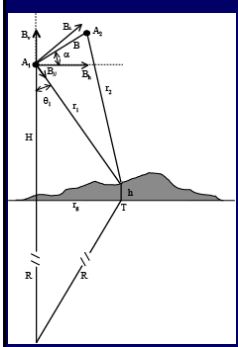
InSAR Processing Step 5 - Flattened interferogram: $\Delta\phi_{init} - \phi_{flat\text{-}earth}$

For the ERS-1/-2 satellites, H is about 800 km, θ_i is about 23° ±3°, λ is 5.66 cm, and $B_\perp$ should be less than 1,100 m for a coherent interferogram.

$$\Delta\phi_{init} - \phi_{flat-earth} \approx -\frac{2\pi}{9600} B_\perp h + \phi_{def}$$

- For an interferogram with $B\perp$ of 100 m, 1 m of topographic relief produces a phase value of about 4°.
- However, producing the same phase value requires only 0.3 mm of surface deformation.
- Therefore, it is evident that the interferogram phase value can be much more sensitive to changes in topography (i.e., the surface deformation ϕ_{def}) than to the topography itself (i.e., h).
- This explains why repeat-pass InSAR is capable of detecting surface deformation at a theoretical accuracy of sub-centimeters.
- Reference: Lu, PE&RS, Vol. 73, No. 3, 245-257, March 2007.

InSAR Processing Step 6 - Topography-only interferogram: ϕ_{topo}

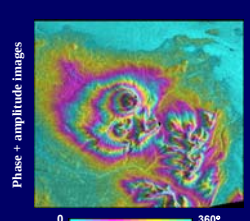


$$r_1 = \sqrt{(H+R)^2 + (R+h)^2 - 2(H+R)(R+h)\cos(\frac{r_g}{R})}$$

$$\theta_1 = \arccos\left[\frac{(H+R)^2 + r_1^2 - (R+h)^2}{2(H+R)r_1}\right]$$

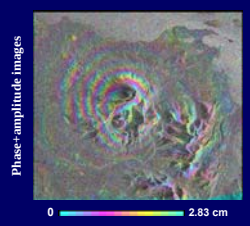
$$\phi_{topo} = -\frac{4\pi}{\lambda}(r_1 - r_2) = \frac{4\pi}{\lambda}(\sqrt{r_1^2 - 2(B_h \sin\theta_1 - B_v \cos\theta_1)r_1 + B^2} - r_1)$$

InSAR Processing Step 6 - Topography-only interferogram: ϕ_{topo}



InSAR Processing Step 7 - Deformation interferogram (+noise):

$\Delta\phi_{def} = \Delta\phi_{init} - \phi_{flat\text{-}earth} - \phi_{topo}$



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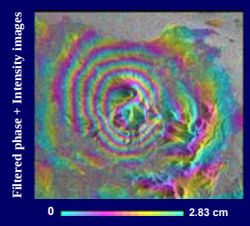
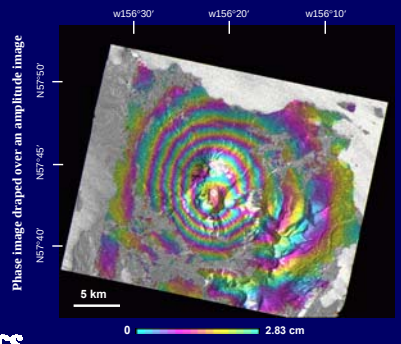
InSAR Processing Step 8 - Deformation interferogram with noise reduction:

$\Delta\phi_{def} = \Delta\phi_{init} - \Delta\phi_{flat} - \Delta\phi_{topo}$



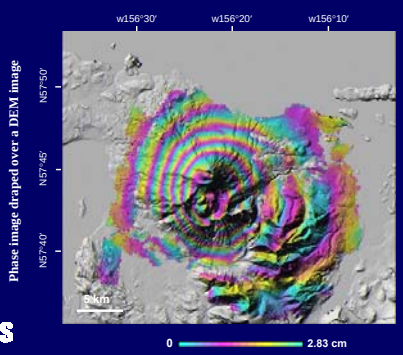
USGS

InSAR Processing Step 9 - Deformation interferogram in map projection (including phase unwrapping and geocoding)

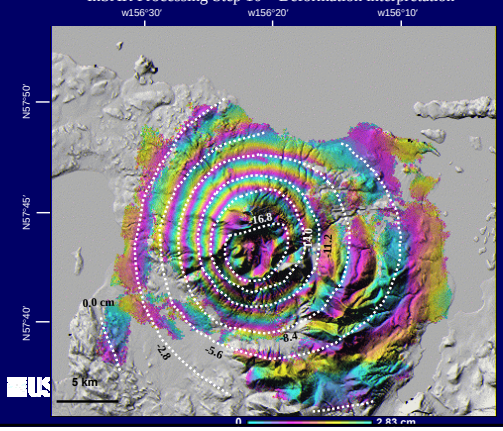


USGS

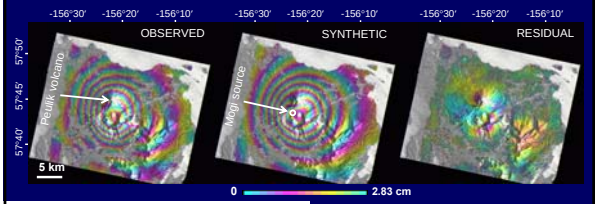
InSAR Processing Step 9 - Deformation interferogram in map projection



InSAR Processing Step 10 – Deformation interpretation



InSAR Processing Step 11 - Deformation modeling

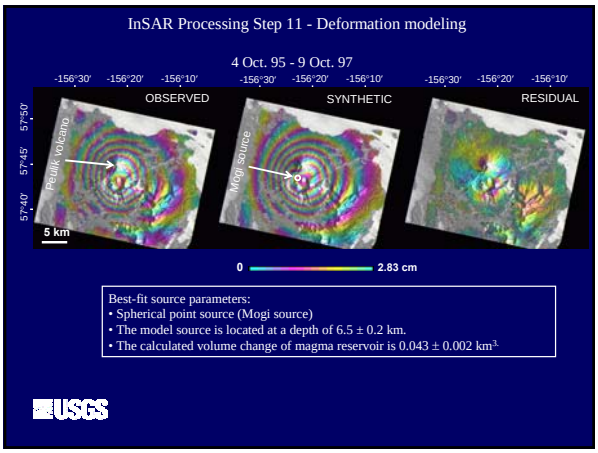


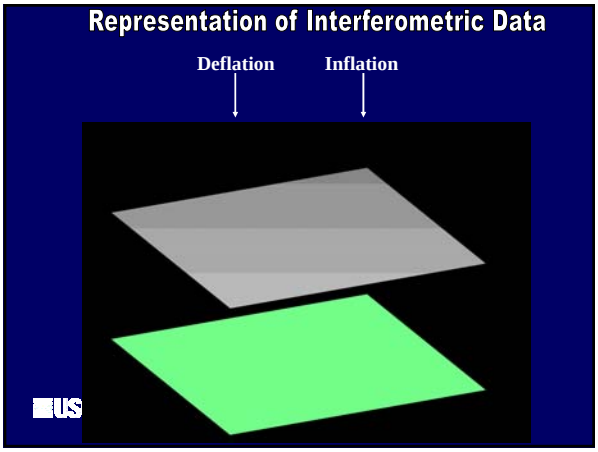
Spherical point source (Mogi source)

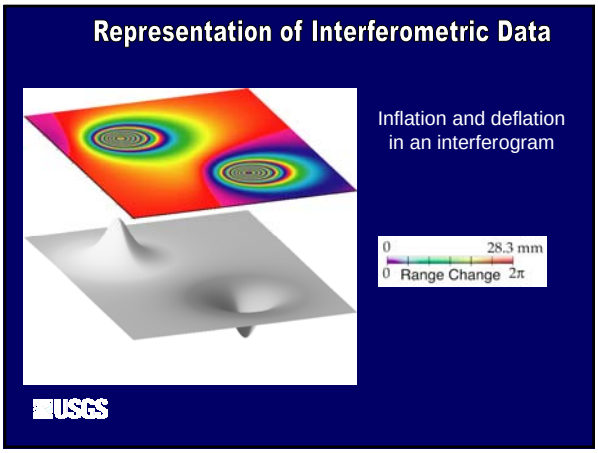
$$u_i\,(x_1 - x_1', x_2 - x_2', 0) = \frac{(1-\nu)(1+\nu)}{2\pi(1-2\nu)} \frac{x_i - x_i'}{R^3} \Delta V$$

where $x'1$, $x'2$, and $x'3$ are horizontal locations and depth of the center of the sphere, R is the distance between the sphere and the location of observation ($x1$, $x2$, and 0), and ν is the Poisson's ratio of host rock.

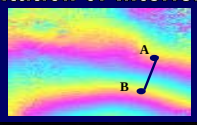
Best-fit source parameters:
- The model source is located at a depth of 6.5 ± 0.2 km.
- The calculated volume change of magma reservoir is 0.043 ± 0.002 km^3.


InSAR Processing Step 11 - Deformation modeling
4 Oct. 95 - 9 Oct. 97
-156°30' -156°20' -156°10'
OBSERVED
SYNTHETIC
RESIDUAL
57°50'
57°45'
57°40'
Peulik volcano
Mogi source
5 km
0
2.83 cm
Best-fit source parameters:
• Spherical point source (Mogi source)
• The model source is located at a depth of 6.5 ± 0.2 km.
• The calculated volume change of magma reservoir is 0.043 ± 0.002 km³
USGS


Representation of Interferometric Data
Deflation
Inflation

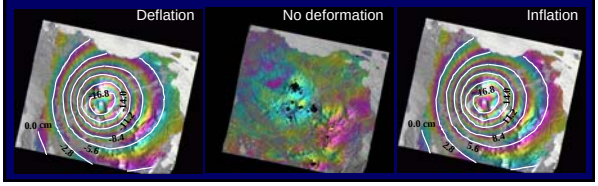

Representation of Interferometric Data
Inflation and deflation in an interferogram
0
28.3 mm
0 Range Change 2π
USGS

Representation of Interferometric Data

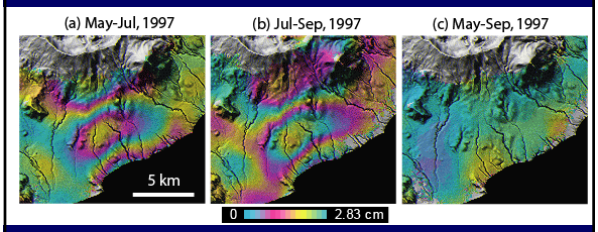


0 — 2π

- Phase Difference from A to B: -2π (one fringe)
- Deformation: B inflates 2.83 cm relative to A.



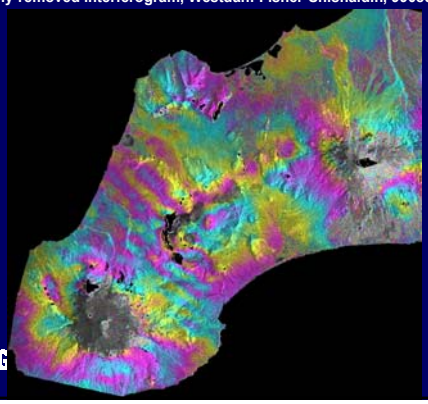
InSAR Artifact: Atmospheric Delays



USGS

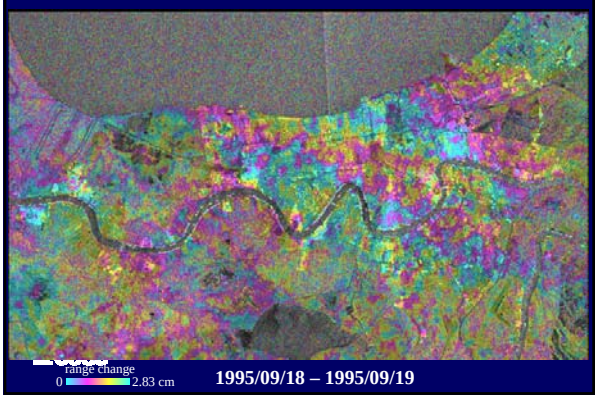
Atmospheric Anomalies

Topography-removed interferogram, Westdahl-Fisher-Shishaldin, 990801-000924

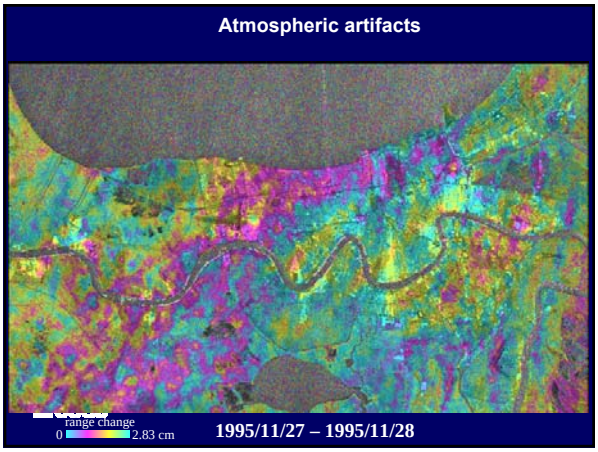


USG

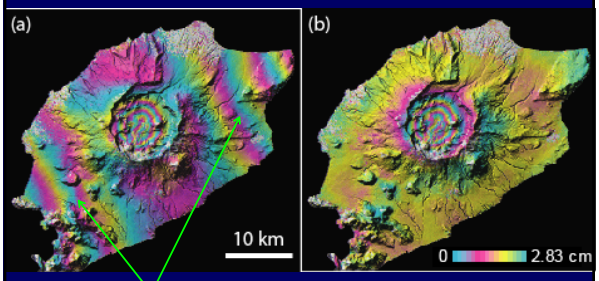
Atmospheric artifacts



Atmospheric artifacts



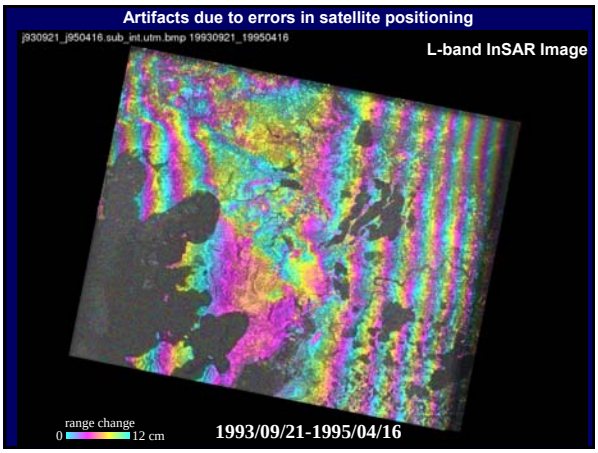
InSAR Artifact: errors in satellite positioning

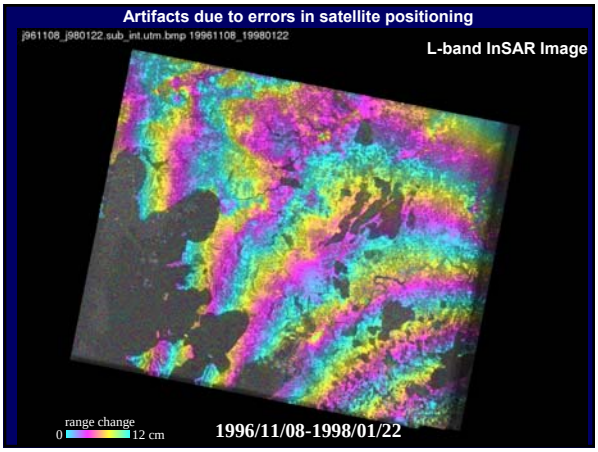


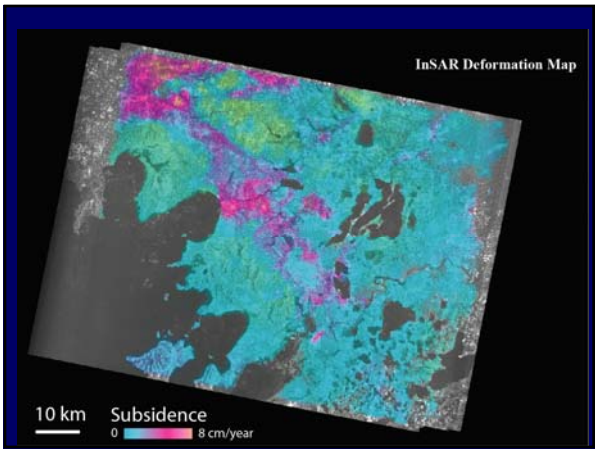
Atmospheric Artifacts due to baseline errors

InSAR deformation image with refined baseline

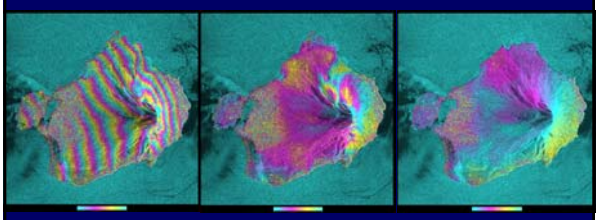
USGS


Artifacts due to errors in satellite positioning
j930921_j950416.sub_int.utm.bmp 19930921_19950416
L-band InSAR Image
range change
0
12 cm
1993/09/21-1995/04/16


Artifacts due to errors in satellite positioning
j961108_j980122.sub_int.utm.bmp 19961108_19980122
L-band InSAR Image
range change
0
12 cm
1996/11/08-1998/01/22


InSAR Deformation Map
10 km
Subsidence
0
8 cm/year

InSAR Artifact: due to errors in satellite positioning & DEM



Original Satellite restitute vectors + 60-m DEM	Precision Satellite restitute vectors + 60-m DEM	Precision Satellite restitute vectors + 10-m DEM

USGS

Multi-interferogram InSAR Processing

Improve deformation measurement accuracy of conventional InSAR through the multi-interferogram approach

USGS

Multi-interferogram InSAR processing

InSAR Differential Phase Equation

For pixel *n* in interferogram *i:*

$$\phi_{n,i} = \phi_{\varepsilon,n,i} + \phi_{def,n,i} + \phi_{Atm,n,i} + \phi_{orbit,n,i} + \sigma_{n,i}$$

DEM Error Term

Deformation

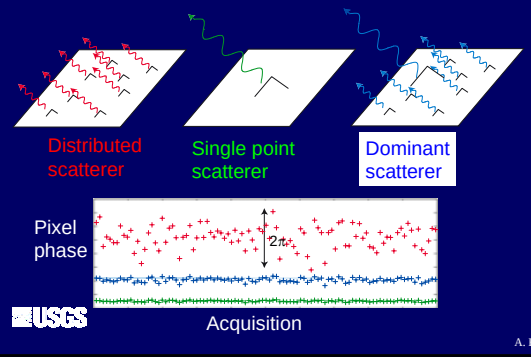
Atmospheric Artifact Term

Orbit Error Term

Noise

USGS

Persistent scatterer principle



A. Hooper

Persistent Scatterer InSAR (PSInSAR)

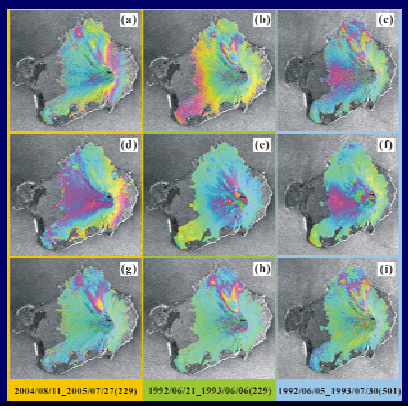
- PSInSAR uses unique characteristics of atmospheric delay anomalies and backscattering of certain ground targets to improve the accuracy of the conventional InSAR deformation measurement from 1-2 cm to 2-3 mm.
- The basic idea behind PSInSAR is to separate the different phase contributions (surface deformation, atmospheric delay anomaly, and decorrelation noise) by iterations, taking into account the spatio-temporal data distribution and the correlation between the point target samples which have unique SAR backscattering characteristics.
- Most of the point targets correspond to single buildings or other stable structures. These points can be used as a "natural benchmark" to monitor terrain motion by analyzing the phase history of each target in the image.

Deformation of Augustine Volcano

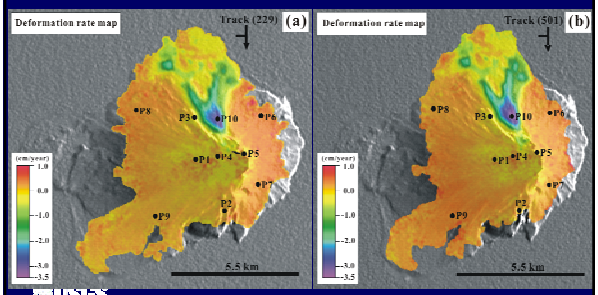
"Deformation" Images

"Atmospheric artifact" Images

Deformation Images obtained via the multi-interferogram approach

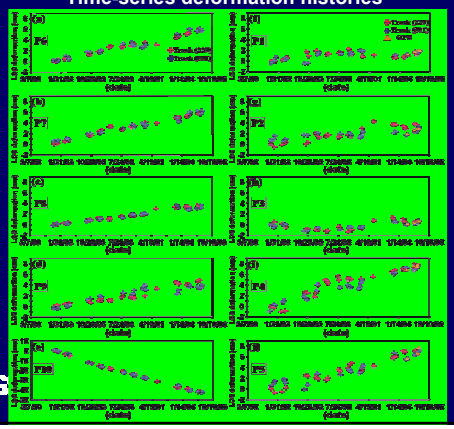


Deformation of Augustine volcano via multi-interferogram approach



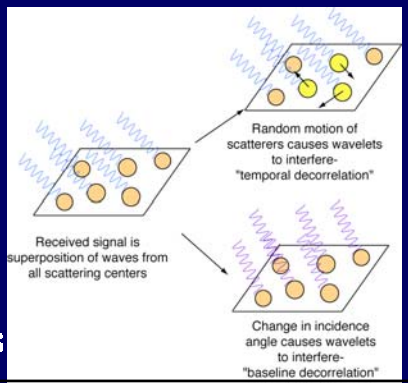
USGS

Time-series deformation histories



USGS

InSAR Decorrelation Sources



USGS

H. Zebker

Loss of InSAR Coherence - Decorrelation

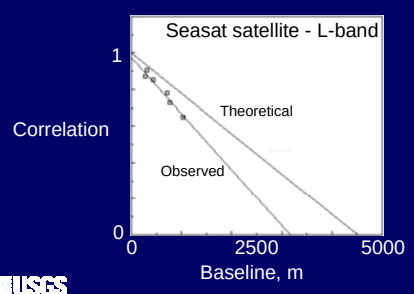
$$Cohrence = \frac{\Sigma s_1 s_2^*}{\sqrt{\Sigma s_1 s_1^* \Sigma s_2 s_2^*}}$$

- Baseline decorrelation
- Temporal decorrelation
- Volume decorrelation
- Rotational decorrelation
- Unspecified noises in system

USGS

Coherence image is a by-product of InSAR processing, useful for landscape characterization

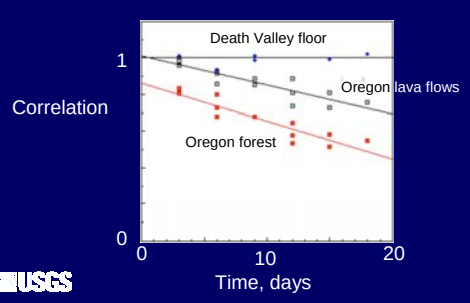
Baseline decorrelation



USGS

H. Zebker

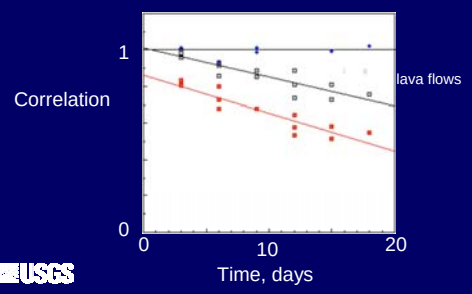
Temporal decorrelation data - L-band



USGS

H. Zebker

Temporal decorrelation data - L-band

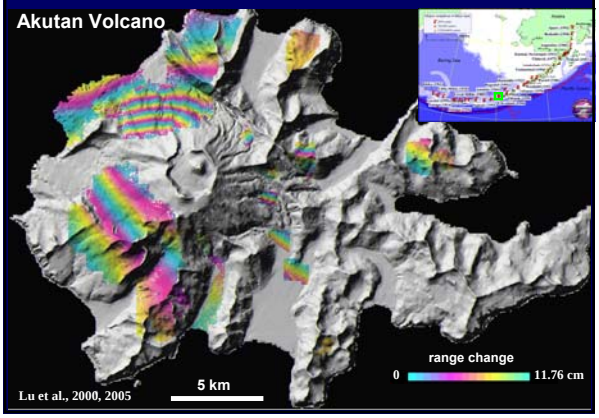


USGS

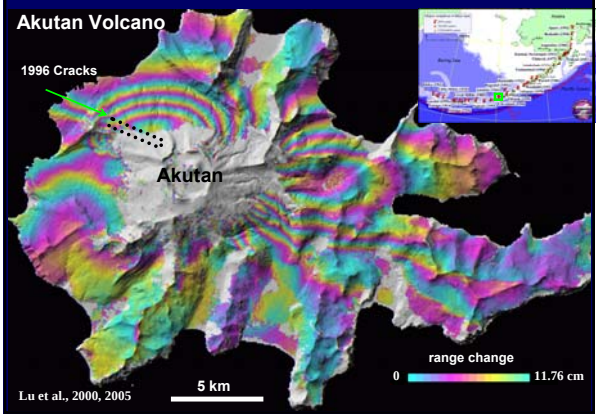
Radar Wavelength vs. Coherence

USGS

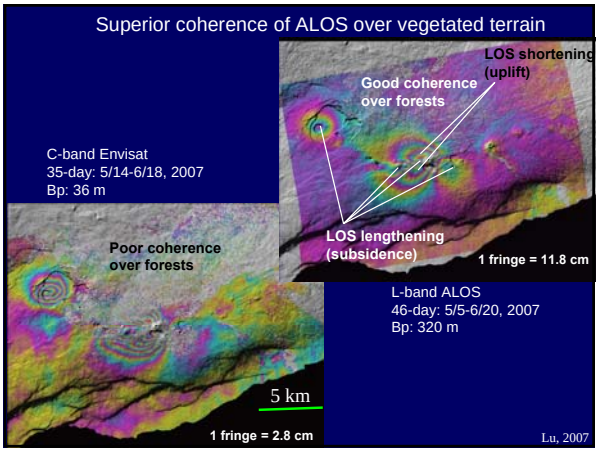
Deformation mapped by ERS (**C-band**, λ = 5.66 cm) InSAR



Deformation mapped by JERS (**L-band**, λ = 23.53 cm) InSAR



Superior coherence of ALOS over vegetated terrain

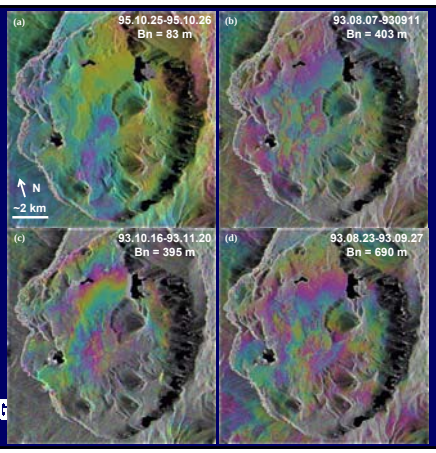


DEM generation from repeat-pass InSAR

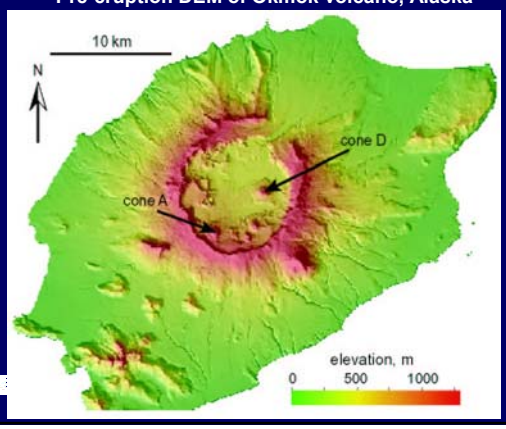
- **Issues affecting DEM accuracy**
  - Baseline uncertainty
  - Atmospheric anomalies
  - Phase decorrelation
  - Surface deformation due to tectonic loading sources
- **Strategies for accurate InSAR-derived DEM**
  - Choose interferograms with large baseline within the limit of phase correlation
  - Use precision orbit data (DLR, Delft), and refine baseline with GCPs
  - Estimate the deformation signal and remove it from the interferograms used for DEM generation
  - Average multiple interferograms $h = \frac{\sum_{i=1}^{4} h_i c_i B_i^2}{\sum_{i=1}^{4} c_i B_i^2}$, h – height, c –coherence, B -baseline

USGS

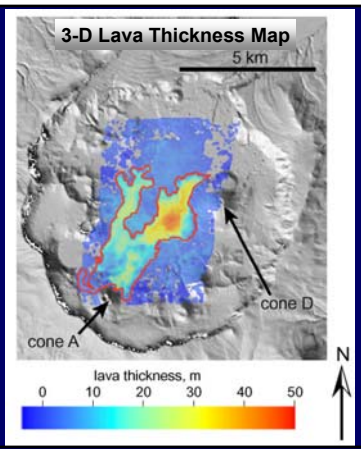
Interfrograms used for DEM generation



Pre-eruption DEM of Okmok volcano, Alaska



3-D Lava Thickness Map



Lu et al., 2003

Thickness of lava flows from the 1997 eruption
by differencing pre- and post-eruption DEMs

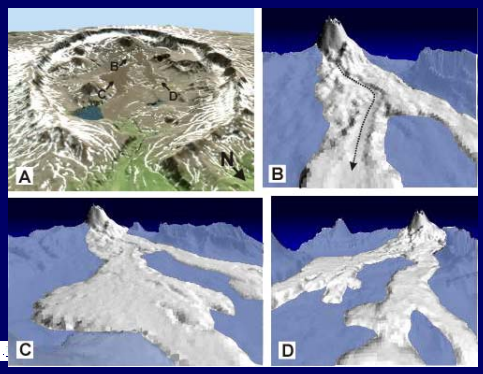
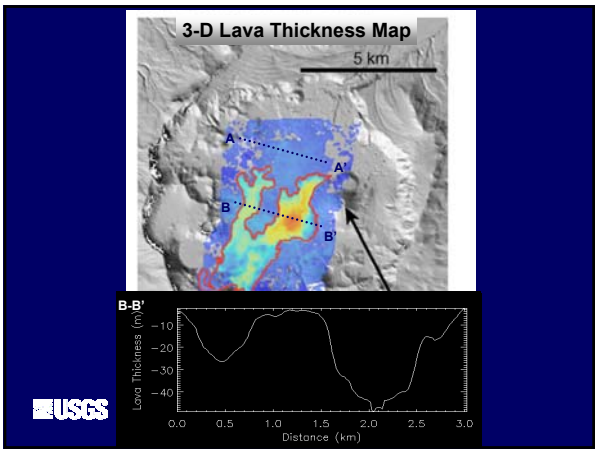


Photo of 1997 Eruption

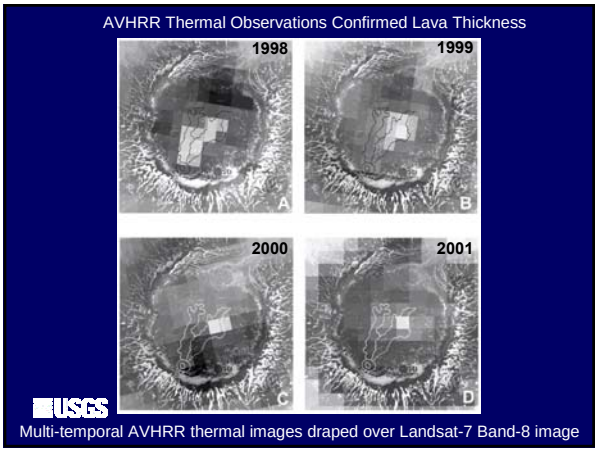
Courtesy of AVO

Photo of New Lava

Courtesy of AVO



AVHRR Thermal Observations Confirmed Lava Thickness



Multi-temporal AVHRR thermal images draped over Landsat-7 Band-8 image

2. InSAR: Applications

USGS

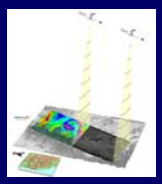
Reference: Lu, Kwoun, & Rykhus, PE&RS, Vol. 73, No. 3, 217-221, March 2007.

About SAR/InSAR

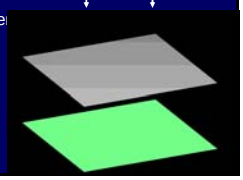
• SAR – all-weather day and night operational imaging capability, sensitive to terrain slope, surface roughness and dielectric constant.

• 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.



Deflation Inflation

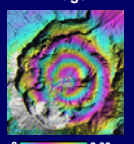


USGS

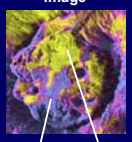
SAR/InSAR Imagery Analysis

InSAR Products

Intensity Image (1) | Intensity Image (2) | Deformation Image | Coherence Image



0 2.83 cm
Range change



low high

• Analysis of (multi-temporal) InSAR deformation images
• Analysis of multi-temporal SAR intensity images
• Analysis of InSAR coherence (degree of changes in backscattering) images

USGS

Synthetic Aperture Radar Satellites

• European ERS-1,	1991-2000,	C-band,	35-day repeat
• Japanese JERS-1,	1992-1998,	L-band,	44-day repeat
• European ERS-2,	1995-now,	C-band,	35-day repeat
• Canadian Radarsat-1,	1995-now,	C-band,	24-day repeat
• European Envisat,	2002-now,	C-band,	35-day repeat
• Japanese ALOS,	2006-now,	L-band,	46-day repeat
• German TerraSAR-X,	2007-now,	X-band,	11-day repeat
• Italian COSMO-SkyMed,	2007-now,	X-band,	16-day repeat
• Canadian Radarsat-2,	2007-now,	C-band,	24-day repeat

Wavelength (λ)
• X-band: λ = ~3 cm
• C-band: λ = ~5.7 cm
• L-band: λ = ~24 cm

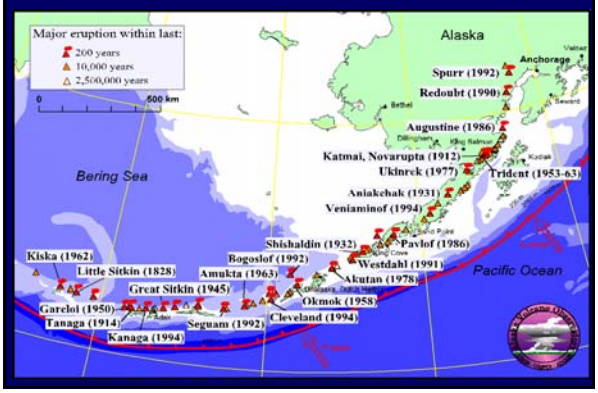
USGS

Volcanoes

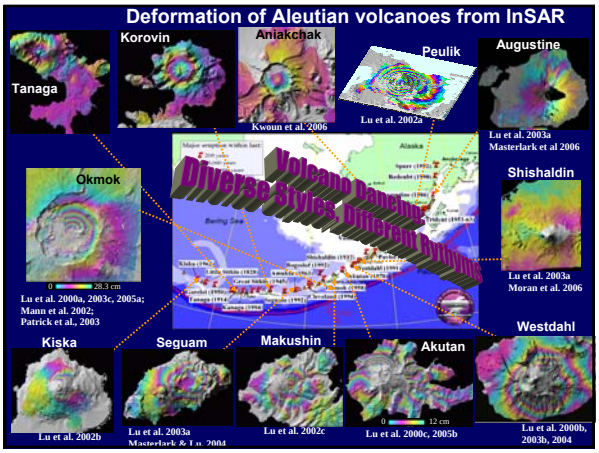
Measuring how a volcano's surface deforms before, during and after eruptions provides essential information about magma dynamics and a basis for mitigating volcanic hazards

USGS

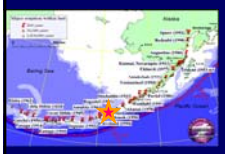
Aleutian Arc Volcanoes



Deformation of Aleutian volcanoes from InSAR

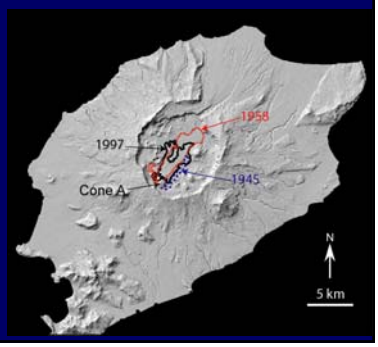


Transient deformation of Okmok volcano – A breathing volcano

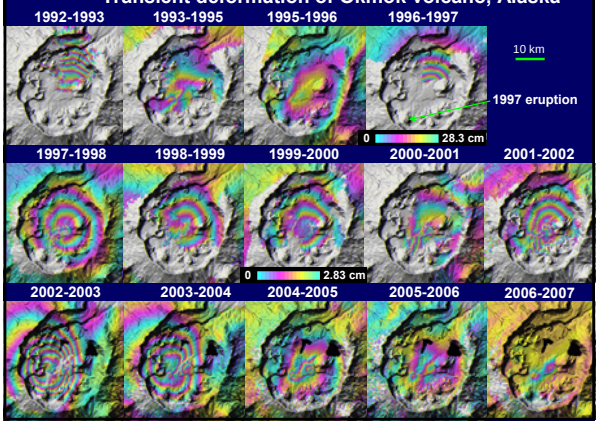


- Shield volcano
- Caldera formed 2050 years ago
- ~10 minor explosive eruptions (ash) in 20th century
- 3 large effusive eruptions (basaltic flows) in 1945, 1958 and 1997
- All eruptions from Cone A

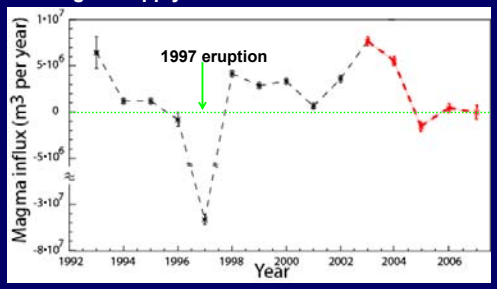
Lu et al., EOS, 1998
Lu et al., JGR, 2000
Mann et al., JGR, 2002
Lu et al., IEEE TGRS, 2003
Lu et al., JGR, 2005



Transient deformation of Okmok volcano, Alaska

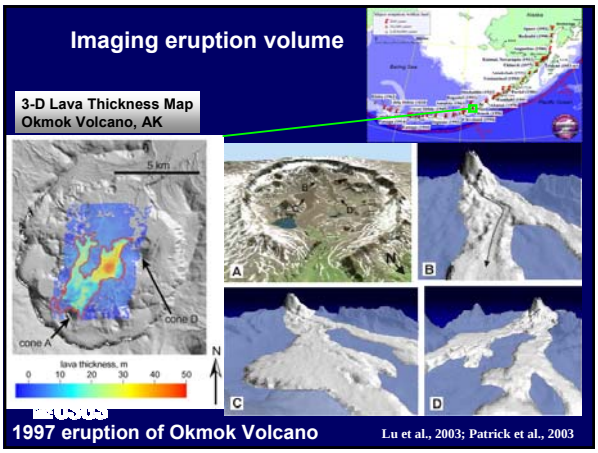


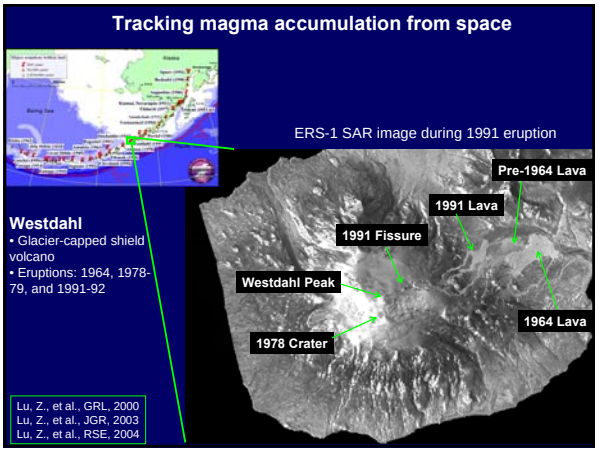
Magma supply rate at the shallow reservoir

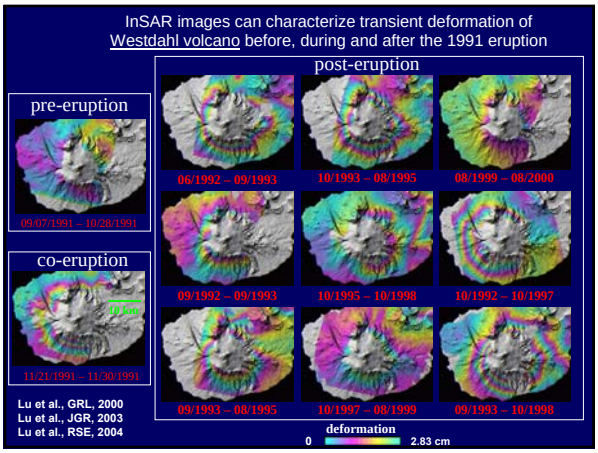


Magma Plumbing System

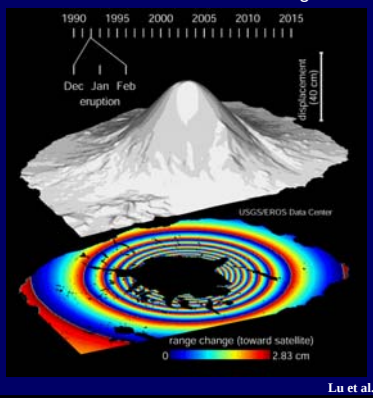
- A magma reservoir residing at 3.2 km beneath the center of the caldera, is responsible for the observed deformation before, during and after the 1997 eruption. The reservoir offsets from the active vent by 5 km
- By Fall 2007, 60~80% of the magma volume lost from the reservoir in the 1997 eruption had been replenished.


Imaging eruption volume
3-D Lava Thickness Map
Okmok Volcano, AK
5 km
cone A
cone D
lava thickness, m
0 10 20 30 40 50
N
A
B
C
D
1997 eruption of Okmok Volcano
Lu et al., 2003; Patrick et al., 2003


Tracking magma accumulation from space
ERS-1 SAR image during 1991 eruption
Pre-1964 Lava
1991 Lava
1991 Fissure
Westdahl Peak
1964 Lava
1978 Crater
Westdahl
• Glacier-capped shield volcano
• Eruptions: 1964, 1978-79, and 1991-92
Lu, Z., et al., GRL, 2000
Lu, Z., et al., JGR, 2003
Lu, Z., et al., RSE, 2004


InSAR images can characterize transient deformation of Westdahl volcano before, during and after the 1991 eruption
pre-eruption
09/07/1991 – 10/28/1991
co-eruption
10 km
11/21/1991 – 11/30/1991
post-eruption
06/1992 – 09/1993
10/1993 – 08/1995
08/1999 – 08/2000
09/1992 – 09/1993
10/1995 – 10/1998
10/1992 – 10/1997
09/1993 – 08/1995
10/1997 – 08/1999
09/1993 – 10/1998
Lu et al., GRL, 2000
Lu et al., JGR, 2003
Lu et al., RSE, 2004
deformation
0
2.83 cm

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



USGS

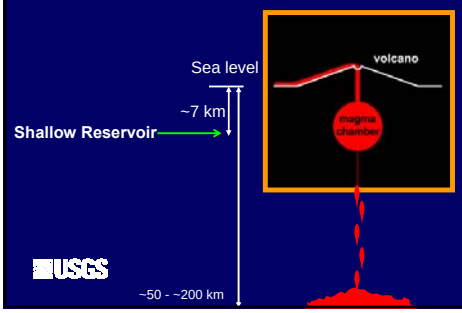
Lu et al., JGR, 2003

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

USGS

Lu et al., JGR, 2003

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



USGS

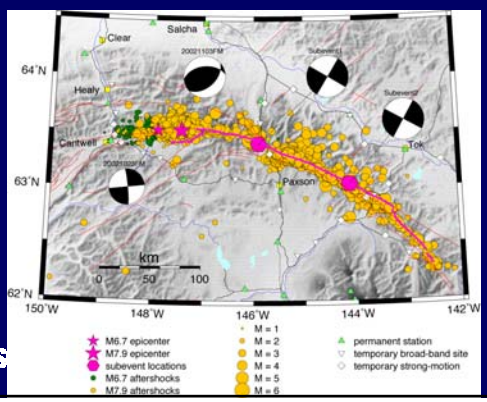
Lu et al., JGR, 2003

Earthquakes

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

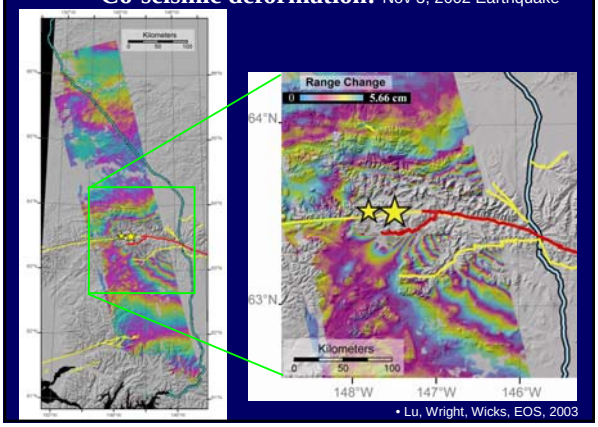
USGS

Nov 3, 2002 Denali Earthquake



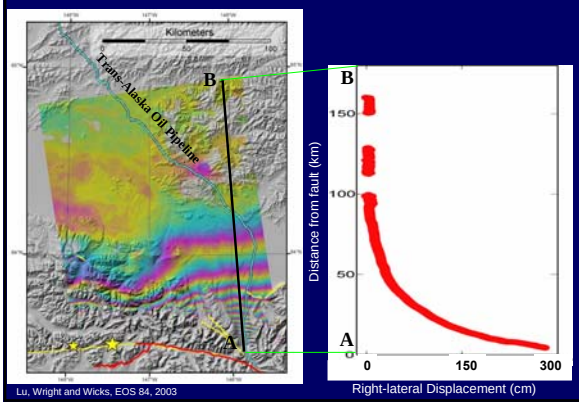
USGS

Co-seismic deformation: Nov 3, 2002 Earthquake



• Lu, Wright, Wicks, EOS, 2003

Co-seismic deformation: Nov 3, 2002 Earthquake



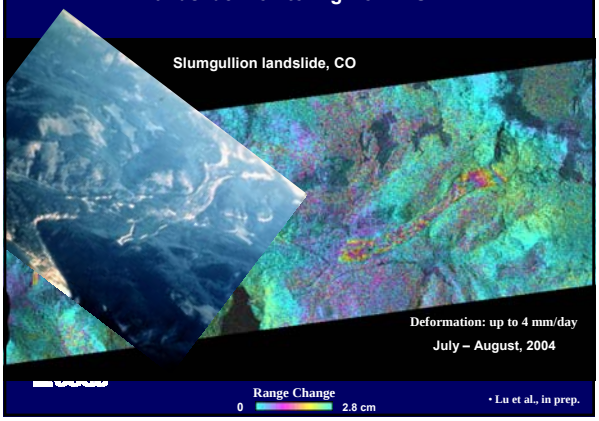
Lu, Wright and Wicks, EOS 84, 2003

Landslides

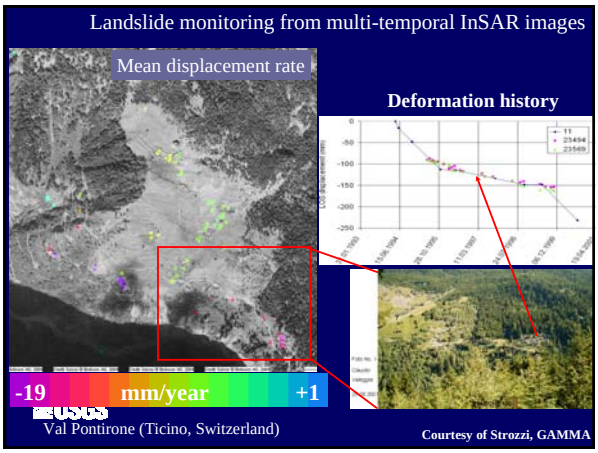
Measuring and documenting how landslides develop and are activated are prerequisites to minimize the hazards they pose in areas of rapid urban growth

USGS

Landslide monitoring from InSAR

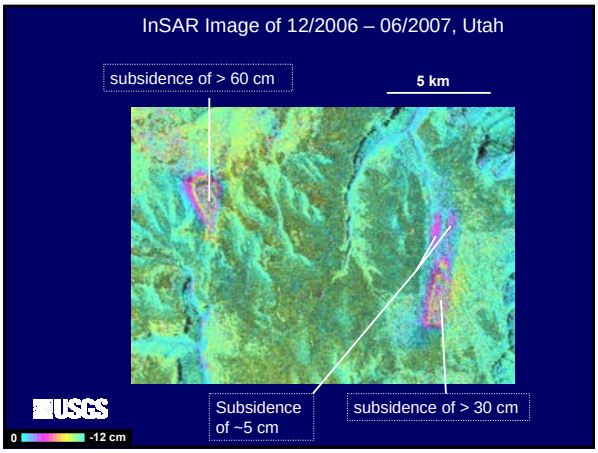


• Lu et al., in prep.

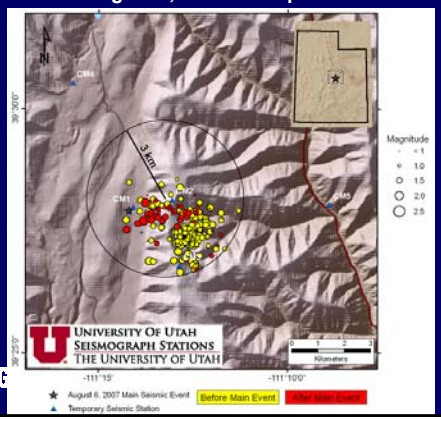


Mapping of Mining-Related Subsidence

USGS

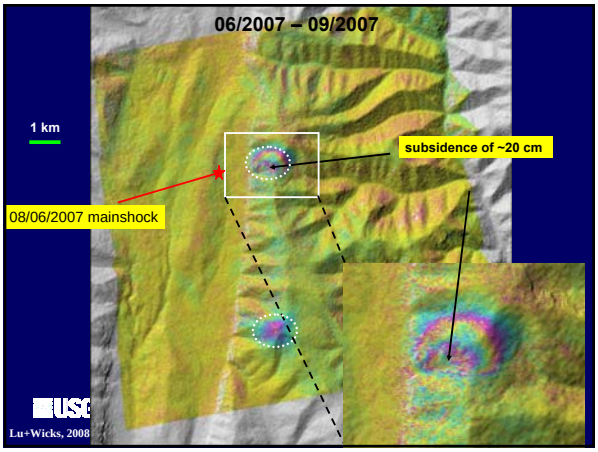


August 6, 2007 Earthquake



USGS

06/2007 – 09/2007



USGS

Lu+Wicks, 2008

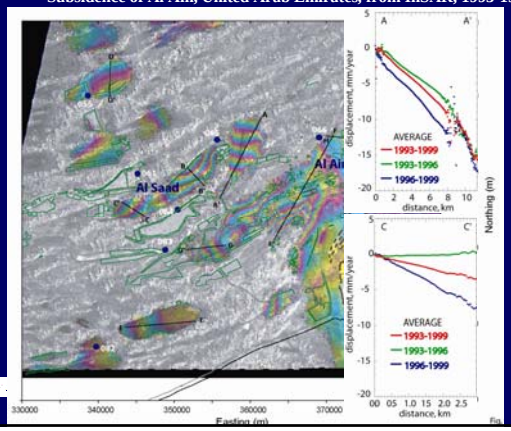
Land Subsidence

due to both man-made and natural hazards

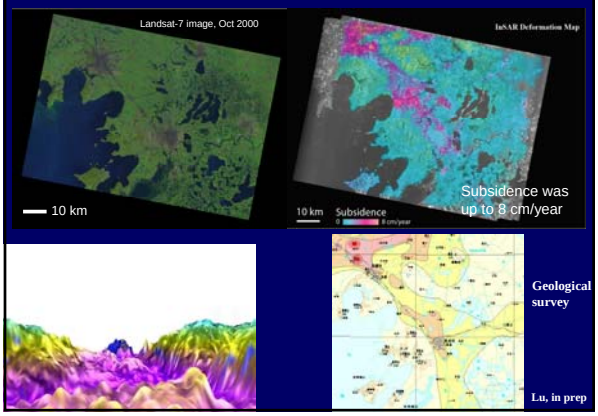
Mapping surface subsidence and uplift related to extraction and injection of fluids in groundwater aquifers and petroleum reservoirs provides fundamental data on reservoir/aquifer properties and processes and improves our ability to assess and mitigate undesired consequences

USGS

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



Subsidence mapping, Su-Zhou, China



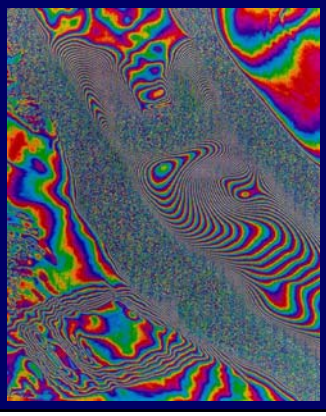
Geological survey

Lu, in prep

Glacier and Ice

USGS

Rutford ice stream, Antarctica



USGS

Goldstein et al., 1993

Other applications …

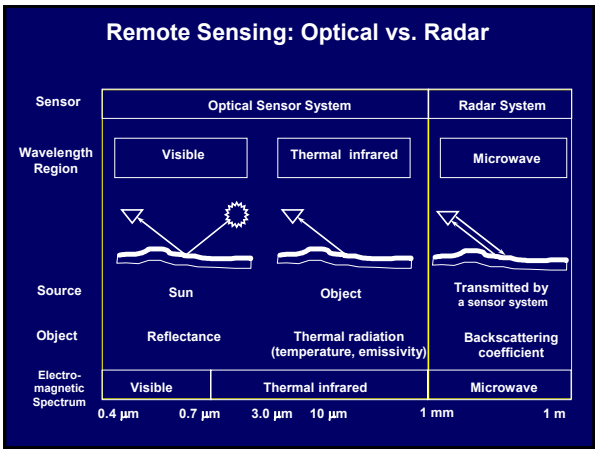
Throughout this workshop

USGS

3. InSAR: Wetland & Hydrology

USGS

Remote Sensing: Optical vs. Radar



Remote Sensing: Optical vs. Radar

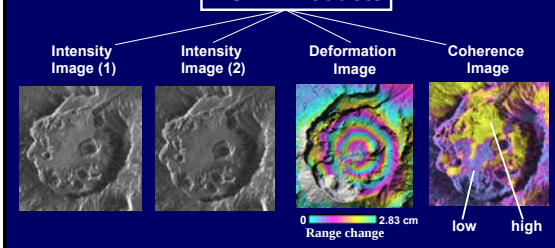
Optical
- passive sensor
- reflectance
- day time acquisition
- cloud problem
- usually nadir
- measure chemical composition and thermal properties

Radar
- active sensor
- backscatter
- day and night
- all weather
- side looking geometry
- measure target physical properties (roughness & dielectric constant)

USGS

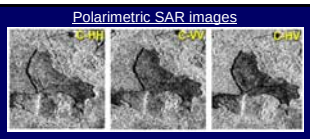
SAR/InSAR Imagery Analysis

InSAR Products



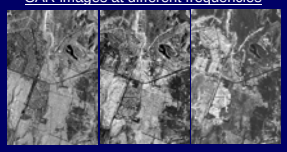
- Analysis of (multi-temporal) InSAR deformation images
- Analysis of multi-temporal SAR intensity images
- Analysis of InSAR coherence (degree of changes in backscattering) images
- Analysis of polarimetric SAR/InSAR images
- Analysis of fusion of SAR and optical images

Polarimetric SAR images



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

SAR images at different frequencies

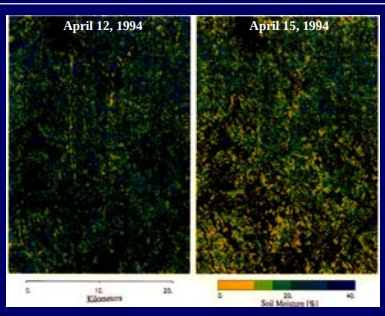


X-band λ = ~3 cm | **L-band** λ = ~24 cm | **P-band** λ = ~70 cm

Courtesy of CCRS

Mapping soil moisture with fully-polarized SAR images

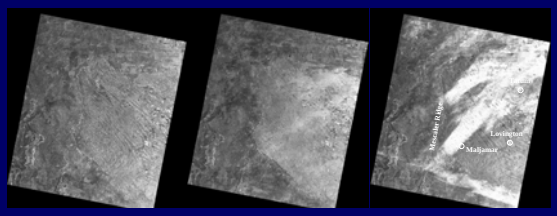
The horizontal resolution (several meters) of soil moisture imagery derived from fully polarimetric SAR data is not attainable otherwise



Landslides often take place when soil moisture exceeds critical thresholds

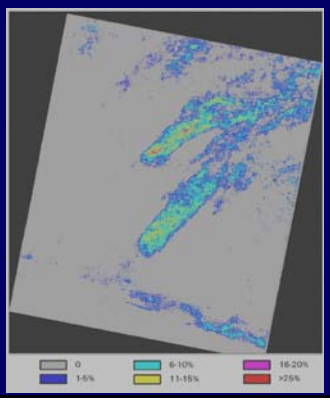
Dubois et al., 1995

Synthetic Aperture Radar (SAR) images over Carlsbad, New Mexico



19921005 | 19930920 | 19951227

Mapping of changes in soil moisture with multi-temporal SAR images
Carlsbad, New Mexico



USGS

Lu and Meyer, IJRS, 2002

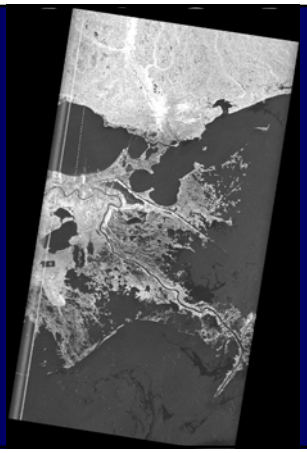
Flooding and Severe Storms

- SAR images can map flooding extents to serve in rapid damage assessments caused by flooding;
- InSAR is an effective tool in the accurate measurement of water-level changes in river valleys and wetlands, which can improve hydrological modeling predictions and enhance the assessment of future flood events over wetlands

USGS

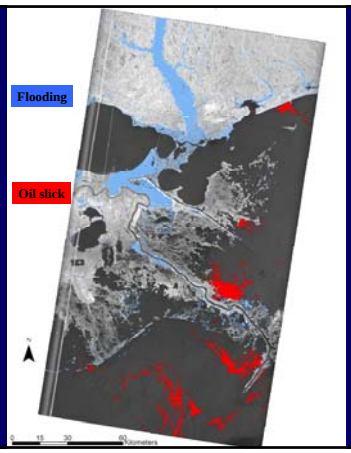
Hurricane Katrina

Radarsat-1 SAR image
Sept 2, 2005



USGS

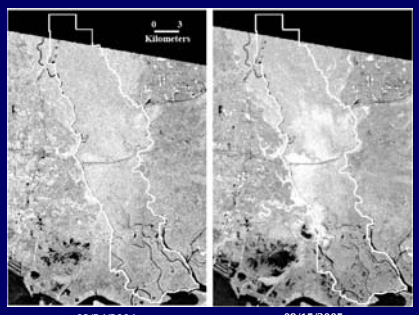
Inundation and possible oil slicks mapped from SAR & Landsat-7 images



USGS

Rykhus & lu, 2007

Radar imagery suggests changes and damages on forests



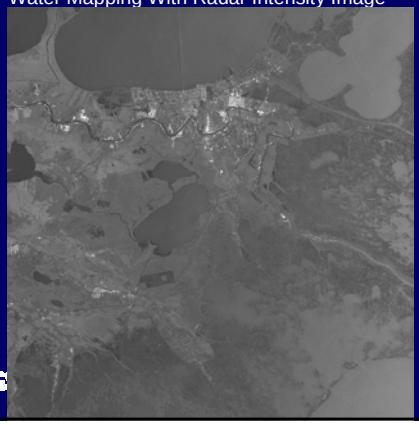
09/24/2004 09/15/2005

USGS

Pearl River flood plain of Louisiana

Ramsey et al., 2008

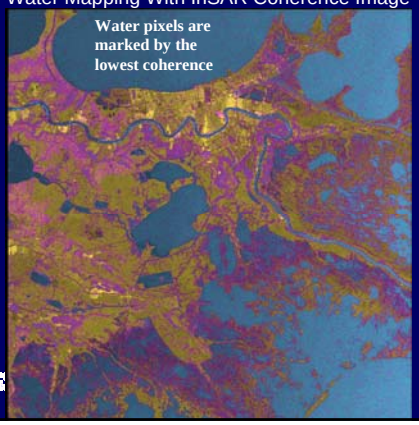
Water Mapping With Radar Intensity Image



USG

Water Mapping With InSAR Coherence Image

- Yellow – Highest coherence
- Blue – Lowest coherence



19951127-19951128

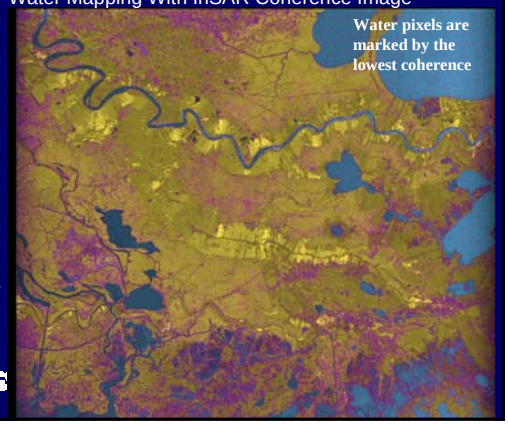
USG

Water Mapping With Radar Intensity Image

USG

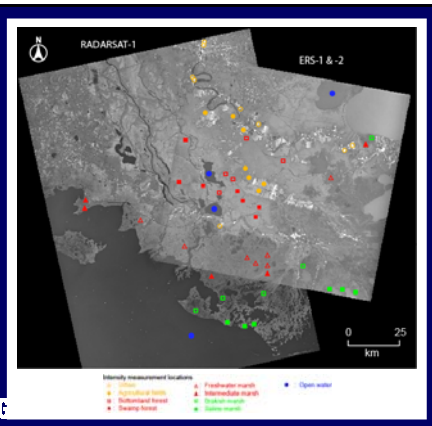
Water Mapping With InSAR Coherence Image

- Yellow – Highest coherence
- Blue – Lowest coherence



19960120-19960121

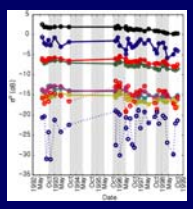
USG



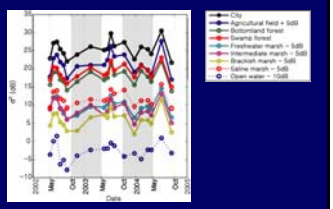
Averaged Backscattering Coefficients

- Averaged σ^o for each landcover type suggests the need for σ^o calibration

(a) ERS-1 & -2

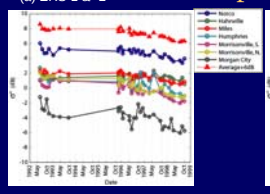


(b) RADARSAT-1

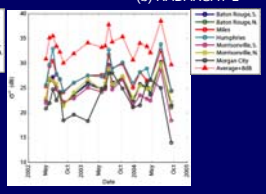


Averaged σ^o over vegetated & developed urban

(a) ERS-1 & -2

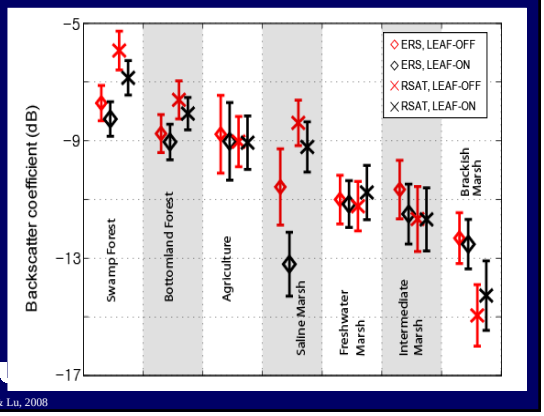


(b) RADARSAT-1



- Averaged σ^o values from urban shows that
  - ERS-1 has some temporal backscatter variation
  - ERS-2 has about 0.66 dB/yr degradation (Meadows et al., 2004) and some degrees of temporal variation.
  - RADARSAT-1 show strong temporal backscatter variations.
- Averaged σ^o values from urban are used for relative backscatter calibration.

Averaged dB values for different vegetation classes



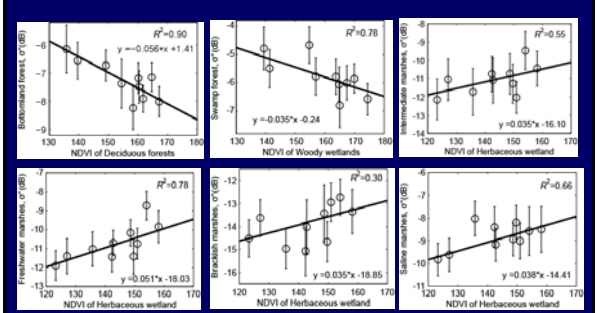
Kwoun & Lu, 2008

SAR Backscatter Coefficients and NDVI

- Seasonal changes of vegetation cover can also be detected by optical sensors.
  - Normalized Difference Vegetation Index (NDVI)
    - Directly related to the photosynthetic capacity and hence energy absorption of plant canopies
    - Useful for the estimation of the leaf-area-index, biomass, chlorophyll concentration in leaves, plant productivity, etc.
- We focus on leaf-off seasons as NDVI changes are subtle during leaf-on seasons.

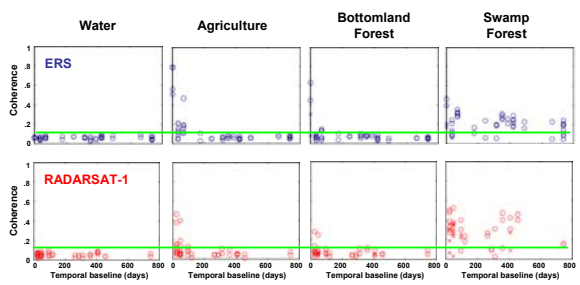
USGS

Radarsat dB (leaf-off season) vs. AVHRR NDVI



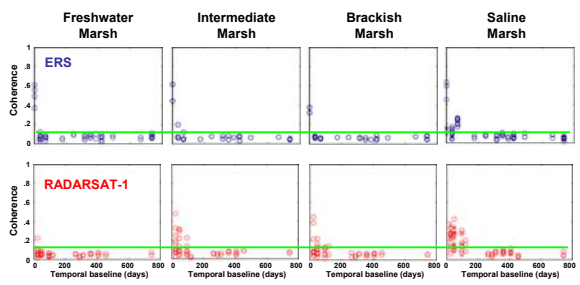
USGS

C-band InSAR Coherence Comparison



USGS

C-band InSAR Coherence Comparison



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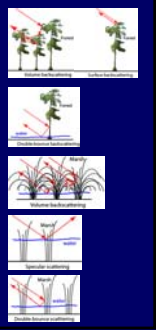
C-band SAR Backscattering Mechanisms

Vegetation	Inference on backscattering mechanism
Bottomland forests	Mostly surface and volume scattering
Swamp forests	Dominantly double-bounce backscattering
Freshwater marshes	Mostly volume scattering
Intermediate marshes	Mostly volume scattering
Brackish marshes	Surface (and volume) scattering; probably specular scattering during leaf-off seasons
Saline marshes	Mostly double-bounce and volume backscatterings



Implications on Wetlands Landcover Classification

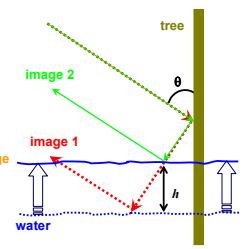
- Single SAR image is not sufficient for coastal wetlands classification; multi-year seasonally averaged σ^os are necessary.
- Season-averaged σ^os may be sufficient to detect swamp forests and brackish marshes
- Freshwater and intermediate marshes may not be readily distinguishable from each other using ERS and RADARSAT data only.
- Classification between bottomland forests and saline marshes can be done by geographic proximity to ocean or using multi-year season-averaged σ^os; saline marshes have distinctive low σ^os of ERS during leaf-on season.
- NDVI can be useful to distinguish between forests and marshes

USGS

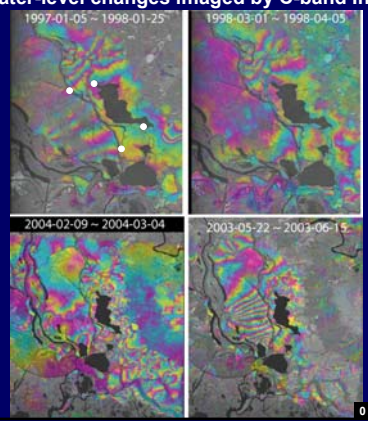
Double-bounced radar signal and water-level change detection

$$h = \frac{\Delta\phi}{4\pi\cos\theta}\cdot\lambda$$

h : water level change
$\Delta\phi$: interferometric phase change
λ : radar wave length
θ : incidence angle



Water-level changes imaged by C-band InSAR

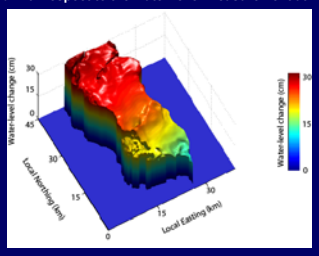


USGS

Lu et al., 2005
Lu & Kwoun, 2008

Volumetric rendering of water-level change

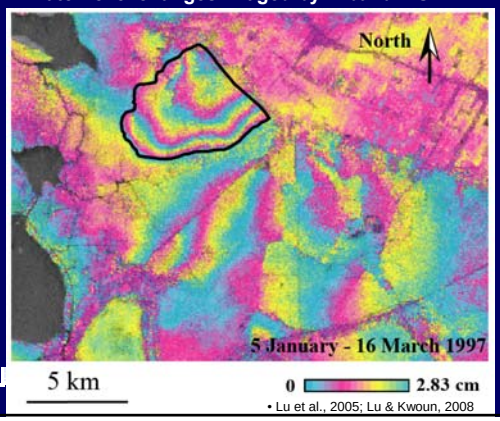
- Within Atchafalaya Basin Floodway between 12/23/2003 and 2/9/2004
- Calibrated with respect to the water-level measurement at Cross Bayou



Total number of SAR image pixels covering the region	: 296469 pixels
Area per pixel	: 2779.06 m^2
Relative volumetric change measured by InSAR	: −5.34486 km^3
Water-level change at the Cross Bayou gage	: +0.2847 m
Adjustment of volumetric change	: 0.23457 km^3
Total volumetric change	: 5.57942 km^3

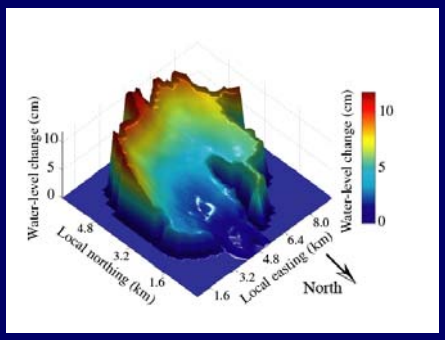
USGS

Water-level changes imaged by C-band InSAR



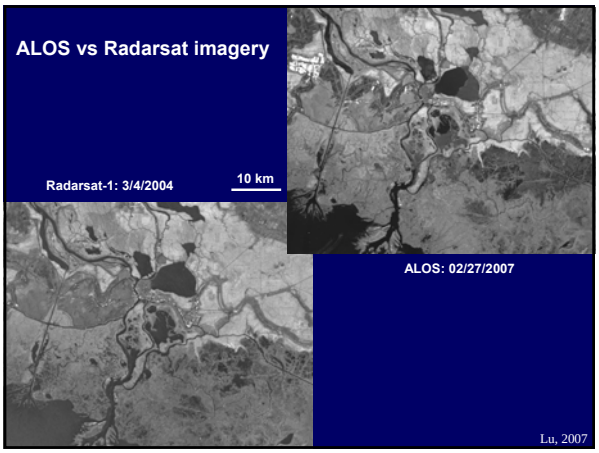
- Lu et al., 2005; Lu & Kwoun, 2008

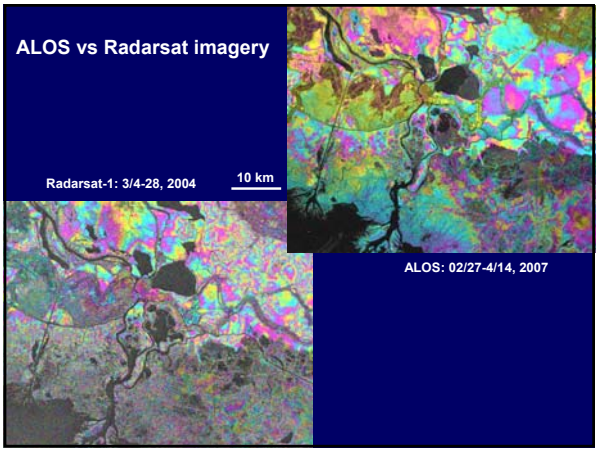
Water-level changes imaged by C-band InSAR

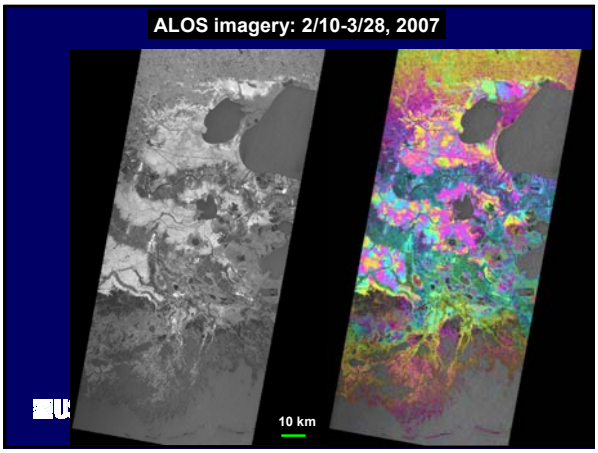


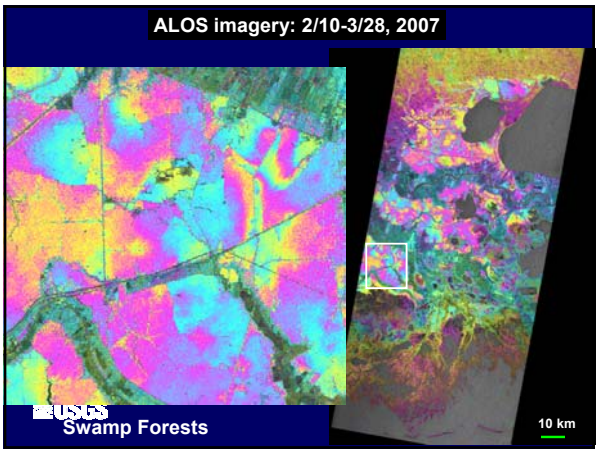
USGS

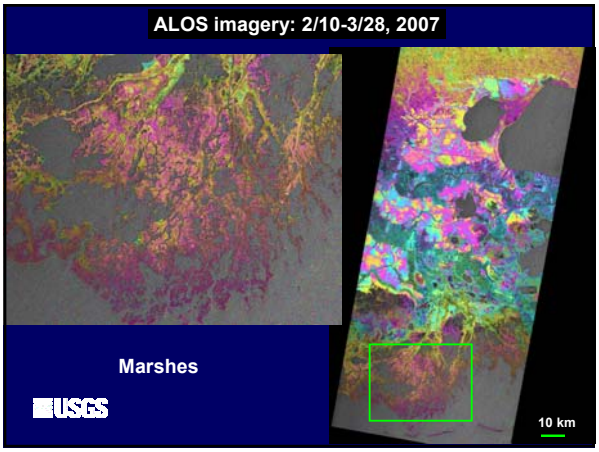
- Lu et al., 2005; Lu & Kwoun, 2008


ALOS vs Radarsat imagery
Radarsat-1: 3/4/2004
10 km
ALOS: 02/27/2007
Lu, 2007


ALOS vs Radarsat imagery
Radarsat-1: 3/4-28, 2004
10 km
ALOS: 02/27-4/14, 2007

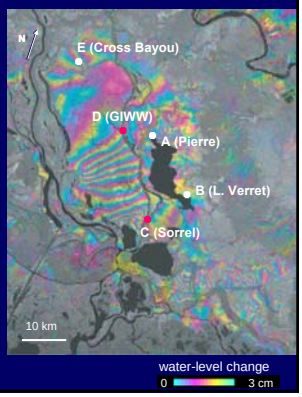

ALOS imagery: 2/10-3/28, 2007
10 km





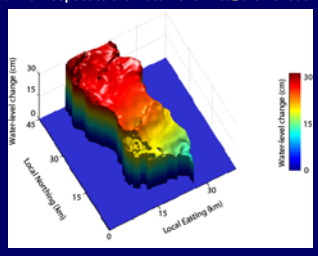
InSAR Images vs Gage Measurements

- Both C-band and L-band InSAR images suggest that water level changes over the study site can be dynamic and spatially heterogeneous, and cannot be represented by readings from sparsely distributed gauge stations.
- InSAR phase measurements are disconnected by structures and other barriers and require absolute water level measurements from gauge stations or other sources to convert InSAR phase values to absolute water level changes.
- Gages in the river (C & D) do not show good correlation with InSAR-derived water-level measurements at nearby pixels over swamp forests.
- Therefore, modeling surface water based on existing gages may not be accurate.
- A minimum of one "absolute" water-level change measurement over a "wetland system" is required to estimate the "true" volumetric water storage.



Volumetric Rendering of Surface Water-level Changes

- Within Atchafalaya Basin Floodway between 05/22/2003 and 06/15/2003
- Calibrated with respect to the water-level measurement at Cross Bayou (E)



Total number of SAR image pixels covering the region	:	296469 pixels
Area	:	842 km^2
Water-level change at the Cross Bayou gage	:	+0.2847 m
Adjustment of volumetric change	:	0.23457 km^3
Total volumetric change	:	2.07 km^3

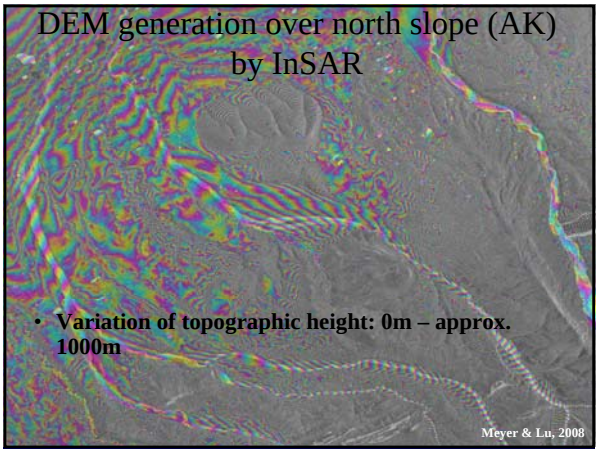
USGS

- SAR backscatter can be used for coastal wetlands classification
  - Multi-year season-averaged backscatter observations provide more robust results
- C-band InSAR can estimate water-level changes beneath moderately dense swamp forests.
- L-band InSAR provides a robust measurement of water-level changes.
- Both C-band and L-band InSAR images suggest that water level changes can be dynamic and spatially heterogeneous, and cannot be represented by readings from sparsely distributed gauge stations.
- InSAR phase measurements are disconnected by structures and other barriers and require absolute water level measurements from gauge stations or other sources to convert InSAR phase values to absolute water level changes.
- A minimum of one absolute water-level change measurement over a "wetland system" is required to estimate the "true" volumetric water storage.

USGS

- Lu et al., 2005
- Lu & Kwoun, 2007
- Kwoun & Lu, 2007

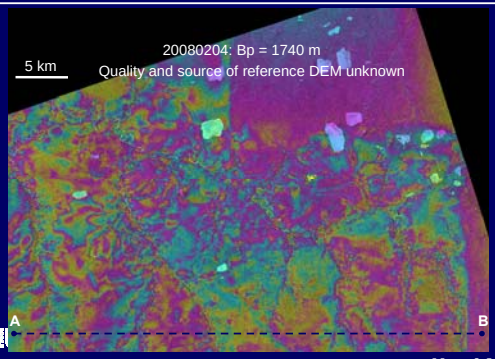
DEM generation over north slope (AK) by InSAR



- **Variation of topographic height: 0m – approx. 1000m**

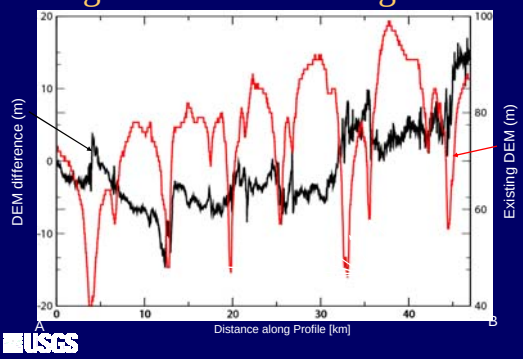
Meyer & Lu, 2008

DEM difference image (10 m per fringe)



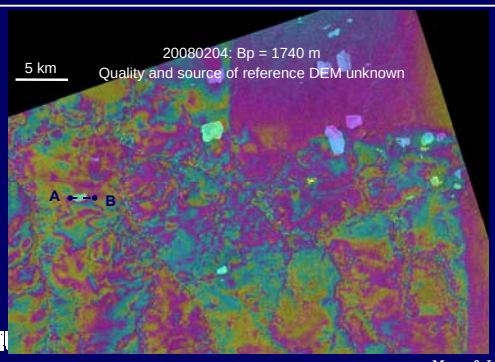
Meyer & Lu, 2008

Height Differences along Profile



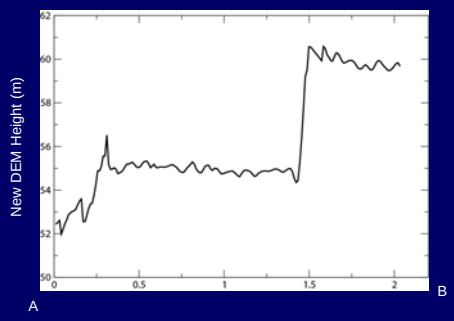
Meyer & Lu, 2008

DEM difference image (10 m per fringe)



Meyer & Lu, 2008

DEM Height along Profile



USGS

Meyer & Lu, 2008

4. InSAR: all the time, everywhere

USGS

Emerging SAR/InSAR Technologies

Future SAR Satellites

- German Tandem-X 2012(?), X-band, fully polarized
- Canadian Radarsat constellations 2012(?), C-band, fully polarized
- ESA C-band constellations 2013(?), C-band, fully polarized
- NASA DESDynI 2013(?), L-band, fully polarized
- …

Future Sensor/Technology Trends

Wavelength: Longer wavelength (L-band) SAR sensors are available. Longer wavelength SAR penetrates into vegetation to improve InSAR deformation mapping accuracy at global scale.

Polarimetry: Fully polarized SAR sensors are included. Fully polarized SAR allows a better characterization of vegetation structure and ground feature.

Multi-Satellites: Near-real-time data acquisitions anywhere on Earth.

Processing Techniques: Multi-temporal, 3-dimensional image analysis; data mining.

Sensor fusion: SAR, optical, and Lidar imagery

Emerging SAR & InSAR Capabilities

Future InSAR provides improved deformation measurement on global scale, whereas past InSAR is plagued by vegetation.

Future SAR can improve land cover mapping and wetland mapping, particularly over regions where weather conditions hinder optical remote sensing.

Future SAR has the potential to map soil moisture. The horizontal resolution (several meters) of soil moisture imagery derived from fully polarimetric SAR data is not attainable otherwise.

Future SAR can enhance snow/ice (hydrology and cryosphere) studies, and improve traffic monitoring over ocean.

Future polarimetric InSAR has the potential to map forest height and biomass, and to generate "bare-earth" elevation.

Operational SAR & InSAR Processing System – Improve SAR/InSAR processing throughput and lay the foundation for routine monitoring of natural hazards and natural resources.

USGS

Incomplete list of free software packages

ROI_PAC: http://www.roipac.org/ROI_PAC
ASF tools: http://www.asf.alaska.edu/softwaretools/
DORIS: http://enterprise.lr.tudelft.nl/doris/
StaMPS: http://www.hi.is/~ahooper/stamps/index.html
IDIOT: http://www.cv.tu-berlin.de/idiot/
…

Incomplete list of commercial packages

(in alphabetical order)
Altamira Information, Spain
Atlantis Scientific Inc (Vexcel)
Envi: SARScape
Gamma RS
PCI: Earthview
TeleRilevamento Europa (TRE), Italy
…

Useful tutorials

ESA: http://earth.esa.int/applications/data_util/SARDOCS/spaceborne/Radar_Courses/
CCRS: http://www.ccrs.nrcan.gc.ca/resource/index_e.php#tutor
ASF: http://asf.alaska.edu/
JPL: http://southport.jpl.nasa.gov/

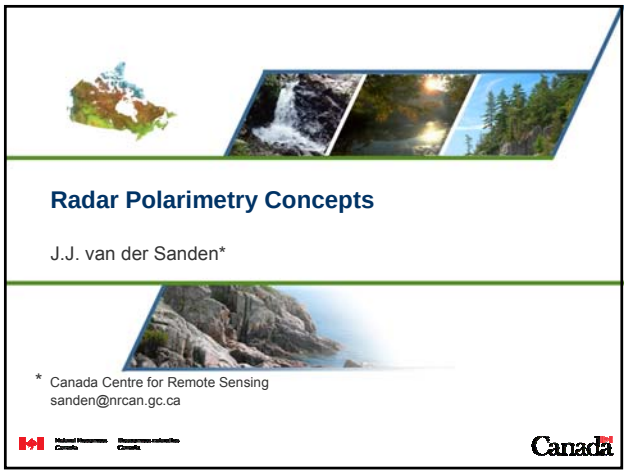
Presentation Overview

Polarimetry - Joost van der Sanden, CCRS

- **Radar Polarimetry Concepts**
- **Polarimetry Applications**

EROS Training

and Education



Outline

- Why Polarimetry ?
- History of Polarimetry
- EM waves, Polarization and Polarimetric Radar
- Polarimetric Data Representations
- Polarimetric Information Extraction
- Polarimetric Calibration Factors
- Summary
- Additional Sources of Information

Canada's Natural Resources – *Now and for the Future*

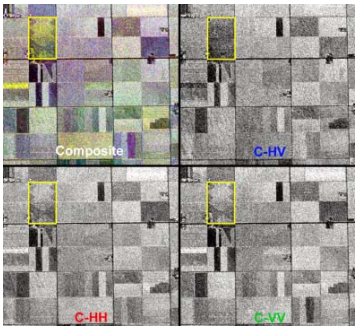
Why Polarimetry ?

- The polarization of the microwaves as received by a SAR is governed by:
  - the (known) polarization of the transmitted microwaves
  - the **structural properties of the target** observed (e.g. surface roughness, architecture)
- Compared to non-polarimetric SAR systems, polarimetric SAR systems have the capability to capture more information concerning the physical structure of the features observed and hence offer more potential for the detection and classification of these features

Canada's Natural Resources – *Now and for the Future*

Polarization and Structure; Example

- C-HV backscatter is less sensitive to row direction as related to direction of planting, tillage or harvesting than either C-HH or C-VV backscatter



Polarimetry; The Challenge

- To assess the information content of polarimetric SAR data (more data ≠ more information)
- To extract the relevant information from the polarimetric SAR data

Both require a thorough understanding of the interaction of the microwaves with the features observed

And then there is wavelength …

- The wavelength governs the extent to which incident microwaves penetrate into the target observed (typically; longer wavelength greater *penetration depth*)
- The *effective* (or perceived) *roughness* of a surface with a given physical roughness is a function of the wavelength (longer wavelength decrease in effective surface roughness)
- The scattering behavior of target components (e.g. leaves, branches, trunks, soil of a forest) is a function of the incident wavelength (*effective size*) (typically; components with physical dimensions similar to the incident wavelength generate backscatter)

And then there is wavelength …

X Band ($\lambda \approx 3$cm)

C Band ($\lambda \approx 5$cm)

L Band ($\lambda \approx 20$cm)

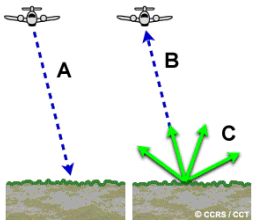
P Band ($\lambda \approx 60$cm)

Small Branches
Leaves

Branches
Trunk
Ground

Penetration is also affected by
- target / sensor geometry
- dielectric properties of target

Radar Backscatter



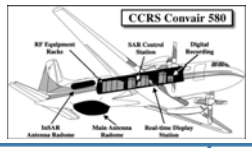
- Radar energy is transmitted to the ground (A)
- The energy is scattered in all directions (C)
- A small part of the energy is scattered back to the radar (B)
- For a monostatic radar, we are only concerned with the **backscatter component**

History of Polarimetry

- 1950s: basic theory developed by Sinclair and Kennaugh
- 1960-1980: further development of polarimetric theory by Huynen, Fung, Boerner, Mueller and Jones
- 1983: first polarimetric SAR airborne system build and demonstrated by NASA/JPL
- 1994: Shuttle Imaging Radar (SIR-C) missions, first civilian polarimetric radar system in space
- 2002: launch Envisat ASAR (C-band) first civilian dual-polarization SAR satellite system
- 2006: launch ALOS PALSAR (L-band) first civilian polarimetric SAR satellite system
- 2007: launch of three civilian satellites with polarimetric capabilities, i.e. Cosmo-Skymed, TerraSAR-X, RADARSAT-2

Airborne Polarimetric SAR Systems

- NASA/JPL AIRSAR P, L, C-bands
- Canadian Convair-580 C-band
- Danish EMISAR L, C-bands
- AeroSensing AES-1 X-band
- Dornier DOSAR X-band
- DLR E-SAR L-band
- TNO PHARUS C-band
- Onera RAMSES X-band



First generation radar satellites

- Operate in a single wavelength, i.e. C-band
- Operate mostly in a single (linear) polarization
- Operate at spatial resolutions ≥ 8 m
- Operate in a single look direction (right)
- Are large stand-alone satellite systems (repeat cycle ≥ 24 days)

	ERS-1	ERS-2	RADARSAT-1	Envisat ASAR
Launch	1991	1995	1995	2002
Frequency	C	C	C	C
Polarizations	1	1	1	≤ 2
Resolution	30 m	30 m	≥ 8 m	≥ 30 m
Repeat cycle	35 d	35 d	24 d	35 d

RADARSAT-1

Envisat ASAR >

Second generation radar satellites

- As a group, offer wavelength diversity
- Offer multi-polarization & polarimetric capabilities
- Operate at spatial resolutions ≥ 1 m
- Some offer selective look direction (right or left)
- Move towards constel-lations of small satellites (e.g. Cosmo-Skymed comprises 4 satellites)

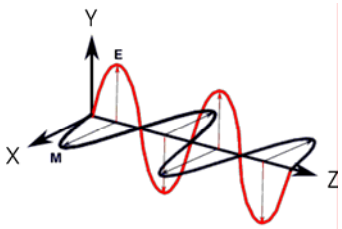
	ALOS PALSAR	Cosmo-Skymed	Terra SAR-X	RADARSAT-2
Launch	2006	2007/09 (8 June)	2007 (15 Jun)	2007 (Dec)
Frequency	L	X	X	C
Polarizations	≤ ∞	≤ ∞	≤ ∞	≤ ∞
Resolution	≥ 7 m	≥ 1 m	≥ 1 m	≥ 3 m
Repeat cycle	46 d	16 d	11 d	24 d

ALOS PALSAR

RADARSAT-2

Cosmo-Skymed >

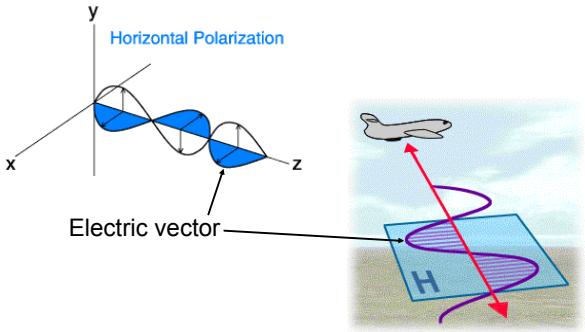
Electromagnetic (EM) waves



- EM waves have an electric (E) and magnetic (M) component
- electric (E) and magnetic (M) vectors are defined in a plane x-y
- Z is the direction of propagation
- the polarization is defined by the locus of the electric vector in the x-y plane
- of interest to SAR imaging is the polarization (i.e. the E-vector)

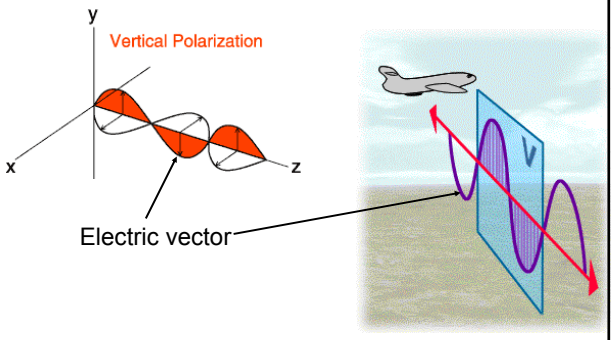
Canada's Natural Resources – *Now and for the Future*

Horizontal Polarization (HH)



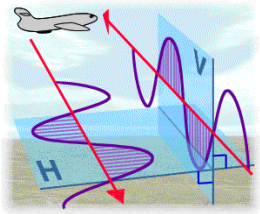
Canada's Natural Resources – *Now and for the Future*

Vertical Polarization (VV)



Canada's Natural Resources – *Now and for the Future*

Horizontal - Vertical Polarization (HV)



H transmitted

V received

This setup measures the cross-polarized component of the backscattered wave

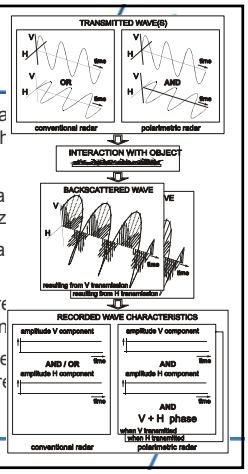
There is also VH operation, but usually VH = HV (reciprocity)

Choice of Polarization

- Basic or operational SARs usually have only one polarization for economy, *e.g.* HH or VV
- Research systems tend to have multiple polarizations, *e.g.* HH, HV, VV, VH
- Multiple polarizations help to distinguish the physical structure of the scattering surfaces:
  - the alignment with respect to the radar (HH *vs.* VV)
  - the randomness of scattering (*e.g.* vegetation - HV)
  - the corner structures (*e.g.* HH, VV *vs.* HV)
  - Bragg scattering (*e.g.* oceans - VV)

Radar Polarimetry

- Polarimetry is the science of using mea
  polarization scattering matrix to infer ph
  Earth's surface
- The scattering matrix is measured by a
  transmitting with two orthogonal polariz
  - On transmission, the two orthogona
    alternated on successive pulses
  - On reception, the 2 polarizations are
    simultaneously, leading to four chan
  - *e.g.* on odd pulses, HH and HV are
    and on even pulses, VV and VH are



Radar Polarimetry Provides …

5 independent measures

3 Backscatter coefficients σ°
amplitudes: HH, VV, HV (=VH)

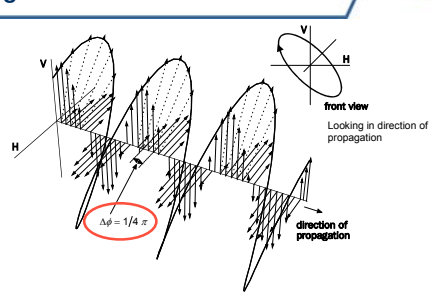
2 Phase differences $\Delta\phi$

$$\phi_{like} = \phi_{hh} - \phi_{vv}$$
$$\phi_{cross} = \phi_{hh} - \phi_{hv}$$

Benefits of Radar Polarimetry

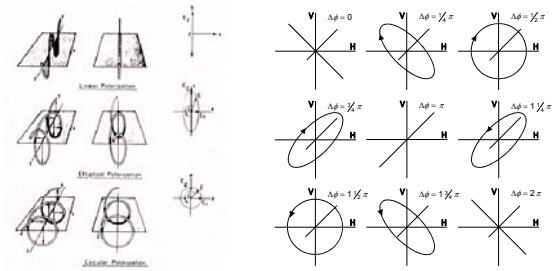
- The five independent measurements capture the complete backscatter behavior for each pixel
  - provides a powerful basis for classification
- The five independent measurements can be used to synthesize the radar return with any polarization
  - to investigate the scattering properties of different features
  - to select the polarization that provides optimum detectability for features of interest

Propagation and Polarization



- Observe the motion of the tip of the electric field vector, as it evolves with time
- Draw this motion in the x-y plane (often the H-V plane is used)

Different Polarizations



The locus of the tip of the electric vector can be linear, circular, or in between (i.e. elliptical). The tip of right- (left-) handed waves rotates (counter-) clockwise (observed in the direction of propagation!).

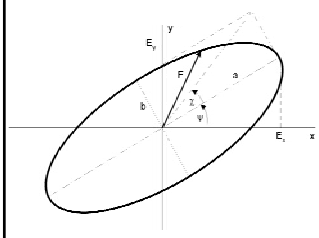
EM Waves Demonstrated

- http://www.amanogawa.com/archive/wavesB.html

Polarization Graphics

- The Polarization Ellipse
- Polarization Signatures
- The Poincaré Sphere

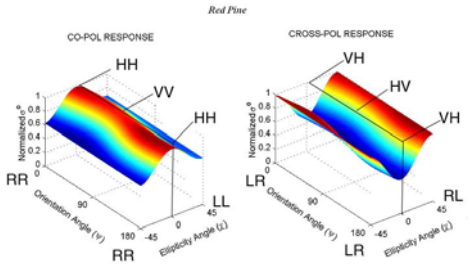
The Polarization Ellipse



Any physical polarization can be described using angles χ and ψ

- Describes fully polarized wave
  - use x & y or H & V axes
- E_x - amplitude of x component
- E_y - amplitude of y component
- Orientation angle, ψ (psi) [0º, 180º]
- Ellipticity angle, χ (chi) [-45º, 45º]
  - relates to ratio of major axis **a** and minor axis **b**
  - sign = direction of rotation
  - χ positive, Left handed (L)
  - χ negative, Right handed (R)

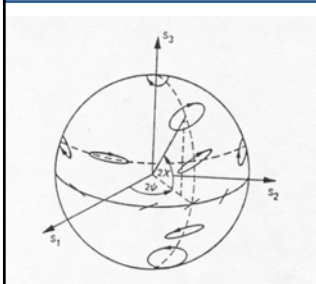
The Polarization Signature



Received polarization is:

… the same as the transmit polarization | **… orthogonal to the transmit polarization**

The Poincaré Sphere

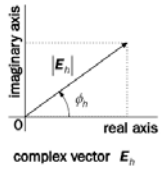


- Linear polarizations – on the equator
- Circular polarizations – at the poles
- Latitude is 2 χ
  - positive in north (Left handed)
  - negative in south (Right handed)
- Longitude is 2 ψ

Polarization Formulas

- Used for computational purposes
  - the polarization vector $\boldsymbol{p}$ (or E)

$$\boldsymbol{p} = \begin{pmatrix} E_h \\ E_v \end{pmatrix} = \begin{pmatrix} |E_h| e^{j\phi_h} \\ |E_v| e^{j\phi_v} \end{pmatrix}$$



where E_h and E_v represent the H- and V-polarized components of the electrical field, $|E_h|$ and $|E_v|$ the matching amplitudes and φ_h and φ_v the corresponding phases (| | indicates modulus of complex number), j is equal to $\sqrt{-1}$

The Scattering Matrix

- The scattering matrix ($\boldsymbol{S}$) describes the polarization transformation properties of the observed feature
- $\boldsymbol{S}$ relates the polarization of the **scattered** waves $\boldsymbol{p}^s$ to the polarization of the **incident** waves $\boldsymbol{p}^i$ according to:

$$\boldsymbol{p}^s = \frac{e^{jk_0 R}}{R} \boldsymbol{S} \boldsymbol{p}^i$$

Where: R is the slant range distance and k_0 the wave number of the incident wave in free space

- $\boldsymbol{S}$ relates the polarization of the **received** and **transmitted** waves according to:

Sinclair (Scattering) Matrix

$$\boldsymbol{S} = \begin{pmatrix} S_{hh} & S_{hv} \\ S_{vh} & S_{vv} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} \sqrt{\sigma_{hh}} e^{j\phi_{hh}} & \sqrt{\sigma_{hv}} e^{j\phi_{hv}} \\ \sqrt{\sigma_{vh}} e^{j\phi_{vh}} & \sqrt{\sigma_{vv}} e^{j\phi_{vv}} \end{pmatrix}$$

Where: $\sqrt{\sigma_{ij}}$ is the measured amplitude in case of i receive and j transmit and φij the corresponding absolute phase

The Scattering Matrix cont.

- The radar cross-section σ_{rt} for any combination of transmitted $\boldsymbol{p}^t$ and received $\boldsymbol{p}^r$ waves is:

$$\sigma_{rt}(\psi_r, \chi_r, \psi_t, \chi_t) = 4\pi \left| \boldsymbol{p}^r \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \boldsymbol{S} \boldsymbol{p}^t \right|^2$$

Sinclair (Scattering) Matrix

- $S_{hv} = S_{vh}$ for reciprocal (natural/distributed) targets

The 4 SLC channels in a RADARSAT-2 polarimetric product represent an estimate of the elements of the 2x2 Sinclair (Scattering) Matrix

Complete *vs.* Partial Polarization

- Completely polarized waves: $|E_h|$, $|E_v|$, and ϕ ($=\phi_h - \phi_v$) are constant, i.e. do not vary over time; as:
  - transmitted by SAR systems
  - received from point (or coherent) targets (deterministic scattering)
- Partially polarized waves: $|E_h|$, $|E_v|$, and ϕ ($=\phi_h - \phi_v$) do vary over time; as
  - received from distributed (or incoherent) targets (non-deterministic scattering)
- Completely unpolarized waves (e.g. natural light): random behavior, the intensity is the same in any direction perpendicular to the direction of propagation

The (Modified) Stokes Vector

- Stokes vector (***F***) is used to describe the polarization properties of 'real' EM waves, i.e. waves the polarization of which varies in time (partially polarized waves)

$$\boldsymbol{F} = \begin{pmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} |E_h|^2 + |E_v|^2 \\ |E_h|^2 - |E_v|^2 \\ 2|E_h||E_v|\cos(\phi_h - \phi_v) \\ 2|E_h||E_v|\sin(\phi_h - \phi_v) \end{pmatrix} = s_0 \begin{pmatrix} 1 \\ \cos(2\psi)\cos(2\chi) \\ \sin(2\psi)\cos(2\chi) \\ \sin(2\chi) \end{pmatrix} = s_0 \boldsymbol{A}$$

with $s_0 = |E_h|^2 + |E_v|^2$ and ***A*** being the normalized Stokes vector.

Example: for HH with χ=0º and ψ=0º
s_0 assumed 1

$$\boldsymbol{F} = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

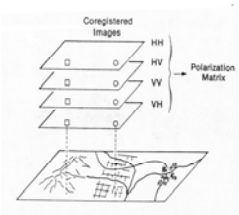
Stokes Scattering Operator

- The Stokes Scattering Operator (***M***) (also known as Stokes Reflection (Kennaugh) Matrix) is the Stokes' equivalent of the Scattering matrix
- ***M*** represents a 4x4, symmetric (reciprocity assumed), matrix
- The radar cross-section σ_{rt} for any combination of transmitted $\boldsymbol{A}^t$ and received $\boldsymbol{A}^r$ waves is:

$$\sigma_{rt}(\psi_r, \chi_r, \psi_t, \chi_t) = 4\pi \boldsymbol{A}^r \boldsymbol{M} \boldsymbol{A}^t$$

The key to polarization synthesis !

Polarization Synthesis



Polarization Synthesis

σ°_{rt}

For any combination of receive (*r*) and transmit (*t*) polarization !

Stokes Scattering Operator

Where * denotes the complex conjugate and

$$S'_{rt} = \sqrt{\sigma_{rt}}\, e^{j\phi_{rt}}$$

S' is Sinclair Scattering Matrix

$$M_{11} = \frac{1}{4}\left(|S'_{hh}|^2 + |S'_{vv}|^2 + 2|S'_{hv}|^2\right)$$

$$M_{12} = \frac{1}{4}\left(|S'_{hh}|^2 - |S'_{vv}|^2\right)$$

$$M_{13} = \frac{1}{2}\mathrm{Re}\left(S'^{*}_{hh}S'_{hv} + S'^{*}_{vv}S'_{hv}\right)$$

$$M_{14} = \frac{1}{2}\mathrm{Im}\left(S'^{*}_{hh}S'_{hv} - S'^{*}_{vv}S'_{hv}\right)$$

$$M_{22} = \frac{1}{4}\left(|S'_{hh}|^2 + |S'_{vv}|^2 - 2|S'_{hv}|^2\right)$$

$$M_{23} = \frac{1}{2}\mathrm{Re}\left(S'^{*}_{hh}S'_{hv} - S'^{*}_{vv}S'_{hv}\right)$$

$$M_{24} = \frac{1}{2}\mathrm{Im}\left(S'^{*}_{hh}S'_{hv} + S'^{*}_{vv}S'_{hv}\right)$$

$$M_{33} = \frac{1}{2}|S'_{hv}|^2 + \frac{1}{2}\mathrm{Re}\left(S'^{*}_{hh}S'_{vv}\right)$$

$$M_{34} = \frac{1}{2}\mathrm{Im}\left(S'^{*}_{hh}S'_{vv}\right)$$

$$M_{44} = \frac{1}{2}|S'_{hv}|^2 - \frac{1}{2}\mathrm{Re}\left(S'^{*}_{hh}S'_{vv}\right)$$

Polarimetric Data Representations

- For completely polarized waves:
  - (Sinclair) Scattering Matrix
  - Kennaugh Matrix
- For partially polarized waves:
  - Stokes Scattering Operator (related to Stokes or Mueller matrix)
  - Covariance Matrix
  - Coherency Matrix …
- The Stokes Scattering Operator, Covariance Matrix, and Coherency Matrix are in power units; this means that energy from adjacent pixels can be averaged to reduce noise and consolidate groups of scatterers into single measurements
- Nearly as many matrices as scientists …
  Formal methods to transfer from one representation to another usually exist

Covariance and Coherency Matrix

$$\boldsymbol{C} = \begin{pmatrix} |\boldsymbol{S}'_{hh}|^2 & \sqrt{2}\boldsymbol{S}'_{hh}\boldsymbol{S}'^*_{hv} & \boldsymbol{S}'_{hh}\boldsymbol{S}'_{vv} \\ \sqrt{2}\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{hh} & 2|\boldsymbol{S}'_{hv}|^2 & \sqrt{2}\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{vv} \\ \boldsymbol{S}'_{vv}\boldsymbol{S}'^*_{hh} & \sqrt{2}\boldsymbol{S}'_{vv}\boldsymbol{S}'^*_{hv} & |\boldsymbol{S}'_{vv}|^2 \end{pmatrix}$$ Covariance Matrix (symmetrized)

$$\boldsymbol{T} = \frac{1}{2}\begin{pmatrix} |\boldsymbol{S}'_{hh}|^2 + 2\mathrm{Re}(\boldsymbol{S}'_{hh}\boldsymbol{S}'_{vv}) + |\boldsymbol{S}'_{vv}|^2 & |\boldsymbol{S}'_{hh}|^2 - 2\mathrm{Im}(\boldsymbol{S}'_{hh}\boldsymbol{S}'_{vv}) - |\boldsymbol{S}'_{vv}|^2 & 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{hh} + 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{vv} \\ |\boldsymbol{S}'_{hh}|^2 - 2\mathrm{Im}(\boldsymbol{S}'_{hh}\boldsymbol{S}'_{vv}) - |\boldsymbol{S}'_{vv}|^2 & |\boldsymbol{S}'_{hh}|^2 - 2\mathrm{Re}(\boldsymbol{S}'_{hh}\boldsymbol{S}'_{vv}) + |\boldsymbol{S}'_{vv}|^2 & 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{hh} - 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{vv} \\ 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{hh} + 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{vv} & 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{hh} - 2\boldsymbol{S}'_{hv}\boldsymbol{S}'^*_{vv} & 4|\boldsymbol{S}'_{hv}|^2 \end{pmatrix}$$

Coherency Matrix (symmetrized)

Polarimetric Information Extraction

$$\mathrm{PPD} = \tan^{-1}\left(\frac{-2M_{34}}{M_{33} - M_{44}}\right)$$

Where M_{xy} Stokes Scattering Operator component

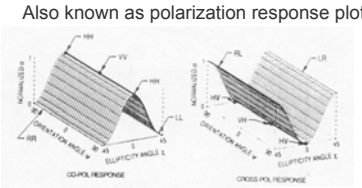
- Polarization signatures
- Target decomposition
- Derived variables, e.g.
  - span (or total power) (TP = M_{11})
  - polarization phase difference (PPD) (of HH and VV)
    - Odd bounce PPD=0º, double bounce PPD=180º, 0º < PPD <180º diffuse scattering
    - Phase difference of HH and HV uniformly distributed, i.e. no specific information re target
  - degree of polarization (*d*); ratio of intensity of completely polarized and completely unpolarized wave components

$$d = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

Where s_x Stokes Vector component

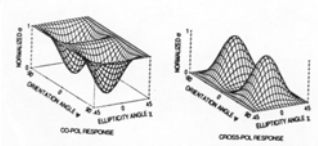
Polarization Signatures

Also known as polarization response plots



Dihedral

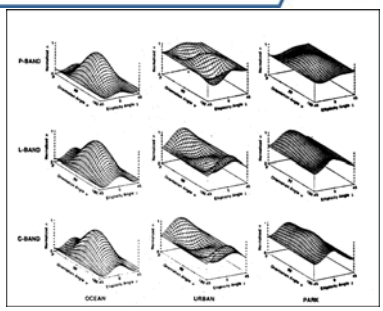
Sphere or trihedral



Source: Ulaby and Elachi, 1990

Polarization Signatures

Co-Polarized component



Source: Zebker *et al.*, 1991

Slightly rough scattering surface | **Double reflections** | **High degree of unpolarized scattering (high pedestal)**

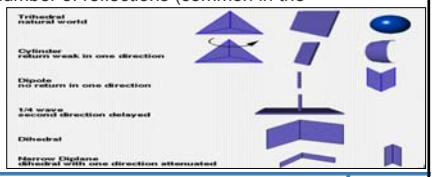
Target Decomposition

- Objective: to infer information re the physical nature of the feature observed from its scattering behavior
- Target decomposition techniques
  - For coherent (point) targets
    - Pauli decomposition
    - Camereon decomposition
    - Symmetric Scattering Characterization Method (Touzi)
  - For incoherent (distributed) targets
    - Huynen decomposition
    - Van Zyl or Freeman-Durden decompostion
    - Cloude-Pottier (H/A/α) decomposition

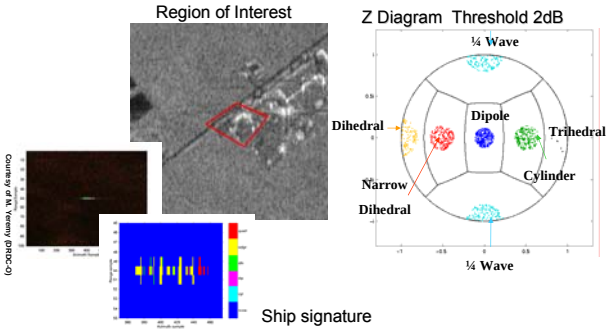
Cameron Decomposition (coherent)

Identified Elemental Scatterers

- Dihedral; even number of reflections (e.g. building-ground, ship-water)
- Cylinder; picks out curved metallic plates (e.g. aircraft fuselage, large diameter, pipe-like object)
- Trihedral; odd number of reflections (common in the natural world)
- Dipole
- ¼ Wave
- Narrow Diplane



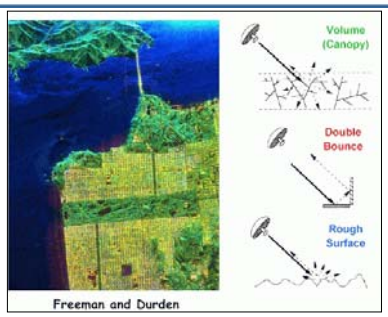
Cameron Decomposition Examples



Van Zyl Decomposition (incoherent)

- The scattering behavior of features imaged in each pixel is classified based on a comparison with the behavior of:
  (1) a target causing an 'Odd' number of reflections e.g. flat metal plate, trihedral
  (2) a target causing an 'Even' number of reflections e.g. dihedral
  (3) a 'Diffuse' scattering target e.g. vegetation
- The Stokes scattering operator constitutes the classification basis
- The evaluated variables are the orientation (ψ) and handedness (sign of χ) of both the transmitted and received wave

Van Zyl Decomposition



Van Zyl, J, Unsupervised Classification of Scattering Behaviour Using Radar Polarimetry Data, *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 27, No. 1, 1989.

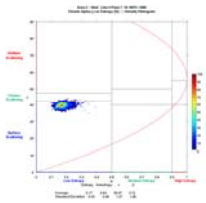
Van Zyl Decomposition

The Decision Rules

- Odd
  - an increase in ψ_t causes an increase in ψ_r
  - the transmitted and received wave have an opposite handedness
- Even
  - an decrease in ψ_t causes an increase in ψ_r
  - the transmitted and received wave have the same handedness
- Diffuse
  - an increase in ψ_t causes an increase in ψ_r
  - the transmitted and received wave have the same handedness
- Unclassified
  - Inconsistent behavior of the received wave in response to a change in the orientation and/or handedness of the transmitted wave

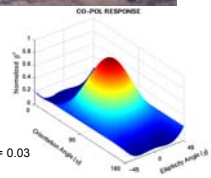
Example; Odd (single) bounce Scattering

Scattering behavior; α-H plane



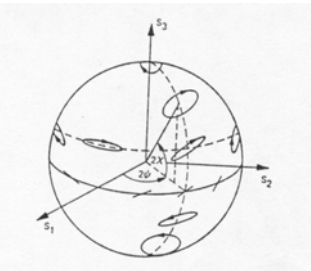
Mud

Typical 'Odd' bounce



$\theta_{inc} = 64^{\circ}$
Ped. Height = 0.03

The Poincaré Sphere

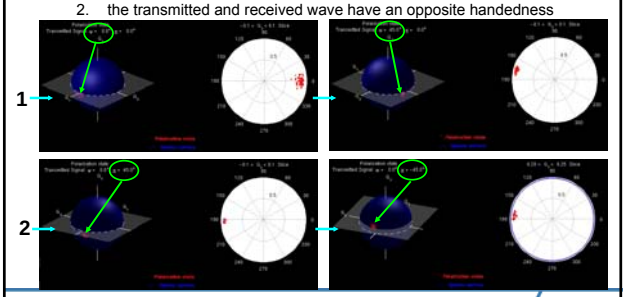


- Linear polarizations – on the equator
- Circular polarizations – at the poles
- Latitude is 2χ
  - positive in north (left hand)
  - negative in south (right hand)
- Longitude is 2ψ

Mud Scattering Behavior

Visualization scattering behavior of Mud using the Poincaré Sphere
Odd bounce, thus:

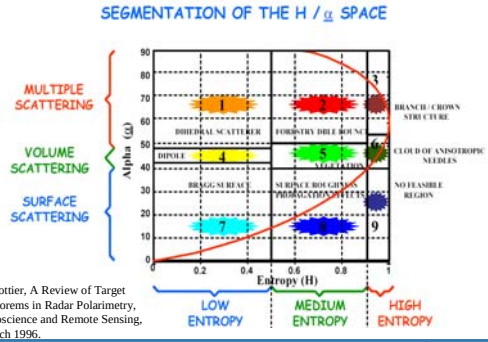
1. an increase in ψ_t causes an increase in ψ_r
2. the transmitted and received wave have an opposite handedness



Cloude-Pottier Decomposition (incoherent)

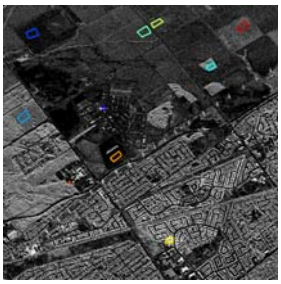
- Uses Coherency Matrix (***T***)
- Three parameters are computed from the eigenvalues/vectors of ***T***, i.e.
  - Entropy (H); randomness of scatter
    - H=0 coherent scatter, H=1 incoherent scatter, 0< H <1 multiple scatter mechanisms
  - Anisotropy (A); relative power of 2nd and 3rd eigenvector
    - 0< A <1
  - Alpha angle (α); average dominant scattering mechanism
    - α=0° odd bounce, α=45° volume scatter, α=90° double bounce

Cloude-Pottier Decomposition (incoherent)

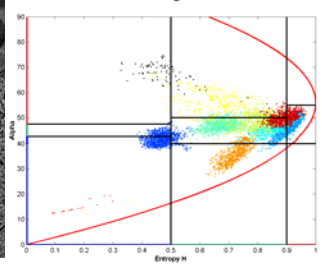


Cloude, S. and E. Pottier, A Review of Target Decomposition Theorems in Radar Polarimetry, IEEE Trans. on Geoscience and Remote Sensing, Vol. 32, No. 2, March 1996.

Cloude-Pottier Decomposition; Example

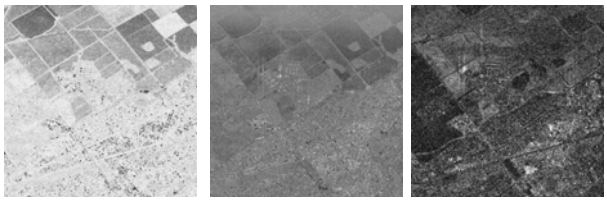


H / α diagram



Cloude-Pottier Decomposition; Example

Entropy α Anisotropy



Polarimetric Calibration Factors

- Inter-channel registration
  - Differences in the signal paths for H and V transmission and reception
- Channel imbalance
  - Differences in the amplitudes and phases of the radar signal gains for H and V transmission and reception
- Cross-talk
  - Signals leaking from H-polarization to V (and V to H) on transmission and reception
- Imbalance and leakage terms are expected to vary from beam to beam, and with elevation angle within a beam

Proper calibration of polarimetric data is crucial!

Summary

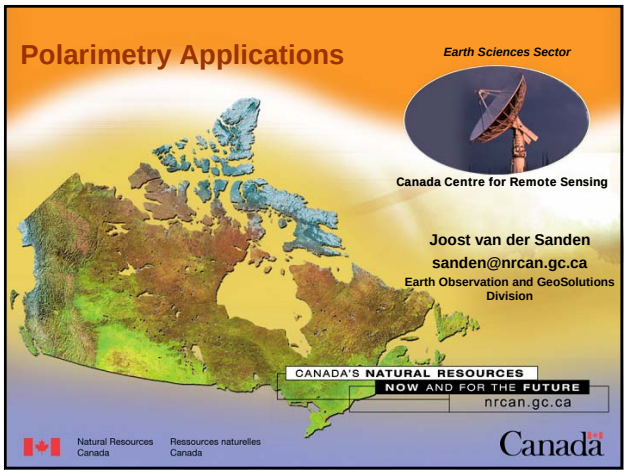
- The full scattering properties of the surface can be measured by a 4-channel polarimetric radar
- The scattering matrix is measured, but the data are usually converted to Stokes, covariance or coherency matrix forms
  - the latter forms are in power units and allow pixel averaging
- The polarimetric data contains much useful information on the terrain, but must be carefully calibrated to yield consistent results
- Interpretation of polarimetric radar data and derived variables, for distributed targets in particular, presents a challenge

Additional Sources of Information

- WWW
  - Canada Centre for Remote Sensing, on-line polarimetry tutorial, http://ccrs.nrcan.gc.ca/resource/tutor/polarim/index_e.php
  - Epsilon.Naught Radar Remote Sensing, on-line polarimetry tutorial, http://epsilon.nought.de/
  - EM waves, polarization, etc. http://www.amanogawa.com/archive/wavesB.html
  - University of New Brunswick on-line course "RADARSAT-2 and Polarimetric Radar Images" http://extend.unb.ca/oalp/courses/for4304.php

Additional Sources of Information

- Selected references re SAR polarimetry
  - Boerner, W.M., H. Mott, E. Lüneburg, C.E. Livingstone, B. Brisco, R.J. Brown, and J.S. Paterson. (1998). "Polarimetry in radar remote sensing: basic and applied concepts", In: F.M.Henderson & A.J.Lewis (Eds.), Principles and applications of imaging radar, New York etc., John Wiley & Sons, Inc., 3 edition, pp. 271-357.
  - Cloude, S.R. and E. Pottier. (1996). "A review of target decomposition theorems in radar polarimetry", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 34, No. 2, pp. 498-518.
  - Evans, D.L., T.G. Farr, J.J. Van Zyl, and H.A. Zebker. (1988). "Radar polarimetry: analysis tools and applications", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 26, No. 6, pp. 774-789.
  - Kong, J.A. (1990). *Polarimetric remote sensing.* New York etc., Elsevier, 520 p.
  - Ulaby, F.T. and C. Elachi. (1990). *Radar polarimetry for geoscience applications.* Norwood, Artech House Inc., 364 p.
  - Zebker, H.A., J.J. Van Zyl, S.L. Durden, and L. Norikane. (1991). "Calibrated imaging radar polarimetry: technique, examples and applications", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 29, No. 6, pp. 942-961.


Polarimetry Applications
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RADARSAT-2 Applications Development at CCRS
• Application fields considered: agriculture, cartography, disaster management, forestry, geology, hydrology, oceans, and sea / land ice
Applications Potential of RADARSAT-2
A Preview
Applications Potential of RADARSAT-2
Supplement One
http://geopub.nrcan.gc.ca/moreinfo_e.php?id=219802
http://geopub.nrcan.gc.ca/moreinfo_e.php?id=220108
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Examples of Applications

1) Agriculture
2) Forestland
3) Coastal Zones
4) Hydrology
5) Sea / River ice
6) Ship / Iceberg detection

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Microwave / Target Interaction Basics

- The radar backscatter of any given target is a function of:
  - Sensor parameters:
    - Frequency or wavelength; penetration depth, effective roughness
    - Polarization; penetration, roughness, architecture
    - Angle of incidence; penetration, roughness
    - Viewing geometry; e.g. row effects, shadowing
  - Target parameters:
    - Dielectric properties (moisture content) govern level of backscatter at a given polarization
    - Structural properties (surface roughness, architecture) govern level of backscatter in different polarizations (**polarimetry !**)

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Polarization and Information Content

- More polarizations = more information because the level of backscatter in different polarizations is governed by the structural properties of the target observed (i.e. surface roughness, architecture)

HH, HV, VV

=

+

VV

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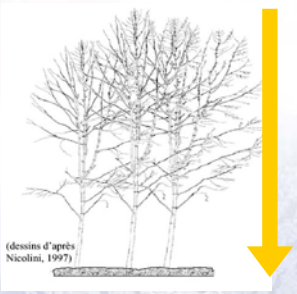
Penetration into the canopy



X Band ($\lambda \approx 3$cm)
C Band ($\lambda \approx 5$cm)
L Band ($\lambda \approx 20$cm)

Small Branches
Leaves

P Band ($\lambda \approx 60$cm)

Branches
Trunk
Ground

Penetration into the canopy is a function of
- geometry of the target
- dielectric constant

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Summary - Agriculture

Anticipated effect of new RADARSAT-2 features on applications potential in terms of data information content. Key: '-' minor, '-/+' moderate, '+' major.

Application	RADARSAT-2 Feature: Selective Single Polarization	Selective Dual Polarization	Quad Polarization	Ultra-Fine Spatial Resolution	Selective Look Direction	Improved Orbit Control
Agriculture						
Crop type	-	-/+	+	-	-	-
Crop condition	-	-/+	+	-/+	-/+	-
Crop yield	-	-	-/+	-/+	-	-

Selective Single Polarization; HH or HV or VV or VH acquired
Selective Dual Polarization; HH + HV or VV + VH acquired
Quad Polarization; HH + HV + VV + VH acquired (amplitude + phase; full polarimetric)

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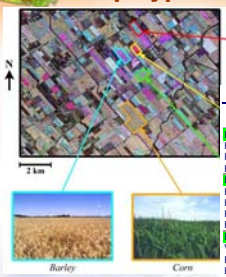
Crop Type



Airborne CV-580 Classification Results (Incidence Angles 46°-57°; July 9th 1998)

	Kappa	Var. Kappa	Percentage correct: Total	Alfalfa	Corn	Soybean	Grains
HH, HV, LL	0.8171	0.0012	94	90	95	96	93
HH, HV, RR	0.9008	0.0014	93	90	95	96	87
HH, HV, VV	0.8177	0.0027	87	90	82	91	93
HH, VV, RR	0.8145	0.0026	87	80	95	91	67
HH, RR	0.7827	0.0028	85	80	82	88	53
HH, HV	0.6870	0.0041	78	80	71	78	93
HV, VV	0.5822	0.0050	71	70	76	57	80
HH, VV	0.5086	0.0049	66	50	79	74	33
RL, LL	0.5070	0.0049	66	10	82	61	73
HV	0.2908	0.0056	45	30	25	61	80
VV	0.2317	0.0056	47	0	47	52	67
RR	0.2305	0.0055	47	0	50	52	60
LL	0.2252	0.0056	47	0	53	48	60
RL	0.2242	0.0054	45	0	47	52	60
HH	0.2127	0.0050	44	60	50	52	7

- A significant increase in classification accuracy is achieved using 3 polarizations (linear or circular) rather than 1 polarization
- Largest increase in accuracy observed when comparing single and dual polarization results

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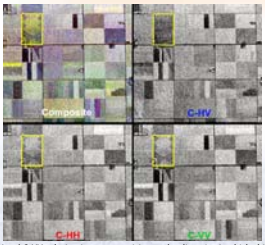
Crop Type

- Cross-polarization (linear or circular)
  - best single polarization for crop type classification
- Imagery at HV
  - particularly useful for mapping small grain crops, but imagery at each polarization brings some information
- Backscatter at HV
  - less sensitive to row direction as related to direction of planting, tillage or harvesting



C-HH and C-VV polarizations are sensitive to the direction in which this crop was harvested. Where the row direction is perpendicular to the radar look direction, backscatter is significantly higher. In the HV polarization, the look direction effect is greatly reduced. This image was acquired with the airborne JPL AIRSAR over Altona, Manitoba (Canada) on October 8, 1994.

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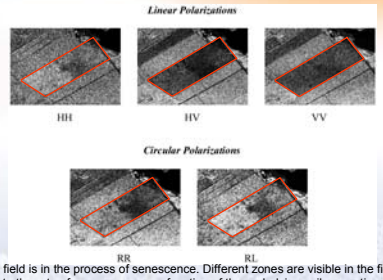
Crop Condition
- Wheat -



This wheat field is in the process of senescence. Different zones are visible in the field and are related to the rate of senescence as a function of the underlying soil properties. Sensitivity to these zones varies as a function of the polarization. These data were acquired south of Ottawa (Canada) by the airborne CV-580 C-SAR (July 9, 1998).

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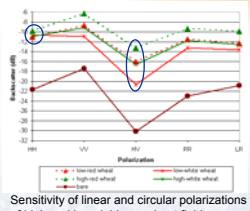
Crop Condition
- Linear and Circular Polarizations -



Sensitivity of linear and circular polarizations to regions of high and low yields on wheat fields.

Crop yields derived from yield monitors were compared to airborne CV-580 data acquired over Clinton, Ontario (Canada) on June 30, 1999. Backscatter for all polarizations was greater in regions associated with higher wheat yields. HH polarized backscatter provided the least differentiation among high and low yielding regions.

HV was most sensitive, with backscatter from high yielding areas greater than low yielding areas by 2.8 dB for red wheat and 4.1 dB for white wheat.

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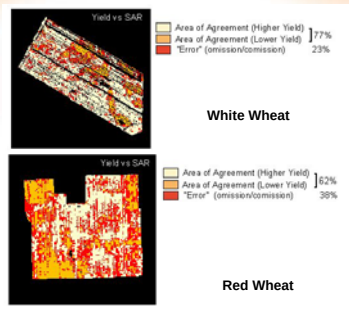
Crop Yield



A classified image of two wheat fields was generated using HH, VV and HV polarizations from CV-580 C-SAR data acquired near Clinton, Ontario (Canada) on June 30, 1999.

These classes were then compared to classes generated from crop yield monitor data (bushels per acre).

A good relationship was established between regions of high and low yield and radar response.

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Concluding Remarks

- The simultaneous acquisition of imagery at multiple polarizations is a significant advantage for crop type and crop condition mapping
- The role of polarimetric parameters for soil and crop information is largely unexplored, although these parameters may have some advantages
- More research is required on the information content of polarimetric parameters
- Agricultural targets are very dynamic; SAR is able to capture some information on crop condition but sensitivity is highly dependent upon crop type and growth stage - the complexity of crop growth means that quantifying productivity and predicting yield is very challenging with or without the use of remote sensing

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Summary - Forestland

Anticipated effect of new RADARSAT-2 features on applications potential in terms of data information content. Key: '-' minor, '-/+' moderate, '+' major.

	RADARSAT-2 Feature					
Application	**Selective Single Polarization**	**Selective Dual Polarization**	**Quad Polarization**	**Ultra-Fine Spatial Resolution**	**Selective Look Direction**	**Improved Orbit Control**
Forestry						
Forest type	-	-	-/+	-/+	-	-
Clearcuts	-/+	-	-	-/+	-	-
Fire-scars	-/+	-	-	-/+	-	-
Biomass	-	-	-	-	-	-

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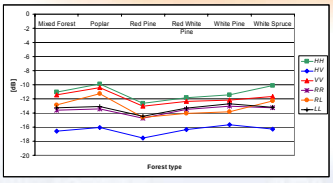
Forest Type Mapping

Observations

- Linear polarizations (HH, VV, HV)
  - low dynamic range (2dB)
  - no significant difference between species (summer, July 29, 1998)
- Circular polarizations (RR, LL, RL)
  - low information content, since mostly volume scattering
  - no additional information compared to linear polarization



July 29, 1998

- Co-polarized and cross-polarized signatures
  - all similar (shape and pedestal), except white spruce (not significant)

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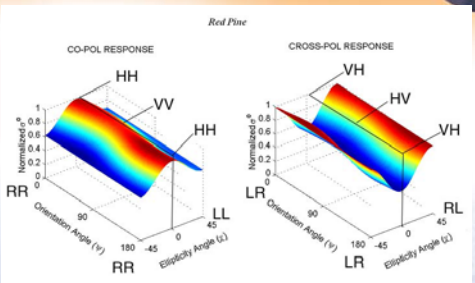
Polarization Signature



Received polarization is:

… the same as the transmit polarization

… orthogonal to the transmit polarization

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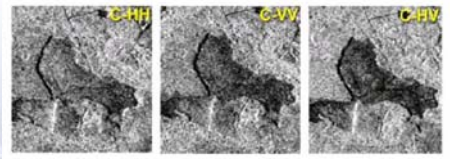
Clearcut mapping and linear feature extraction

- Current studies
  - contrast between clearcut and forest is larger in cross-polarization (HV) than in like-polarization (HH or VV)
  - HV provide a better basis for detection and delineation of linear features
  - analysis of the unpolarized component of the scattering matrix may enhance the contrast between forest and clearcut



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Concluding Remarks

- Low dynamic range in C-band; limits potential for species discrimination and prohibits biomass estimation for medium and high biomass forests (> 50 tons/ha dry)
- Cross-polarization will constitute the best configuration for detection and mapping of anthropogenic features (derived from human activities)
- Low biomass (and height) targets such as those in regenerated areas, northern latitude shrubs should be investigated
- Environmental parameters have been proven to have significant influence on polarimetric SAR data

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Summary – Coastal Zones (Oceans)

Anticipated effect of new RADARSAT-2 features on applications potential in terms of data information content. Key: '-' minor, '-/+' moderate, '+' major.

	RADARSAT-2 Feature					
Application	**Selective Single Polarization**	**Selective Dual Polarization**	**Quad Polarization**	**Ultra-Fine Spatial Resolution**	**Selective Look Direction**	**Improved Orbit Control**
Oceans						
Winds	-/+	-	-	-	-	-
Ships	-/+	-	-/+	+	-/+	-/+
Waves	-	-	-/+	-	-	-
Currents	-	-	-	-	-	-
Coastal zones	-	-/+	-/+	-/+	-	-

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Applications Considered

- Shoreline detection
  - information in support of: maritime navigation, coastal change mapping (climate warming), definition of boundaries
- Substrate mapping
  - information in support of: environmental sensitivity mapping (to e.g. erosion, oil spill), habitat mapping, accessibility mapping
- Slick detection
  - information in support of: cleanup of oil spills and other pollutants

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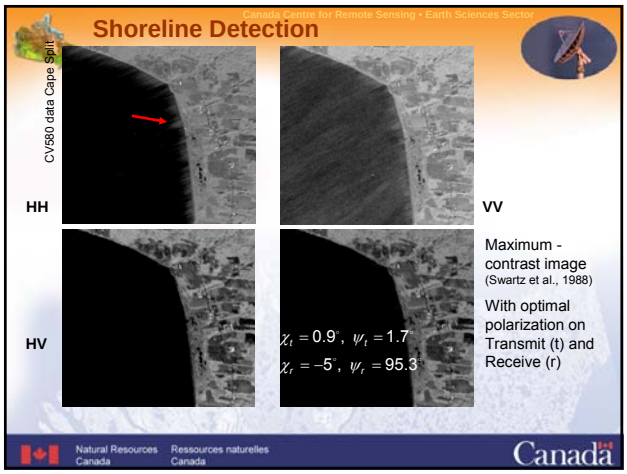
Canada Centre for Remote Sensing • Earth Sciences Sector
Shoreline Detection
CV580 data Cape Split
HH
VV
HV
$\chi_t = 0.9^\circ$, $\psi_t = 1.7^\circ$
$\chi_r = -5^\circ$, $\psi_r = 95.3^\circ$
Maximum - contrast image
(Swartz et al., 1988)
With optimal polarization on Transmit (t) and Receive (r)
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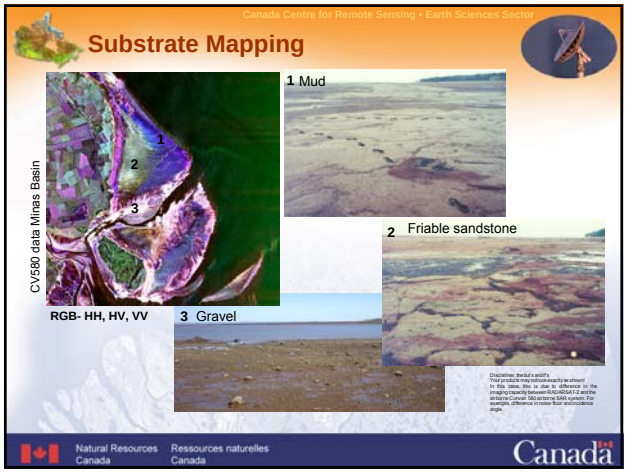
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Substrate Mapping
CV580 data Minas Basin
1
2
3
RGB- HH, HV, VV
1 Mud
2 Friable sandstone
3 Gravel
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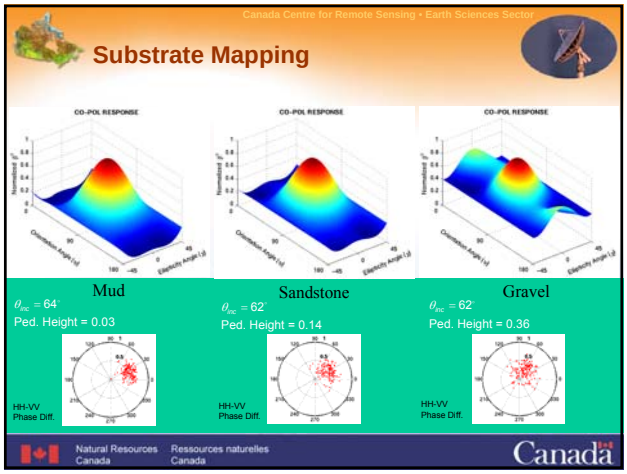
Canada Centre for Remote Sensing • Earth Sciences Sector
Substrate Mapping
CO-POL RESPONSE
CO-POL RESPONSE
CO-POL RESPONSE
Mud
$\theta_{inc} = 64^\circ$
Ped. Height = 0.03
Sandstone
$\theta_{inc} = 62^\circ$
Ped. Height = 0.14
Gravel
$\theta_{inc} = 62^\circ$
Ped. Height = 0.36
HH-VV Phase Diff.
HH-VV Phase Diff.
HH-VV Phase Diff.
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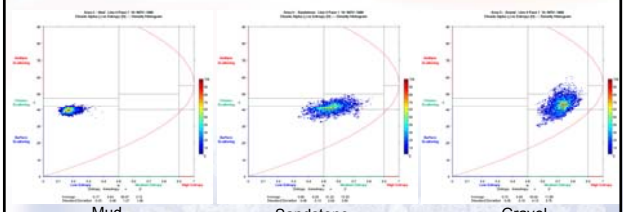
Substrate Mapping

Scattering behavior; α-H plane (Cloude and Pottier, 1996)



Mud | Sandstone | Gravel

Typical 'Odd' bounce

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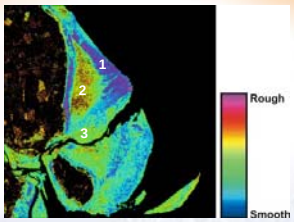
Substrate Mapping



Quantification of surface roughness

Based on polarimetric attribute known as 'circular polarization coherence'. Attribute is a function of soil surface roughness and local incidence angle but is independent of soil moisture.

References: Mattia, F. et al. (1997) IEEE Transactions on Geoscience & Remote Sensing, Vol. 35, No. 4, pp. 954-965; Schuler, D.L. Et al. (2002) IEEE Transactions on Geoscience & Remote Sensing, Vol. 40, No. 3, pp. 687-698; Hajnsek, I. et al. (2002) In: *Proceedings of IGARSS'02*, Toronto, 24-28 June 2002, pp. 420-422.

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Slick Detection

- Slicks imaged through localised suppression of capillary waves (Bragg scale, C-band ≈ 5 cm)
- Detection optimum in moderate wind conditions (3 m s^{-1} to 10 m s^{-1})
- SAR can identify location of oil spills and map their extent, but
  - cannot determine oil slick thickness
  - difficulty in distinguishing between oil and "look-alikes", e.g. areas of low wind, grease ice and natural surfactants

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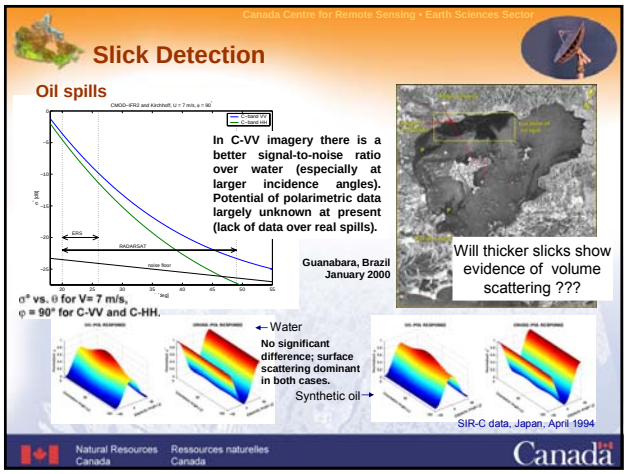
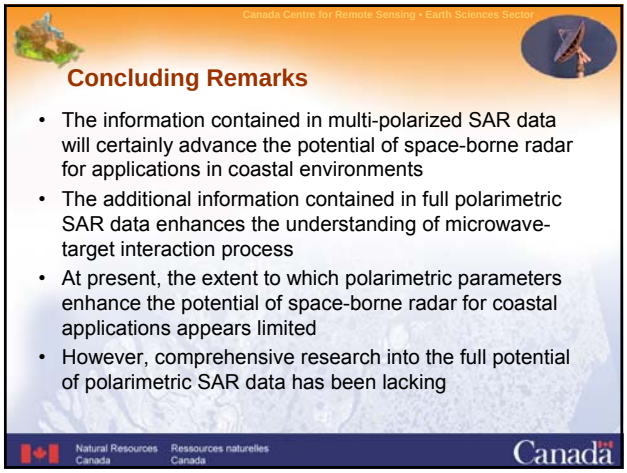
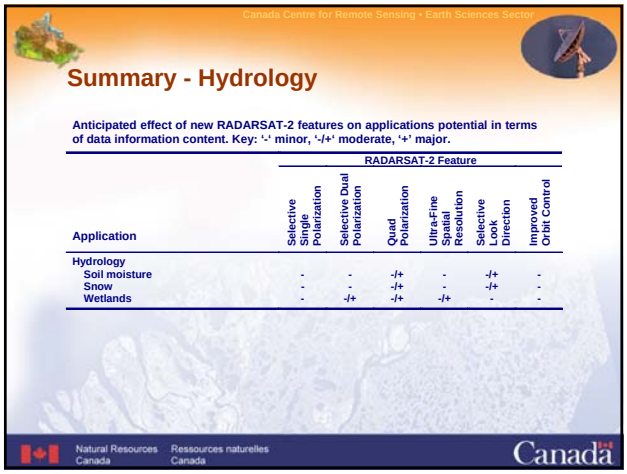
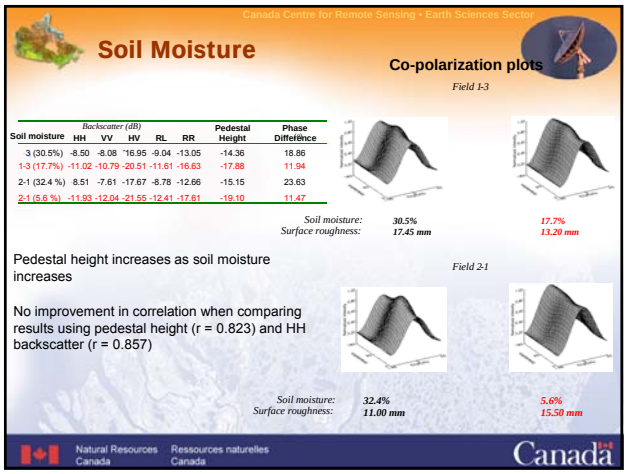


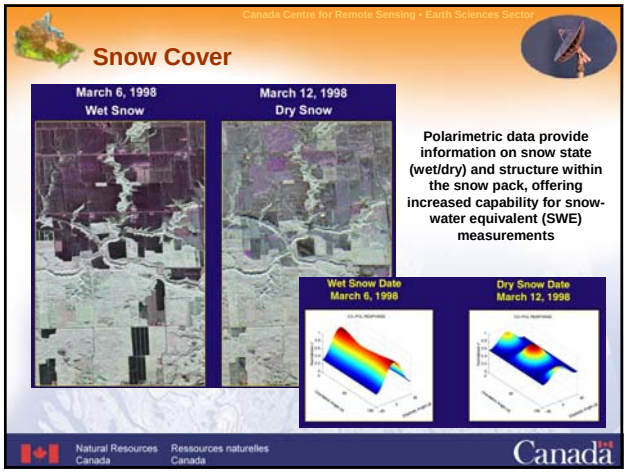


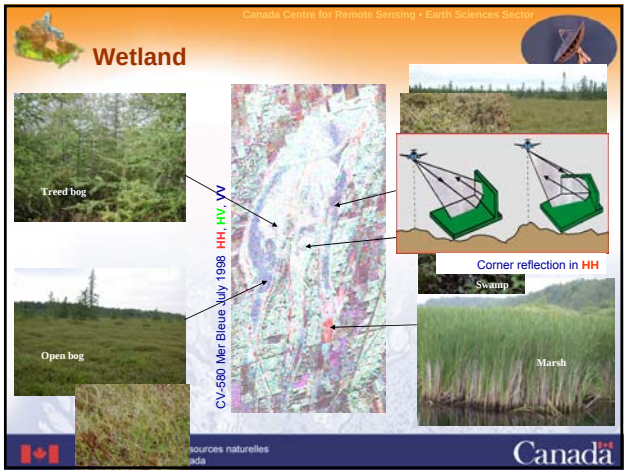


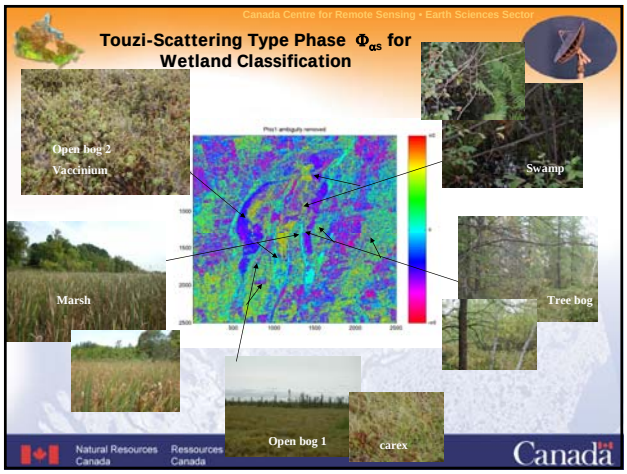
Application	Selective Single Polarization	Selective Dual Polarization	Quad Polarization	Ultra-Fine Spatial Resolution	Selective Look Direction	Improved Orbit Control
Hydrology						
Soil moisture	-	-	-/+	-	-/+	-
Snow	-	-	-/+	-	-/+	-
Wetlands	-	-/+	-/+	-/+	-	-

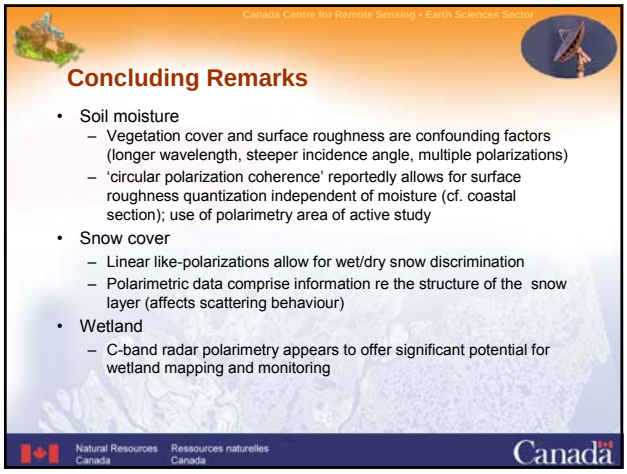


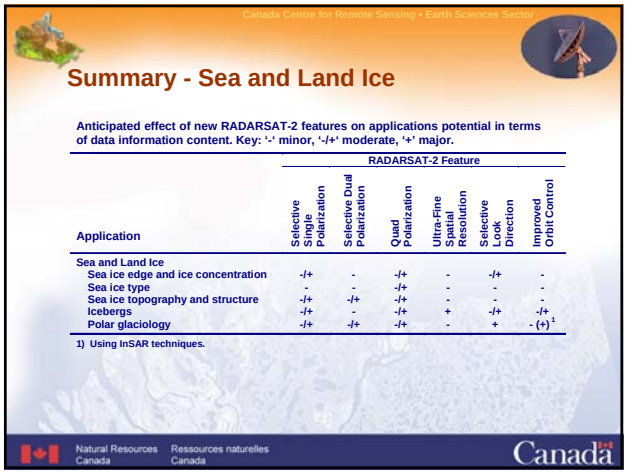
Soil moisture	Backscatter (dB) HH	VV	HV	RL	RR	Pedestal Height	Phase Difference
3 (30.5%)	-8.50	-8.08	-16.95	-9.04	-13.05	-14.36	18.86
1-3 (17.7%)	-11.02	-10.79	-20.51	-11.61	-16.63	-17.88	11.94
2-1 (32.4 %)	8.51	-7.61	-17.67	-8.78	-12.66	-15.15	23.63
2-1 (5.6 %)	-11.93	-12.04	-21.55	-12.41	-17.61	-19.10	11.47











Application	RADARSAT-2 Feature: Selective Single Polarization	Selective Dual Polarization	Quad Polarization	Ultra-Fine Spatial Resolution	Selective Look Direction	Improved Orbit Control
Sea and Land Ice						
Sea ice edge and ice concentration	-/+	-	-/+	-	-/+	-
Sea ice type	-	-	-/+	-	-	-
Sea ice topography and structure	-/+	-/+	-/+	-	-	-
Icebergs	-/+	-	-/+	+	-/+	-/+
Polar glaciology	-/+	-/+	-/+	-	+	- (+) [1]

1) Using InSAR techniques.

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Sea Ice

Interpretation / Analysis Issues

- Ambiguity between water and ice at low incidence angles and in high wind conditions
- Confusion between open water and thin ice conditions
- Masking of ice signatures under wet (spring) conditions
- Inability to robustly and unambiguously separate between ice types (growth stages)

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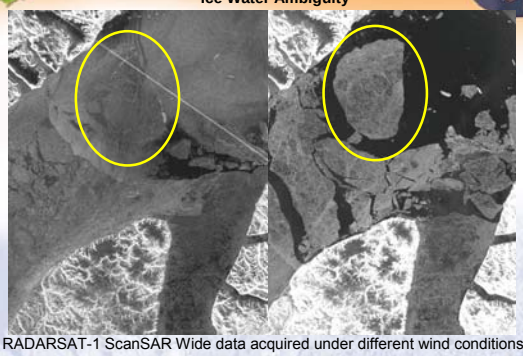
Sea Ice

Ice Water Ambiguity



RADARSAT-1 ScanSAR Wide data acquired under different wind conditions

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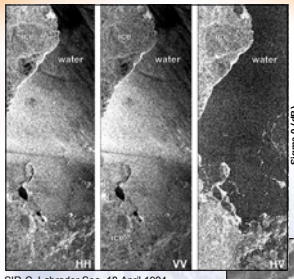
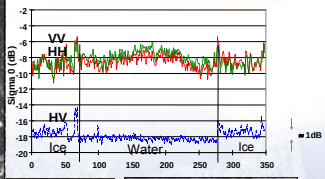
Sea Ice

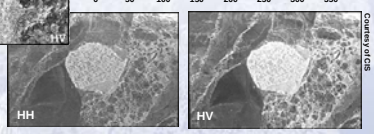


SIR-C, Labrador Sea, 18 April 1994, incidence 26 ° -31°

Cross-polarization data is foreseen to offer improved information about ice edge and ice structure



Ice edge & structure



Courtesy of CIS

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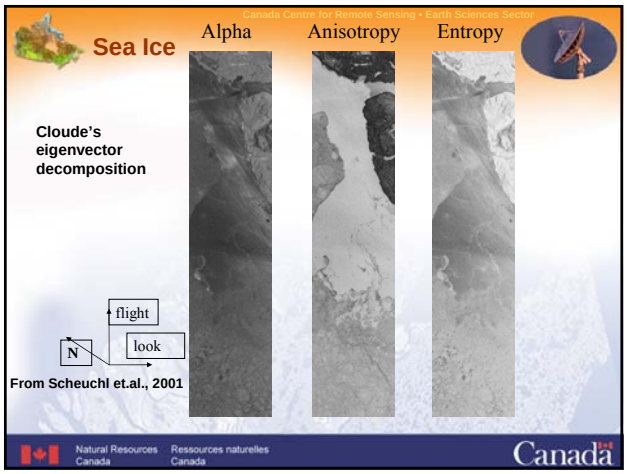
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Sea Ice
Alpha
Anisotropy
Entropy
Cloude's eigenvector decomposition
flight
look
N
From Scheuchl et.al., 2001
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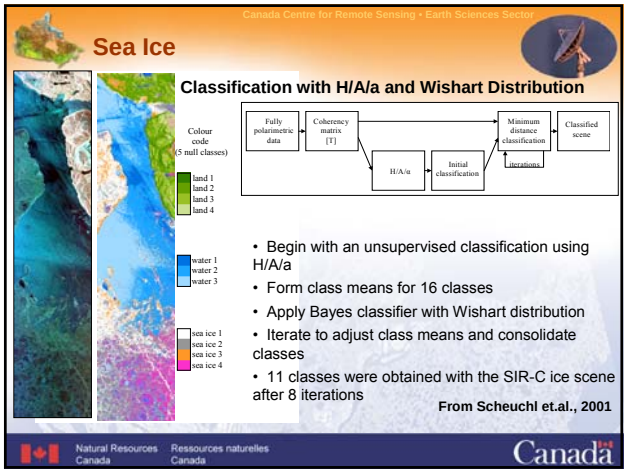
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Sea Ice
Classification with H/A/a and Wishart Distribution
Fully polarimetric data
Coherency matrix [T]
H/A/α
Initial classification
Minimum distance classification
Classified scene
iterations
Colour code (5 null classes)
land 1
land 2
land 3
land 4
water 1
water 2
water 3
sea ice 1
sea ice 2
sea ice 3
sea ice 4
• Begin with an unsupervised classification using H/A/a
• Form class means for 16 classes
• Apply Bayes classifier with Wishart distribution
• Iterate to adjust class means and consolidate classes
• 11 classes were obtained with the SIR-C ice scene after 8 iterations
From Scheuchl et.al., 2001
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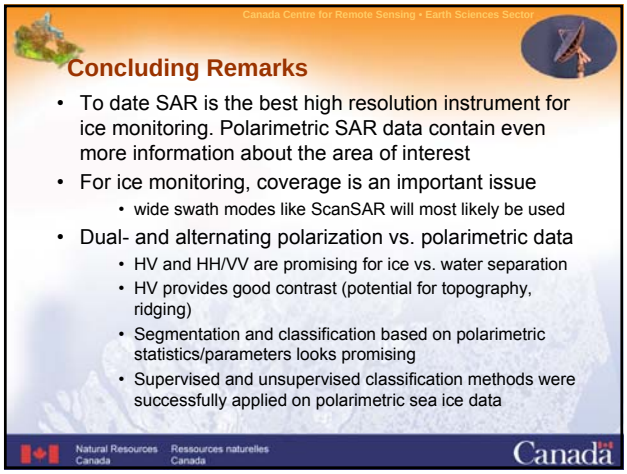
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Concluding Remarks
• To date SAR is the best high resolution instrument for ice monitoring. Polarimetric SAR data contain even more information about the area of interest
• For ice monitoring, coverage is an important issue
• wide swath modes like ScanSAR will most likely be used
• Dual- and alternating polarization vs. polarimetric data
• HV and HH/VV are promising for ice vs. water separation
• HV provides good contrast (potential for topography, ridging)
• Segmentation and classification based on polarimetric statistics/parameters looks promising
• Supervised and unsupervised classification methods were successfully applied on polarimetric sea ice data
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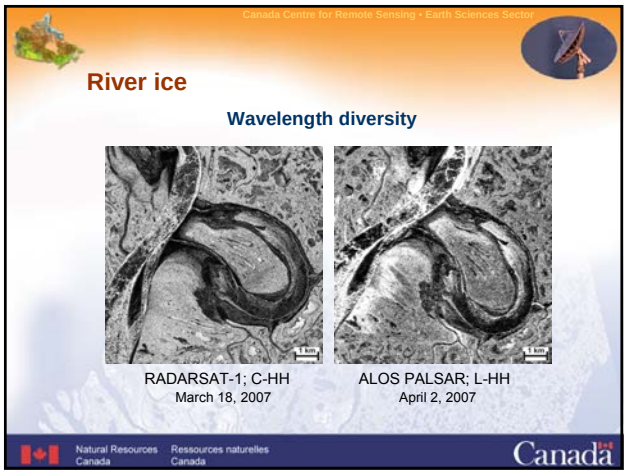
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River ice
Wavelength diversity
RADARSAT-1; C-HH
March 18, 2007
ALOS PALSAR; L-HH
April 2, 2007
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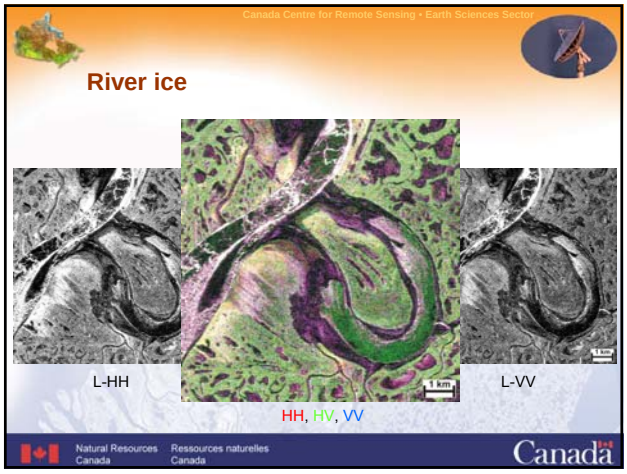
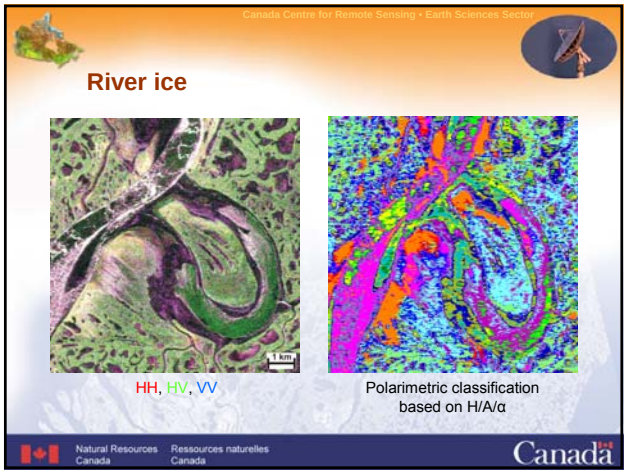

Canada Centre for Remote Sensing • Earth Sciences Sector
River ice
L-HH
L-VV
HH, HV, VV
Natural Resources Canada
Ressources naturelles Canada
Canada


Canada Centre for Remote Sensing • Earth Sciences Sector
River ice
HH, HV, VV
Polarimetric classification
based on H/A/α
Natural Resources Canada
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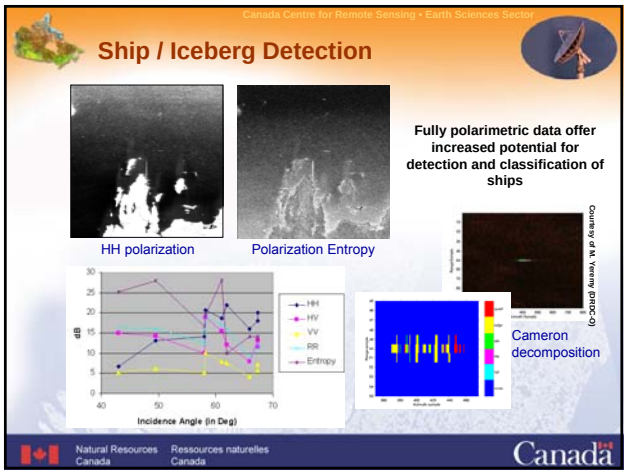
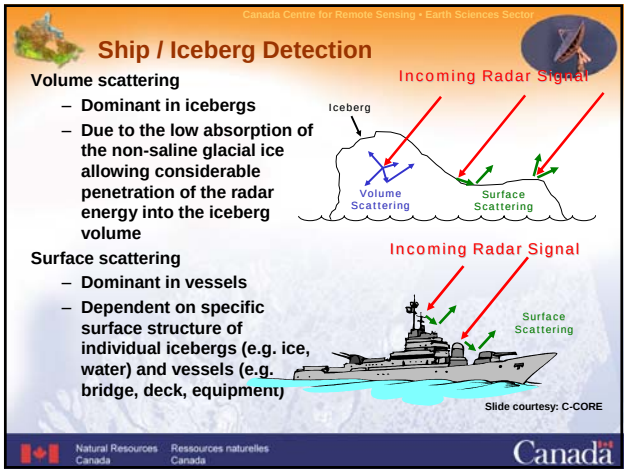
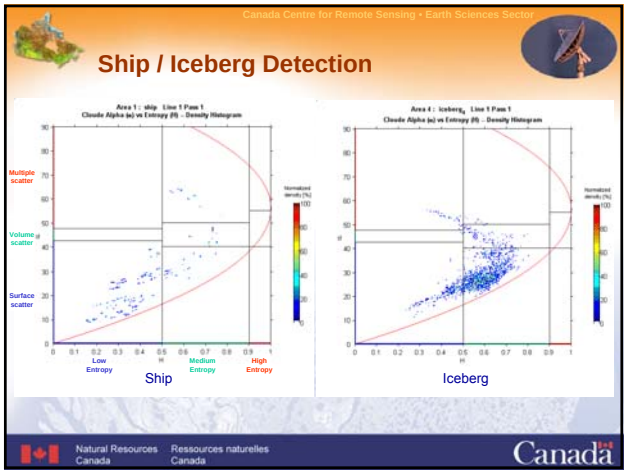

Canada Centre for Remote Sensing • Earth Sciences Sector
Ship / Iceberg Detection
HH polarization
Polarization Entropy
Fully polarimetric data offer increased potential for detection and classification of ships
Courtesy of M. Yeung (DRDC-O)
Cameron decomposition
dB
Incidence Angle (in Deg)
HH
HV
VV
RR
Entropy
Natural Resources Canada
Ressources naturelles Canada
Canada


Canada Centre for Remote Sensing • Earth Sciences Sector
Ship / Iceberg Detection
Volume scattering
– Dominant in icebergs
– Due to the low absorption of the non-saline glacial ice allowing considerable penetration of the radar energy into the iceberg volume
Surface scattering
– Dominant in vessels
– Dependent on specific surface structure of individual icebergs (e.g. ice, water) and vessels (e.g. bridge, deck, equipment)
Incoming Radar Signal
Iceberg
Volume Scattering
Surface Scattering
Incoming Radar Signal
Surface Scattering
Slide courtesy: C-CORE
Natural Resources Canada
Ressources naturelles Canada
Canada


Canada Centre for Remote Sensing • Earth Sciences Sector
Ship / Iceberg Detection
Multiple scatter
Volume scatter
Surface scatter
Low Entropy
Medium Entropy
High Entropy
Ship
Iceberg
Natural Resources Canada
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Ship / iceberg discrimination

Conclusions

- Successfully Demonstrated Discrimination of SAR Iceberg and Ship Targets
  - ~100% CV-580 SAR
  - 98% Simulated RADARSAT-2 Fine
  - 97% Simulated RADARSAT-2 Standard
- Notable Observations:
  - Iceberg scatter appears to be largely dependant on incidence angle
  - The cross polarization channel was found to be the strongest feature group

Slide courtesy: C-CORE

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Application potential of RADARSAT-1 and RADARSAT-2

KEY

-	minimal
-/+	limited
+	moderate
++	strong

3/32 18/32

Application	Satellite: RADARSAT-1	Satellite: RADARSAT-2
Agriculture		
Crop type	-/+	++
Crop condition	-/+	++
Crop yield	-	-/+
Cartography		
DEM interferometry	+	+
DEM stereoscopy	++	++
DEM polarimetry	N.A.	-/+
Cartographic feature extraction	+	++
Disaster Management		
Floods	++	++
Geological hazards	-/+	+
Hurricanes	+	+
Oil spills	+	+
Search and rescue	-/+	+
Forestry		
Forest type	-/+	-/+
Clearcuts	-/+	+
Fire scars	-/+	+
Biomass	-	-
Geology		
Terrain mapping	-/+	+
Structure	+	++
Lithology	-/+	-/+
Hydrology		
Soil moisture	-/+	+
Snow	-/+	+
Wetlands	-/+	+
Oceans		
Winds	+	++
Ships	+	++
Waves	-/+	-/+
Currents	-/+	+
Coastal zones	-/+	+
Sea and Land Ice		
Sea ice edge and ice concentration	+	++
Sea ice type	+	+
Sea ice topography and structure	-/+	++
Icebergs	-/+	+
Polar glaciology	-/+	+

1) Use of single date images assumed.

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Day 3

- Software Demonstrations (FnFCE and PWS)
- Radar Applications at EROS
- Radar Intelligence for Carp and Critters
- Hybrid Multi-Sensor SAR-Optical Approach to Mapping and Monitoring Wetlands
- Overview of Lidar and Its Applications
- Hydrologic Derivatives from Lidar
- Discussion

EROS Training

and Education

Presentation Overview

Software Demonstrations -
Kevin Murnaghan, CCRS; Brian Brisco, CCRS

- Surface Water (FnFCE)
- Polarimetric Work Station (PWS)

EROS Training

and Education

Earth Sciences Sector

Mapping Open Fresh Water using SAR Imagery and an Automated Water Body Extraction Tool

N. Short, R. Landry, D. Raymond, B. Brisco, and J. van der Sanden
Presented by Kevin Murnaghan

Canada Centre for Remote Sensing,
588 Booth St., Ottawa, ON, K1A 0Y7, Canada

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Content

- Background on surface water mapping and remote sensing
- Overview of the water body extraction tool - FnFCE
- Results from four study sites
- Ongoing development and future of the tool

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Introduction

- Fresh water an important resource, arguably becoming more so as populations grow
- Climate change influencing surface water distribution, particularly in northern permafrost environments
- Canada's large areas logistically difficult to monitor
- Remote sensing perfect approach

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Background

- **Previous methods of water body mapping using remote sensing have tended to be:**
  - Small scale - study, site and air photo / sensor specific
  - Sometimes manual delineation, subjective
  - Or semi-automated but with numerous processing steps - image classification, region growing and edge detection, therefore user intensive
- **Ideally the application needs a large scale, quick, simple and repeatable methodology**

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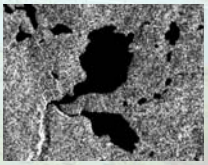
Why choose SAR?

- **SAR collects imagery independent of cloud cover, optical data restricted by frequent and persistent cloud**
- **SAR not subject to sun-glint and low sun angles**
- **Sediment in water can cause confusing spectral returns**
- **Distinction between land and water generally very clear in SAR imagery**



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Automated water body extraction tool - FnFCE

- **FnFCE = Forest non-Forest Class Extraction, initially a CCRS developed forestry application, later modified to include a flood mapping capability**
- **Used successfully in emergency flood situations, decided to investigate routine monitoring of surface water bodies**
- **FnFCE is software that combines image processing and geospatial operators to extract water extent polygons from RADARSAT-1 imagery. It operates as a menu system from the Arc/Info environment.**

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FnFCE method

1. Reads a RADARSAT-1 image (SGF) product and checks the ancillary data record to determine the incidence angle range of the image.

2. Uses a water model to predict the likely backscatter value for water in a C-band HH radar image with these incidence angles – this value is the 'water seed'.

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FnFCE method cont…

3. Statistically analyses a histogram of image backscatter values around the 'water seed', looking for a trough in the frequency

4. The lowest point of the trough becomes the water threshold value

5. All pixels with backscatter values below the water threshold are classified as water (Lo), all others are land (Hi)

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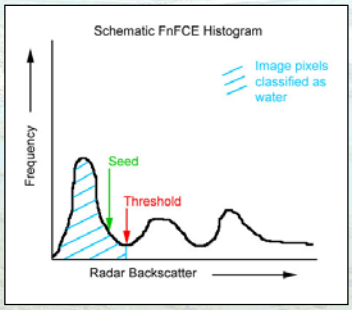
FnFCE method cont…



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FnFCE method cont…

6. Uses geospatial operators and topological rules to extract vectors around groups of water pixels from the classified image

7. Resulting water polygons are exported as ArcGIS interchange format E00

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FnFCE method cont…

- It is quick, water polygons can be generated from a RADARSAT-1 image product in about one hour (geo-referencing is separate and takes additional time)
- Sometimes the water threshold value is not perfect, user can preview the results and adjust this

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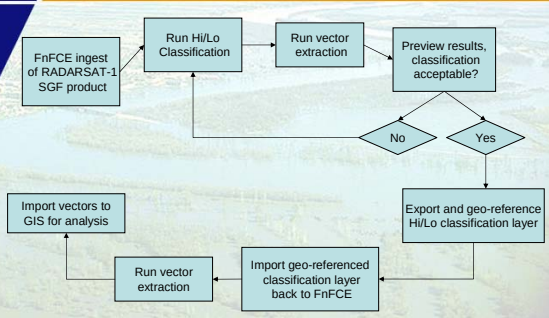
FnFCE Workflow



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Considerations

- Most suitable for flat areas as terrain shadows would be misclassified as water, although area masks can be applied
- Minimum water polygon size of 1 hectare, necessary to maintain software performance and plausibility of results

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Considerations

- Water roughened by strong winds or river rapids is not distinguishable from land
- Date of image acquisition is also important, as ice will obscure land/water boundaries

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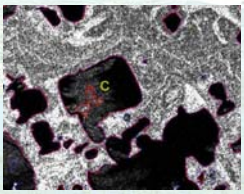
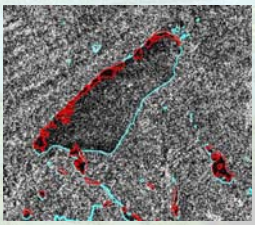
Wind affected examples



FnFCE polygons in red, NTDB hydrography polygons in blue



Of our 23 images, only one had to be completely discarded, two others were partially affected by wind

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Pilot Sites

Four sites chosen in consultation with Parks Canada and Environment Canada.

Site	Environment	Investigations
Cache Lake, NT	Tuktut Nogait National Park	Water availability for ecology
Old Crow Flats, YT	Vuntut National Park	Climate change induced falling water levels
Fort Mackay, AB	Oil sands area	Inter and intra-annual fluctuations in water levels
St. Denis, SK	Wildlife preserve in agricultural area	Inter and intra-annual fluctuations in water levels

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Pilot Sites

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RADARSAT-1 data from the archive

Study site	Year	Date	Mode	Reason for selection
Cache Lake	1997	Sep-04	S7-D	End of summer water levels
	1999	Jun-10	S1-A	Early summer water levels
	2005	Sep-30	S1-A	End of summer water levels /onset of fall freeze-up
Old Crow Flats	1997	Aug-11	S2-D	Late summer water levels
	1998	Sep10	S4-D	End of summer water levels, very warm year
	2000	May-25	S4-A	Spring melt season
	2000	Jul-12	S4-A	Early summer water levels
	2000	Aug-05	S4-A	Mid summer water levels
	2002	Sep-09	S2-A	End of summer water levels
	2006	Sep-01	S5-A	End of summer water levels

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RADARSAT-1 data from the archive

Study site	Year	Date	Mode	Reason for selection
St. Denis	1997	Aug-21	F3-A	Late summer water levels
	1998	Sep-05	S3-D	End of summer water levels compare F1 of Sep 12
	1998	Sep-12	F1N-D	End of summer water levels, compare S3 of Sep 05
	2000	May-28	S5-D	Early season comparisons
	2000	Aug-25	S3-D	Late season comparison
	2003	Sep-10	S5-D	Dry year, inter-annual comparisons
	2005	Sep-07	S1-A	Wet year, inter-annual comparisons
Fort Mackay	1998	Aug 08	S6-D	Start of time series, dry time in dry year
	2000	Aug24	S3-D	Wet year, just before big storm
	2000	Aug27	S1-D	Just after big storm
	2001	Jun23	S4-A	Early season image. Dryish year.
	2005	Aug19	S6-D	Average year, average month
	2006	Jul14	S5-D	Mid-summer, wettish year

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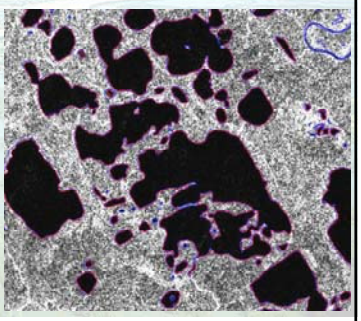
Results
Old Crow Flats, 10 Sep' 1998

FnFCE polygons in red
1:50,000 NTDB polygons in blue

Good agreement, although small and narrow features - land bridges, peninsulas, islands, river channels and ponds - not extracted due to 1 hectare minimum.



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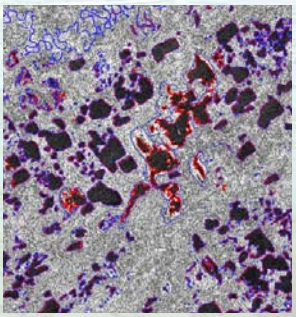
Results
Old Crow Flats, 9 Sep' 2002

FnFCE polygons in red, 1:50,000 NTDB polygons in blue

Areas of discrepancy stand out clearly in red

Note that the NTDB vectors include temporal water extent, so these differences are not necessarily examples of long term change.



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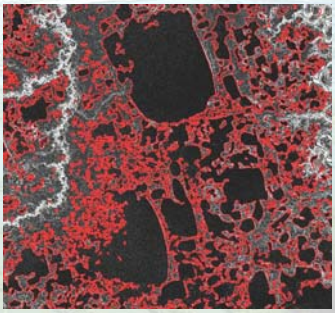
Seasonal Change
Old Crow Flats, 25 May, 2000

Spring

snowmelt and flooding



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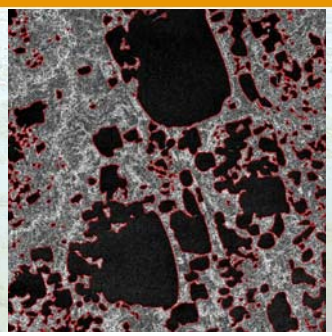
Seasonal Change
Old Crow Flats, 12 July, 2000

Summer

lower water levels



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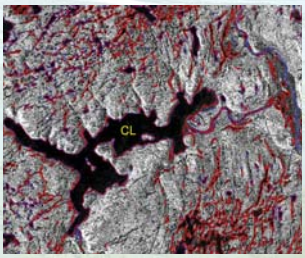
Seasonal Change
Cache Lake, 10 June, 1999

Spring

widespread surface waterlogging

CL = Cache Lake
FnFCE polygons in red,
1:50,000 NTDB water polygons in blue



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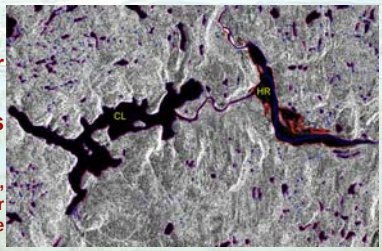
Seasonal Change
Cache Lake, 4 Sep', 1997

Late summer

low water levels

FnFCE polygons in red, 1:50,000 NTDB water polygons in blue



Generally drier surface, although Hornaday River (HR) shows high water levels

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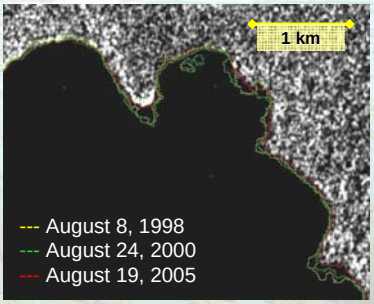
McClelland Lake, Fort Mackay, AB

Inter-annual variability in lake extent

Background image is August 19, 2005



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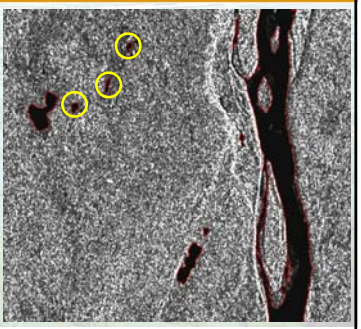
Long-term change
Fort Mackay, 8 Aug', 1998

Summer 1998

Three small water bodies exceed the 1 ha size threshold.

RADARSAT-1 S6 D



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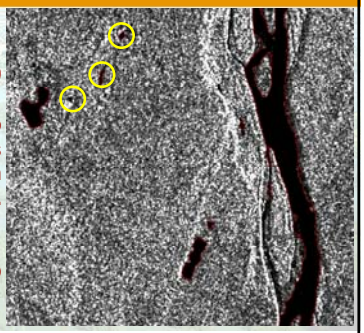
Long-term change
Fort Mackay, 24 Aug', 2000

Summer 2000

Only two water bodies large enough to be extracted.

RADARSAT-1 S3 D



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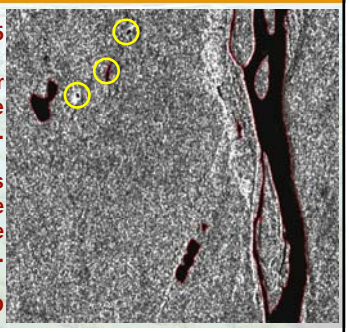
Inter-annual Change
Fort Mackay, 19 Aug', 2005

Summer 2005

Only one water body still large enough to be extracted.

Area has isolated patches of permafrost, therefore localised lake drainage expected.

RADARSAT-1 S6 D



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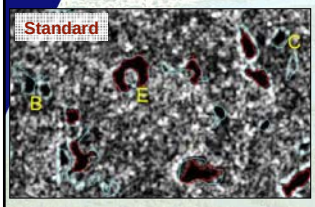
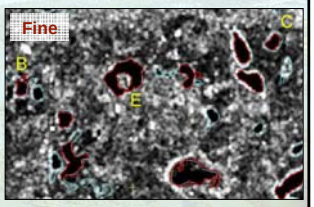
St. Denis
Small scale site

Small water bodies, high resolution SAR data (Fine Mode) extracts slightly more lakes than the Standard Mode.

Note: only 2mm of rain fell between the two image acquisitions



S3 – Desc. September 5, 1998



F1 – Desc. September 12, 1998

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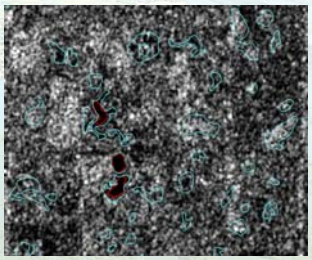
Inter-annual change St. Denis

2003, a very dry year



FnFCE polygons - Red
NTDB polygons - Blue

Standard 5 – Desc. September 10, 2003

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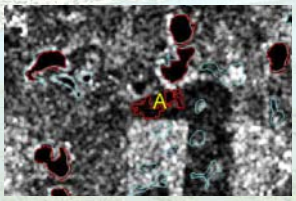
Impact of vegetation in southern sites

Certain crops and vegetation types are sometimes misclassified as water. This complicates the application over southern sites.



FnFCE polygons - Red

NTDB polygons - Blue

Fine 1 – Desc. September 12, 1998

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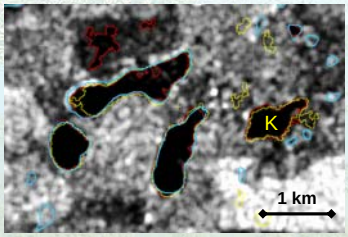
New water body? St. Denis

Presence of new water body. Not marked on paper maps or in the digital NTDB layer.



FnFCE polygons:
1998 – Yellow
2000 – Red

NTDB polygons - Blue

August 25, 2000 S3.

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Conclusions

- When surface not significantly wind roughened, FnFCE reliably delivers outlines of medium to large water bodies
- FnFCE quick and efficient method, worth developing further the authors believe
- Extracted polygons document changes in seasonal and inter-annual surface water availability

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Conclusions cont…

- Due to polygon size restrictions, analysis and comparisons with other data sources must be done at the appropriate scale.
- Due to possible misclassifications, quantitative analysis should be done on specific water body basis. Qualitative analysis can be done at the scene scale.

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Future development

- Expand the code to import other sensor data – ENVISAT, RADARSAT-2, ERS-1/2, ALOS
- Add additional water models for different SAR polarizations and wavelengths
- Add functionality to enable user defined training areas to identify the water seed

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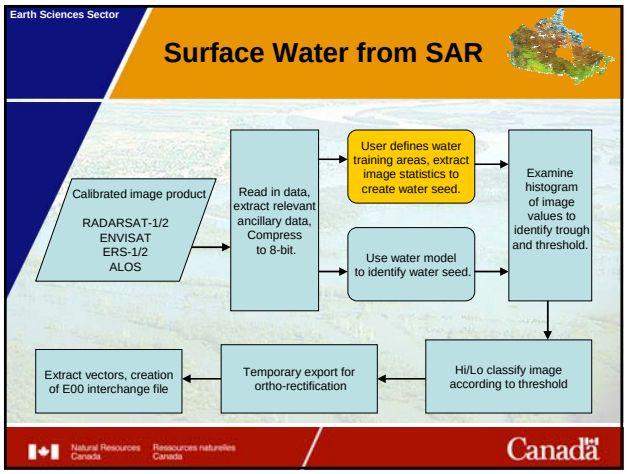
Earth Sciences Sector
Surface Water from SAR
Calibrated image product
RADARSAT-1/2
ENVISAT
ERS-1/2
ALOS
Read in data, extract relevant ancillary data, Compress to 8-bit.
User defines water training areas, extract image statistics to create water seed.
Use water model to identify water seed.
Examine histogram of image values to identify trough and threshold.
Hi/Lo classify image according to threshold
Temporary export for ortho-rectification
Extract vectors, creation of E00 interchange file
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Polarimetric Workstation

Kevin Murnaghan
Kevin.Murnaghan@nrcan.gc.ca
Canada Centre for Remote Sensing

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Canada

History

- Dr. Touzi started development twenty years ago
- Features incorporated in Polsig early 1990's
- 2000
  - Graphical user interface added
  - Programmed in Matlab

Developers

- Stefan Nedeclu
- Francois Charbonneau
- Aleksandar Jevtic
- Targ-analysis
  - Dr. Hawkins
  - Dr. Livingstone
  - John Wolfe

Data Sources

- Convair SAR 580
- SIR-C
- NASA-JPL AIRSAR
- Latest version added RADARSAT-2
- Future version will add ALOS

Study Areas

- Polygons are defined on top of imagery

Local area Tools

- Polarimetric Signature
- Statistics
- Histogram
- Poincare Sphere
- Channel Coherence
- Cloude Decomposition Histogram

Image Synthesis

- Sigma Naught – transmit and receive polarization
- Coherence
- Swartz-Contrast
- Phase difference
- Future version to add Touzi decomposition

Presentation Overview

Radar Applications at EROS - Russell Rykhus, SGT

- Measuring Permafrost Thaw Subsidence using InSAR
- Wildfire monitoring using Radarsat-1 amplitude and InSAR coherence data
- Oil exploration activities observed using SAR data
- SAR amplitude data used to map lake ice conditions in Northern Alaska

EROS Training and Education

Radar Applications at EROS

Russell Rykhus, SGT, contractor to U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD rykhus@usgs.gov. Work performed under USGS contract 08HQCN0005.

Zhong Lu, USGS Cascades Volcano Observatory (CVO), 1300 SE Cardinal Court, Vancouver, Washington, lu@usgs.gov

U.S. Department of the Interior
U.S. Geological Survey

Outline

- Measuring permafrost thaw subsidence using InSAR
- Wildfire monitoring using Radarsat-1 amplitude and InSAR coherence data
- Oil exploration activities observed using SAR data
- SAR amplitude data used to map lake ice conditions in northern Alaska

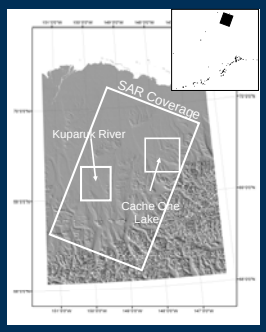
Measuring Permafrost Thaw Induced Subsidence with InSAR

Monitoring permafrost thaw subsidence will improve our understanding of hydrologic processes and the release of large stores of carbon into the atmosphere

Rykhus, R.P., and Lu, Z., 2008. InSAR detects possible thaw settlement in the Alaskan Arctic Coastal Plain: Canadian Journal of Remote Sensing, v. 34, no. 2, p. 100-112.

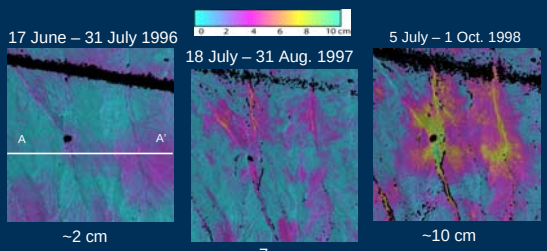
Thaw Subsidence

- JERS-1 ~70 % overlap
- To increase temporal coverage we obtained JERS-1 data from 4 adjacent tracks
- Northern Alaska
  - Cache One Lake
  - Kuparuk River



USGS

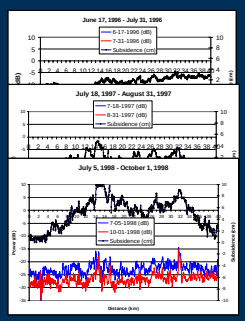
Thaw Subsidence



USGS

Thaw Subsidence

- 1996 – 2 cm of subsidence (44 day interferogram)
- 1997 – 5 cm of subsidence (44 day)
- 1998 – about 10 cm of subsidence (88 day)

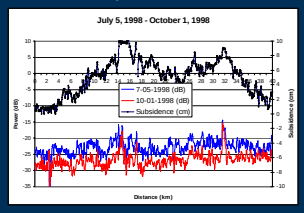


USGS

Thaw Subsidence

- Was the subsidence solely due to changing soil moisture conditions?
- Not likely as the subsidence is not accompanied by a change in amplitude

Kuparuk River

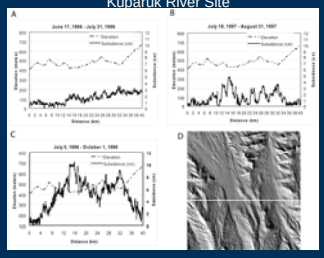


USGS

Thaw Subsidence

- Do the interferometric fringes simply show the area's topography?
- Kuparuk elevation varies by ~500 m
- USGS DEM was used to remove topographic effects
- Ridge lines and slopes experienced significant subsidence

Kuparuk River Site



USGS

Thaw Subsidence - Conclusion

- The least amount of subsidence occurred in 1996
- The largest amount of subsidence was observed in the interferograms from 1998
- There may be some phenological dependence in the data
- L-band InSAR data is useful for monitoring possible subsidence associated with the thawing of the active layer
- Long-term monitoring with InSAR can be used to study the effects of a warming Arctic on the permafrost

USGS

Thaw Subsidence - Conclusion

However,

- other hydrologic processes such as the downslope movement of water at the ice/thaw interface and changing soil moisture conditions contribute to the InSAR derived subsidence estimates

USGS

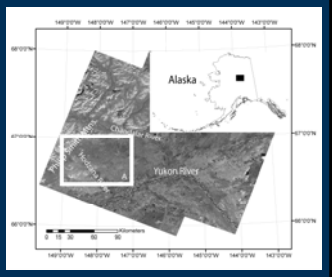
Wildfire Monitoring using Radarsat-1 Amplitude and InSAR Coherence

Wildfires play an important role in maintaining and regenerating fire-dependant ecosystems. In cloud-prone and smoke-covered conditions, SAR provides the best method to study the effects of wildfires.

USGS

Wildfire Monitoring

- Yukon River Basin, Alaska
- Boreal forest fire that burned during the summer of 2003
- The fire is referred to as the B346 fire



USGS

Wildfire Monitoring

- C-band Radarsat-1 amplitude images
- Eight pre-fire images
- Four images while the fire actively burned
- 12 post-fire images

- Burned boreal forest vegetation appears brighter than the unburned forest

USGS

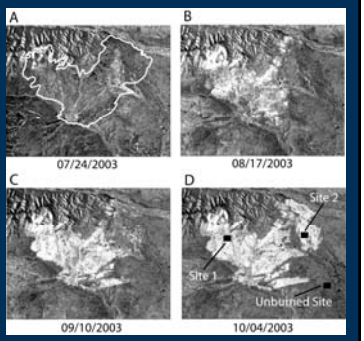
Wildfire Monitoring

- Started on about 24 July 2003 and out by 4 Oct. 2003

- The fire increased amplitude values by ~5 – 6dB

- We mapped the fire's progression and how the fire intensified over its duration.

USGS

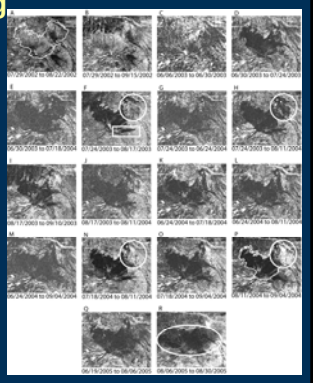


Wildfire Monitoring

- Coherence is a qualitative way to measure the amount of change between 2 InSAR observations

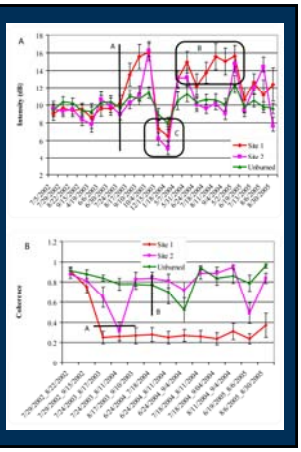
- The fire causes a complete loss of coherence over the shortest observation periods

USGS



Wildfire Monitoring

- Using 2 burned sites and 1 unburned site we analyze the temporal effects of the fire
- Temporal profile of the fires effect on the intensity signal (top)
- Temporal profile showing the effect of the fire on the coherence data (bottom)



USGS

Wildfire - Conclusion

- The relatively frequent acquisitions (24 days) by the Radarsat-1 sensor allowed us to map the progression and intensification of the B346 wildfire.
- SAR intensity and coherence data provide unique information related to burn severity and post-fire vegetation recruitment.

USGS

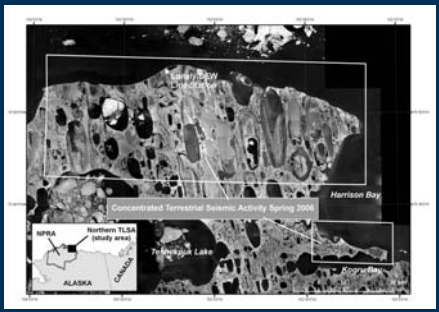
SAR Data Maps Winter Seismic Survey Activity in Northern Alaska

Monitoring winter seismic activities will help us understand the cumulative effects of oil exploration on a fragile environment.

Jones, B.M., Rykhus, R.P., Lu, Z., Arp, C.D., and Selkowitz, D.J., 2008. Radar imaging of winter seismic survey activity in the National Petroleum Reserve-Alaska: Polar Record, v. 44, no. 3, p. 227-231.

USGS

Seismic Survey



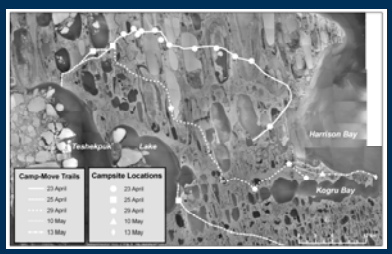
USGS

Seismic Survey

USGS

Seismic Survey

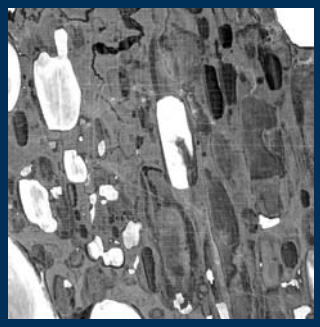
- Progression of the winter seismic survey from 23 April through 13 May 2006
- The survey builds roads on top of the snow/ice



USGS

Seismic Survey

- Temporal average for 7 Radarsat-1 scenes improves detail
- Construction of the survey lines caused a bright back-scattered return compared to background levels



USGS

Seismic Survey - Conclusion

- SAR imagery revealed various activities associated with oil exploration
- SAR imagery can provide information on the location of winter seismic activity and could be used as a monitoring tool for land and resource managers as increased petroleum-based activity occurs in the TLSA and NPR-A

USGS

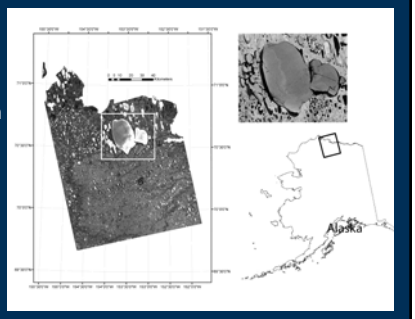
Monitoring Lake Ice Near Teshekpuk Lake, Alaska

Monitoring Arctic lake ice conditions will improve our understanding of the ecological impacts of a warming climate and its effect on the regions energy balance.

USGS

Lake Ice

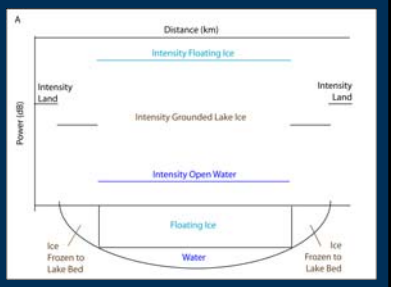
- Teshekpuk Lake, Alaska
- Acquired both Radarsat-1 & ERS-2 data
- Used all Radarsat-1 modes



USGS

Lake Ice

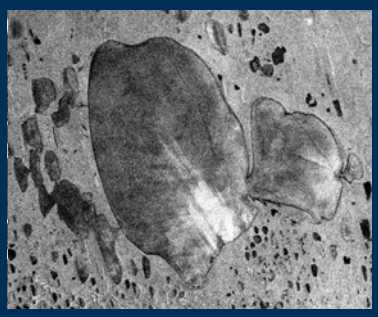
- Radar must be able to differentiate:
  - Open Water
  - Floating Ice
  - Ice Frozen to the Lake Bed
  - Frozen Ground



USGS

Lake Ice

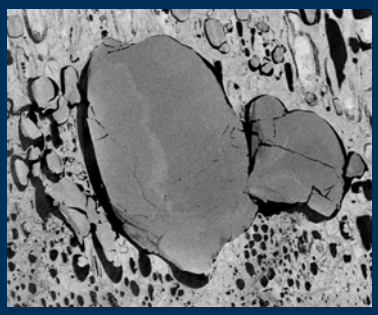
- 23 April 2006
- 25 April 2006
- 29 April 2006
- 02 May 2006
- 06 May 2006
- 10 May 2006
- 13 May 2006
- 17 May 2006
- 20 May 2006



USGS

Lake Ice

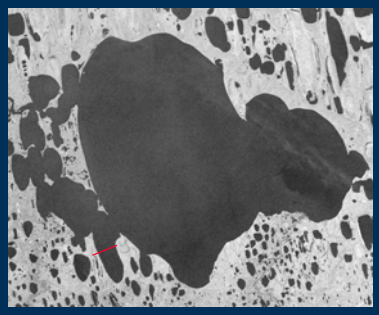
- 23 May 2006
- 24 May 2006
- 02 June 2006
- 10 June 2006
- 13 June 2006
- 16 June 2006
- 17 June 2006
- 23 June 2006
- 27 June 2006
- 30 June 2006



USGS

Lake Ice

- 04 July 2006
- 06 July 2006
- 07 July 2006
- 10 July 2006
- 13 July 2006
- 21 July 2006
- 24 July 2006
- 30 July 2006

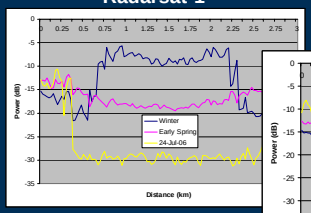


USGS

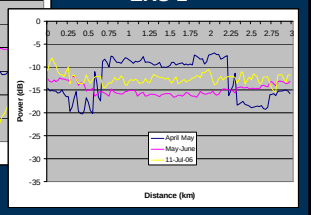
Lake Ice

Backscatter Response

Radarsat-1



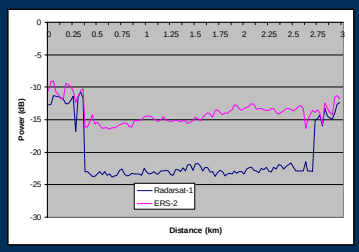
ERS-2



USGS

Lake Ice

- Comparison of averaged backscatter intensity values for ERS-2 and Radarsat-1 wind contaminated scenes



USGS

Lake Ice - Conclusion

- SAR data is able to differentiate several lake ice classes
- Frequent acquisitions provides information relating to approximate dates of ice formation, initial thawing, and ice free conditions
- Radar data can be used to infer lake depth and depth of the ice
- Higher resolution radar data will better monitor shoreline erosion caused by floating ice

USGS

Thank You

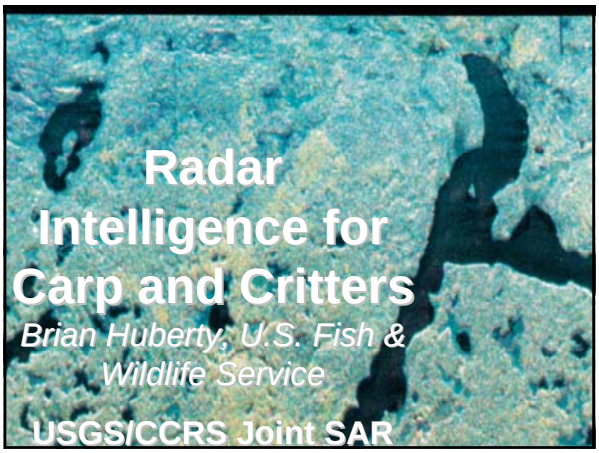
USGS

Presentation Overview

Radar Intelligence for Carp and Critters - Brian Huberty, USFWS

EROS Training

and Education


Radar Intelligence for Carp and Critters
Brian Huberty, U.S. Fish & Wildlife Service
USGS/CCRS Joint SAR

"We can't rely on the Americans to give us satellite data when we want it."
Bhupendra Jasani
King's College, UK

So….
ESA and EU spending $3.6 Billion for the Global Monitoring for Environment and Security (GMES) system!

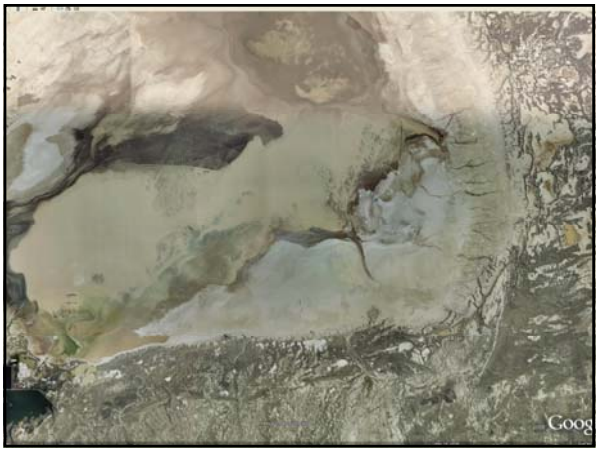
Let's Play,
Where is it?

Google

Google

Google

Google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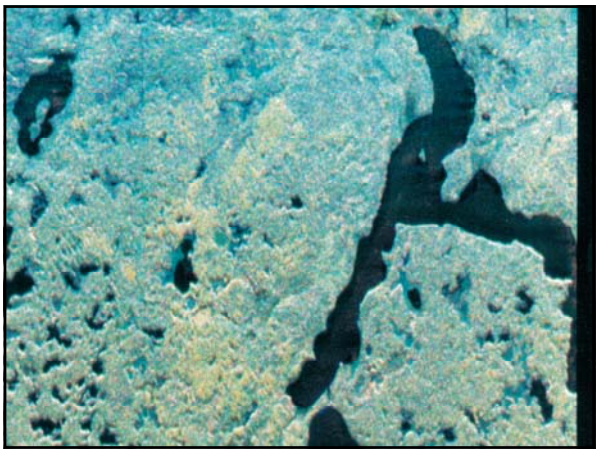
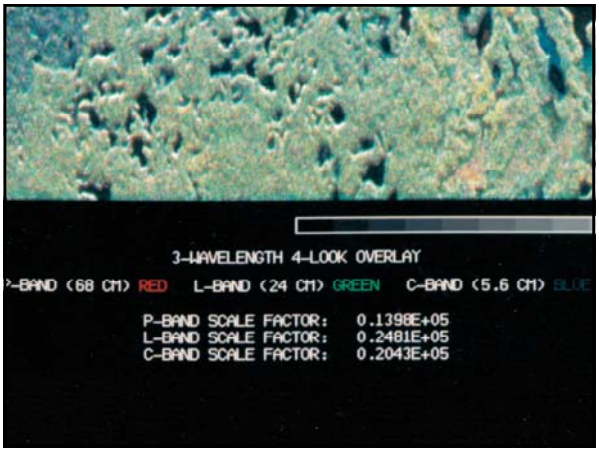
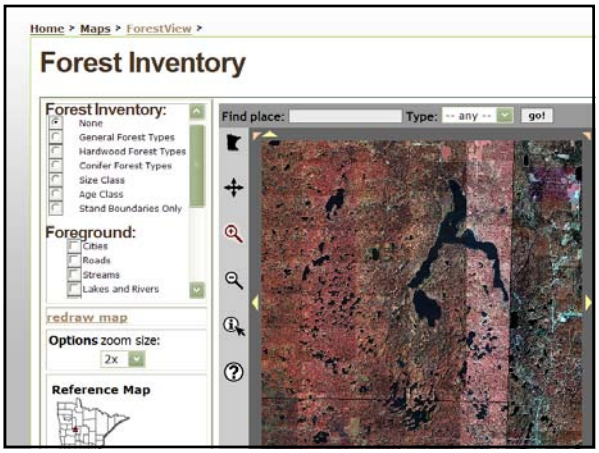


ITASCA STATE PARK MINNESOTA

Headwaters of the Mississippi River

JPL Aircraft SAI
DATA ACQUIRED:
DATE: 08-JUN-88
TIME (GMT): 19:20:41
DATA CORRELATED:
DATE: 16-DEC-88
RADAR FREQUENCY: PLC OVERLAY
RADAR GEOMETRY:
ALTITUDE (M): 8728
NEAR RANGE (M): 9488.431
TRACK ANGLE (DEG): 270.0


3-WAVELENGTH 4-LOOK OVERLAY
-BAND (68 CM) RED L-BAND (24 CM) GREEN C-BAND (5.6 CM)
P-BAND SCALE FACTOR: 0.1398E+05
L-BAND SCALE FACTOR: 0.2481E+05
C-BAND SCALE FACTOR: 0.2043E+05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Forest Inventory:
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General Forest Types
Hardwood Forest Types
Conifer Forest Types
Size Class
Age Class
Stand Boundaries Only
Foreground:
Cities
Roads
Streams
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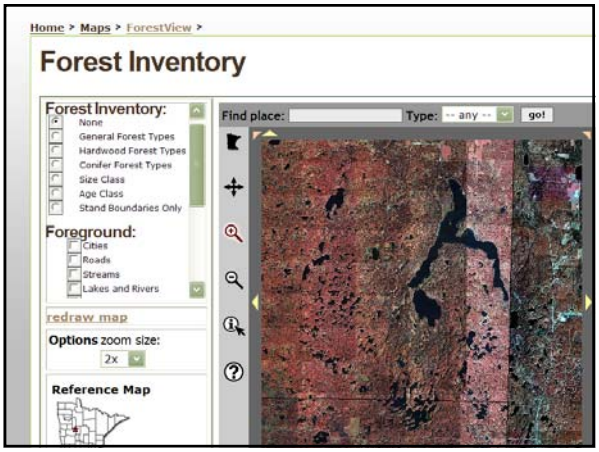
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Forest Inventory:
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General Forest Types
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Size Class
Age Class
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go!

Home > Maps > ForestView >
Forest Inventory
Forest Inventory:
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General Forest Types
Hardwood Forest Types
Conifer Forest Types
Size Class
Age Class
Stand Boundaries Only
Foreground:
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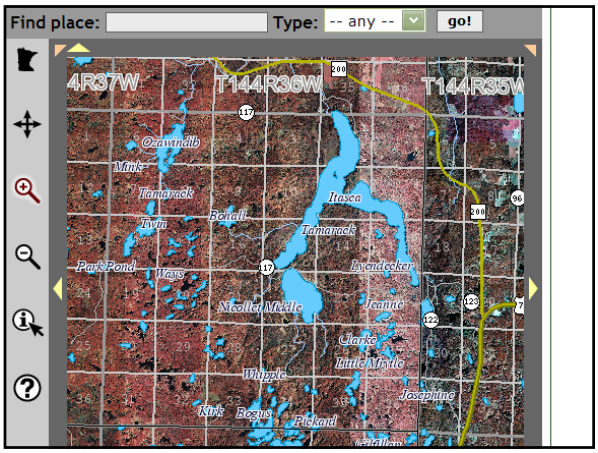
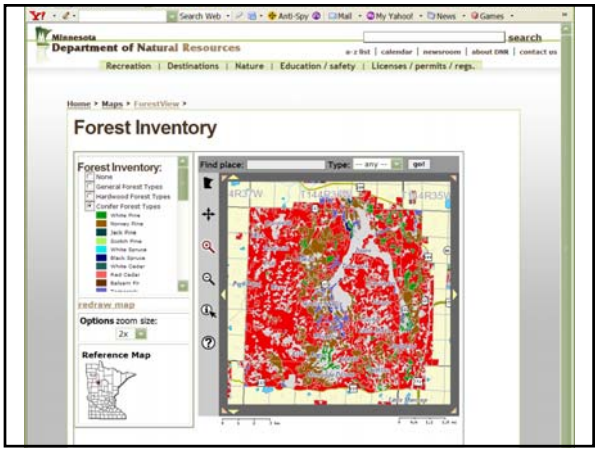

Find place:
Type:
-- any --
go!
T144R36W
T144R35W
Ozawindib
Mink
Tamarack
Twin
Bohall
Itasca
Tamarack
Park Pond
Ways
Lyendecker
Nicollet Middle
Jeanne
Clarke
Little Middle
Whipple
Josephine
Kirk
Bogus
Pickard


Minnesota
Department of Natural Resources
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Recreation | Destinations | Nature | Education / safety | Licenses / permits / regs.
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Forest Inventory
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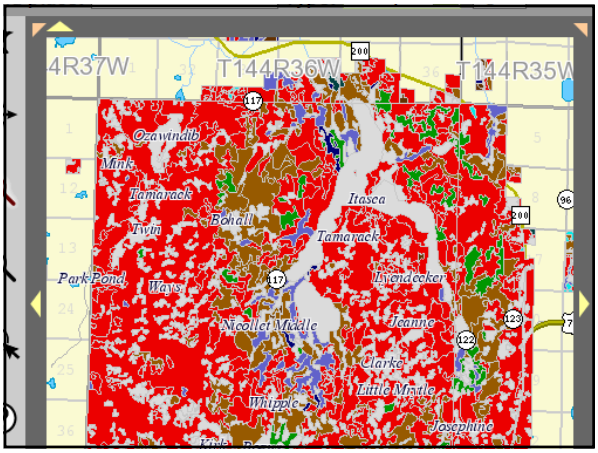
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Jeanne
Clarke
Little Middle
Whipple
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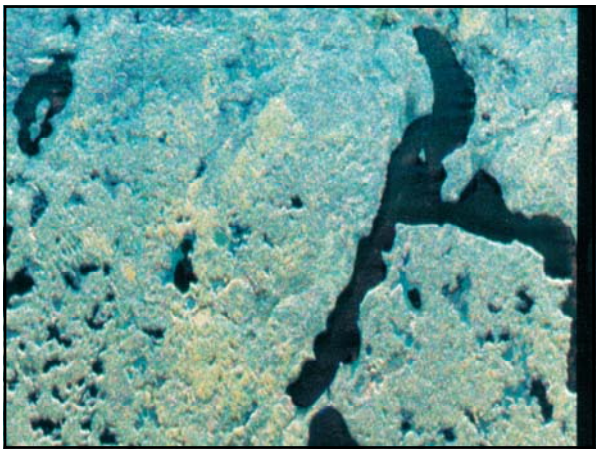

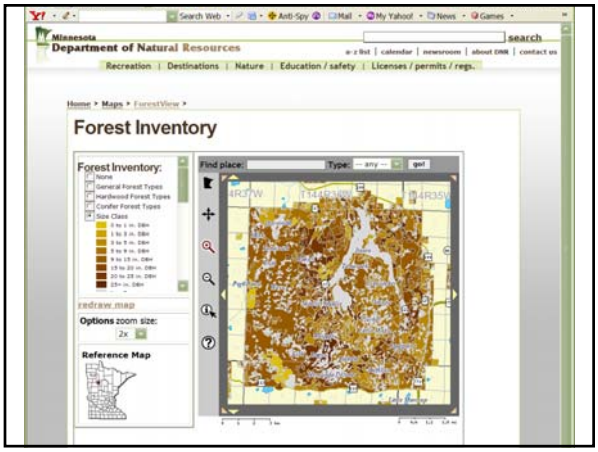
Minnesota
Department of Natural Resources
search
Recreation | Destinations | Nature | Education / safety | Licenses / permits / regs.
Home > Maps > ForestView >
Forest Inventory
Forest Inventory:
Find place:
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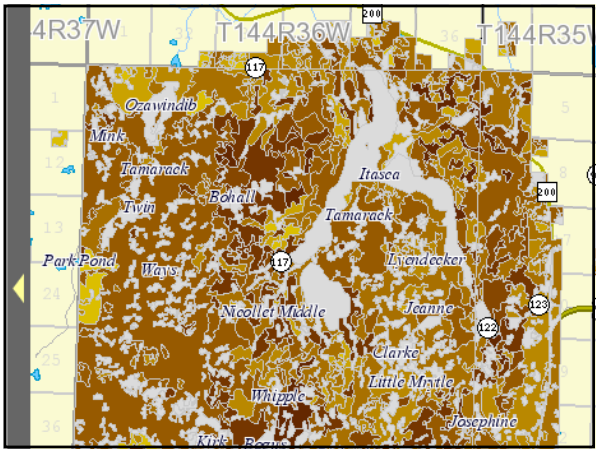
redraw map
Options zoom size:
Reference Map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T144R36W
T144R35W
200
117
Ozawindib
Mink
Tamarack
Bohall
Twin
Itasca
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Park Pond
Ways
Lyendecker
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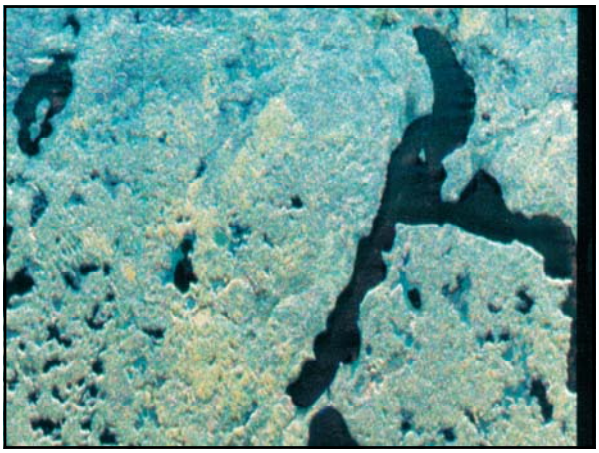
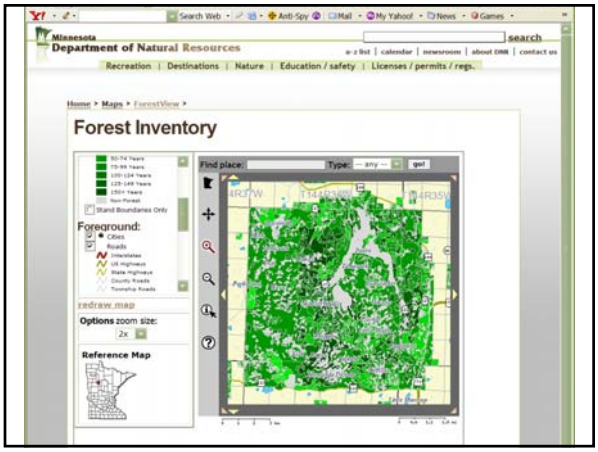
Jeanne
123
122
Clarke
Little Myrtle
Whipple
Josephine




Minnesota
Department of Natural Resources
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Type:
go!
Foreground:
redraw map
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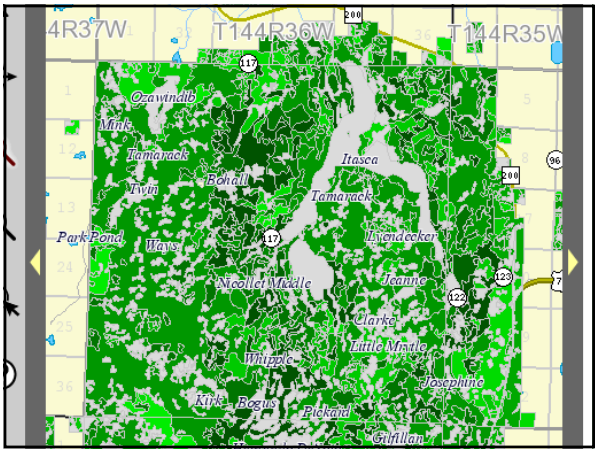
2x
Reference Map


4R37W
T144R36W
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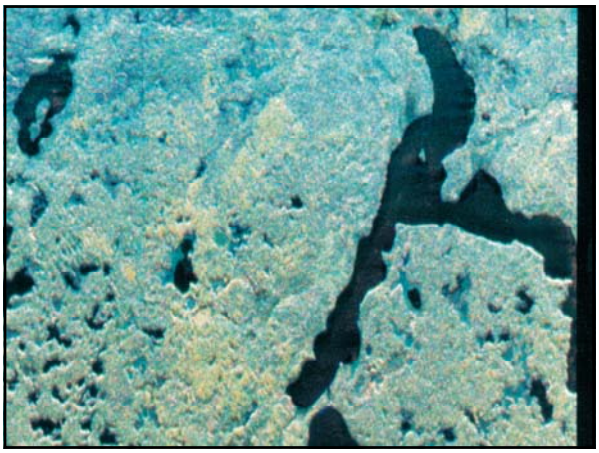
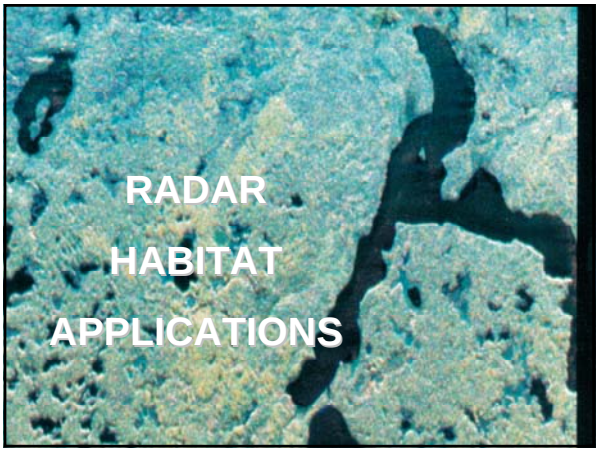
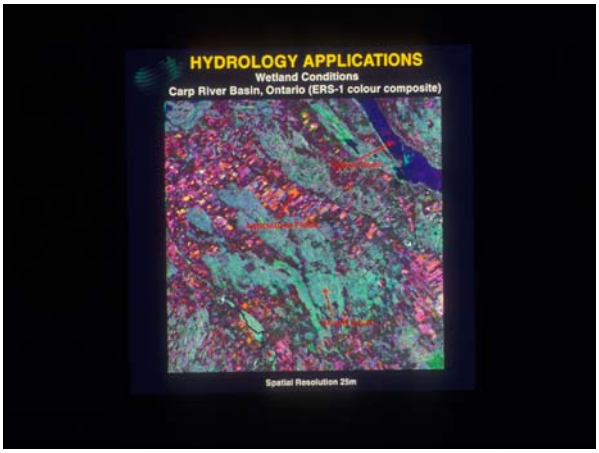
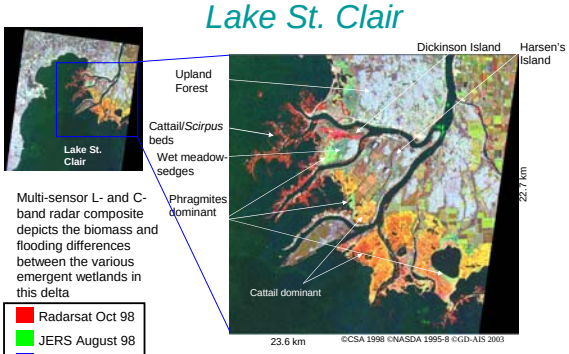
Lysendecker
Moeller Middle
Jeanne
Clarke
Little Moose
Whipple
Josephine
Kirk
Bogus
Pickard
Griffian




RADAR
HABITAT
APPLICATIONS


HYDROLOGY APPLICATIONS
Wetland Conditions
Carp River Basin, Ontario (ERS-1 colour composite)
Spatial Resolution 25m

SAR Multi-Sensor Composite of *Lake St. Clair*

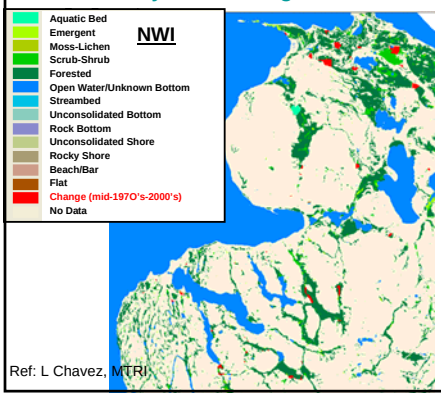


Multi-sensor L- and C-band radar composite depicts the biomass and flooding differences between the various emergent wetlands in this delta

- Radarsat Oct 98
- JERS August 98
- JERS March 95

Ref: L Chavez, MTRI

Wetland Hybrid Change Detection



2.6% overall change to 9 counties (UP, Mac and Leelenau)

wetland to upland
2546 hectares (ha)

upland to wetland
3 ha.

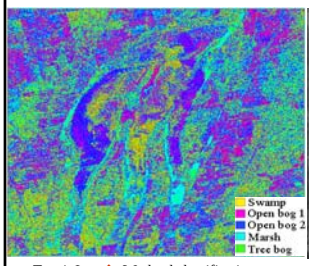
emergent to woody wetland
1304 ha

woody to emergent
7.2 ha

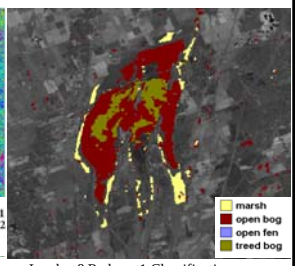
wetland to open water (including aquatic bed)
124 ha.

Ref: L Chavez, MTRI

RADARSAT-2 ↑ Better classification
➢than RADARSAT-1 & Landsat

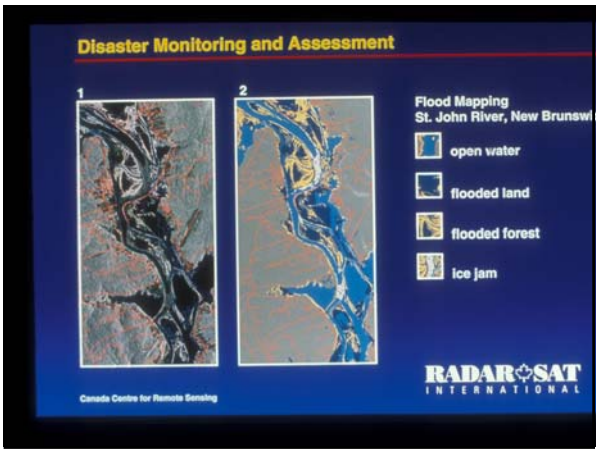


Touzi-Φαs ↑ Wetland classification
Obog 1 (carex), Obog 2(vaccinium)



Landsat&Radarsat1 Classification
(J. Li and W. Chen, IJRS, Vol.26, 2005)

ref: B. Brisco

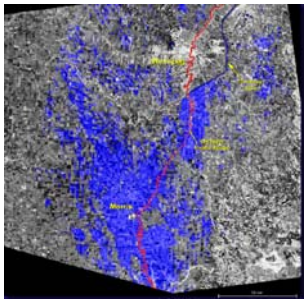


First Operational Flood Application in Canada
Red River, Manitoba

April 27, 1997 7:48 AM

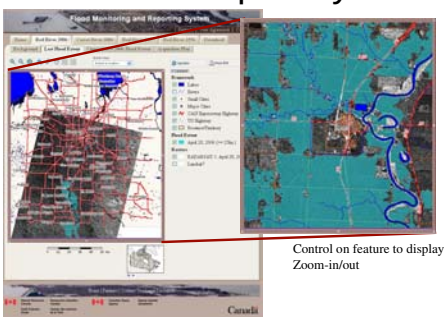
Standard 2

Descending Pass



ref: B. Brisco

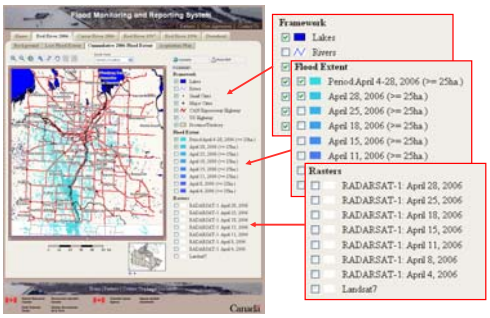
Real-Time MapServer Capability



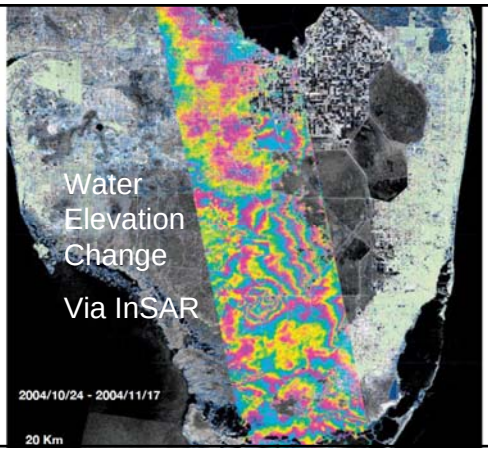
Control on feature to display
Zoom-in/out

ref: B. Brisco

Control on displayed information



ref: B. Brisco



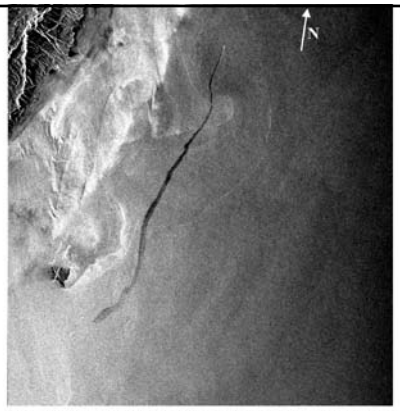
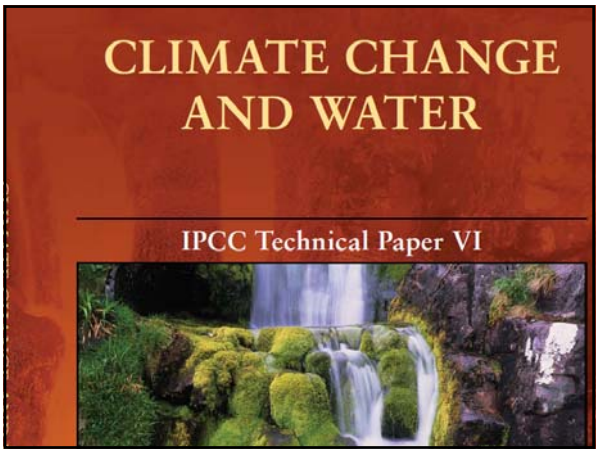
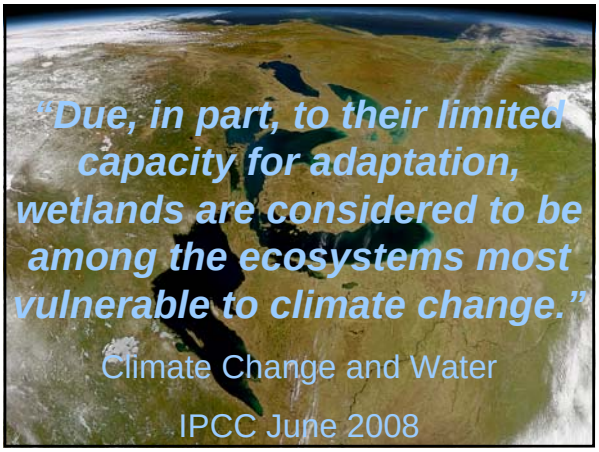


Figure. 11.1. A ship traveling northward (bright spot at the front of the black line) discharging oil. The oil disperses with time causing the oil trail to widen. The oil trail is more than 80 km long. This ERS-1 (C-band, VV) SAR image was acquired on 20 May 1994 at 1420 UTC over the Pacific Ocean, east of Taiwan (orbit 14874, frame 2364, frame center 24°0N/N, 121°41E). The imaged area is 100 km x 100 km. ©ESA 1994

Oil
Pollution


CLIMATE CHANGE
AND WATER
IPCC Technical Paper VI


"Due, in part, to their limited capacity for adaptation, wetlands are considered to be among the ecosystems most vulnerable to climate change."
Climate Change and Water
IPCC June 2008

ANY
QUESTIONS?

Brian_huberty@fws.gov
(612) 713-5332

Presentation Overview

Hybrid Multi-Sensor SAR-Optical Approach to Mapping and Monitoring Wetlands - Laura Bourgeau-Chavez, MTRI

EROS Training

and Education

Outline

- Why combine Optical-IR with Radar?
- Background on Project for developing Great Lakes Coastal Wetland Mapping and Monitoring Methods http://www.gis.org/wetlands/final-report.html
- Hybrid SAR-Optical Wetland Mapping Techniques
  - Mapping coastal wetlands of the Great Lakes
  - Mapping Canadian peatlands for assessing vulnerability of peatland types to wildfire
- Mapping and monitoring inundation with SAR intensity data (Great Lakes and South Florida)

Summarize-Recommendations of GLCWC throughout

Sensors: Optical/IR Capabilities for mapping wetlands

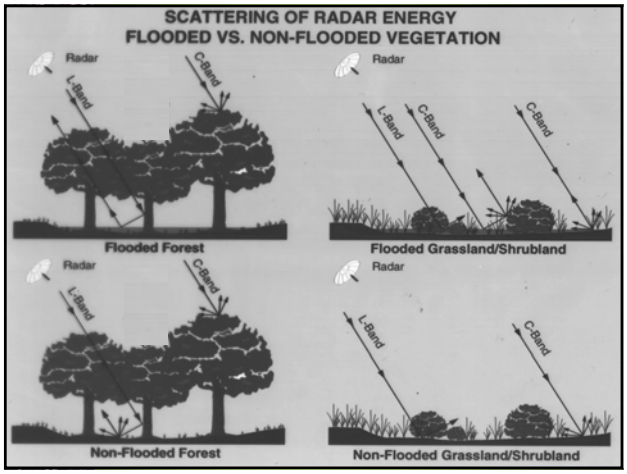
- Passive systems good for mapping covertypes and land use
- Measure spectral reflectance and emittance characteristics of vegetation
- Can be used to map flooding in open areas and wetness in open canopied vegetative cover, but not closed canopies

Sensors: *Radar*

- **Synthetic Aperture Radar (SAR) Complements Multi-Spectral Capabilities**
  - SAR is an active system that interacts differently with vegetative ecosystems based upon biomass, structure and moisture characteristics
  - Capable of detecting inundation in closed canopy and open canopy ecosystems
  - Useful for land cover and wetland classification

Satellite Sensors: *Radar*

- **C-band SARs** (5.7 cm wavelength), useful for detecting flooding beneath herbaceous canopies.
  - **Radarsat-I** Launched in 1995
  - **ERS-1** Launched in 1991
  - **ERS-2** Launched in 1995
  - **Radarsat-II** Launched in 2007
- **L-band SARs** (23 cm wavelength) useful for detecting forested wetlands and some high biomass herbaceous wetlands.
  - **JERS-1** Operational from 1992-98
  - ALOS **PALSAR**—launched Spring 2006 Successor Satellite
  - NASA **DESdynI** proposed Satellite—2015?



Great Lakes Project: Monitoring Indicators of Wetland Health

Great Lakes Coastal Wetlands Consortium (GLCWC) sponsored Pilot Projects to develop and demonstrate methods for wetland monitoring:

- *Methods needed to be*:
  - cost-effective
  - Robust
  - Implementable by resource managers

Evaluate Scientific Indicators of Wetland Health

- **Flora/Fauna**
  - Invertebrates
  - Fish
  - Amphibians
  - Birds
  - Plant community
  - Contaminants
- **Physical/ Chemical**
  - Water levels
  - Sediment
  - P and N
  - Other water Chemistry
- **Landscape**
  - Area by type
  - Restored area
  - Habitat adjacent
  - Land use adjacent
  - Human impact measures

Remotely Monitoring Landscape Scale Indicators of Heath

Project Goals and Criteria

- Develop robust remote sensing techniques for potential **operational** use to evaluate landscape indicators
- **Minimize cost** but maximize effectiveness
- to detect areas as small as **2 hectares (5 acres)** in the Great Lakes Basin

- ***Solution*:** medium resolution (~30 m) sensors (minimal mapping unit smaller than 1 ha)

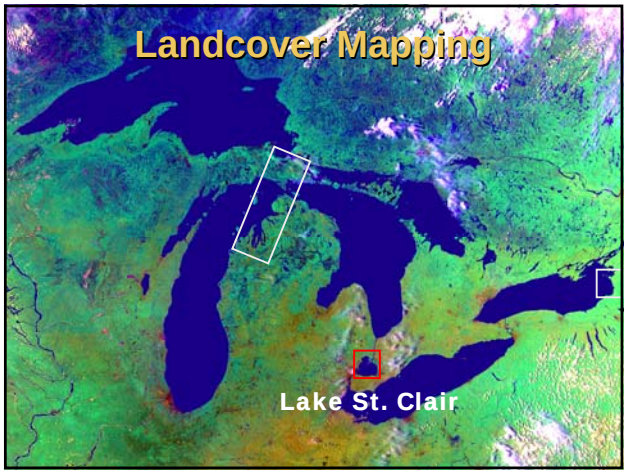
Remotely Monitoring Great Lakes Coastal Wetlands

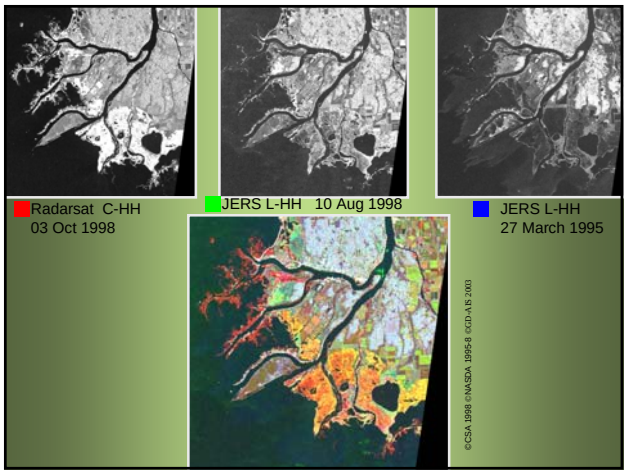
- ***Approach*** Combine satellite imaging radar data from multiple sensors with classical Landsat data to:
  1. Develop techniques to map wetlands and other coastal land cover/land use with minimal *in situ* data (Landsat-SAR fusion)
  2. Monitor extent of inundation in wetlands (SAR)
  3. Demonstrate a robust cost-effective method to monitor change (existing maps and Landsat)

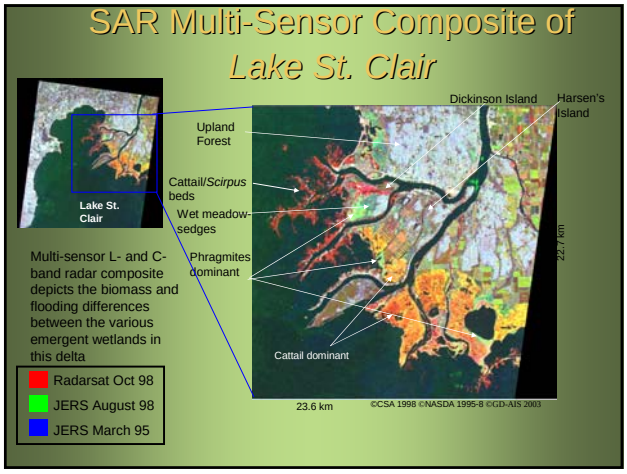
I will be presenting on approaches 1 and 2

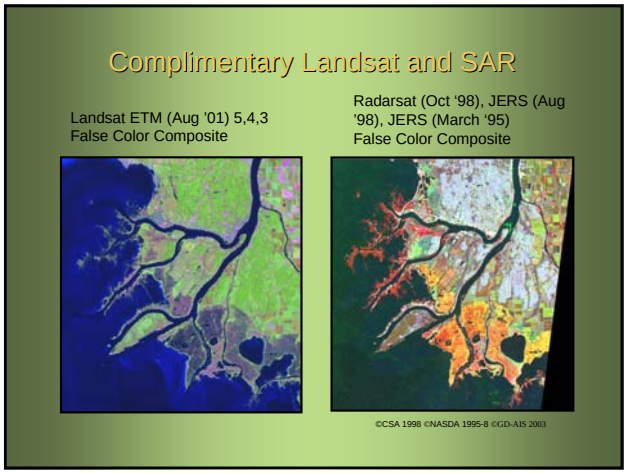
Remotely Monitoring Great Lakes Coastal Wetlands

- Techniques demonstrated are with 30 m resolution imagery but can be applied to any resolution Optical or SAR imagery, fine to coarse, satellite or airborne sensors
- Repeat nature of the orbiting satellites allow a synoptic view of the landscape from the same view angle, same altitude, and on a routine basis, allowing multiple seasons of data to be analyzed which benefits monitoring




Radarsat C-HH
03 Oct 1998
JERS L-HH 10 Aug 1998
JERS L-HH
27 March 1995
©CSA 1998 ©NASDA 1995-8 ©GD-AIS 2003

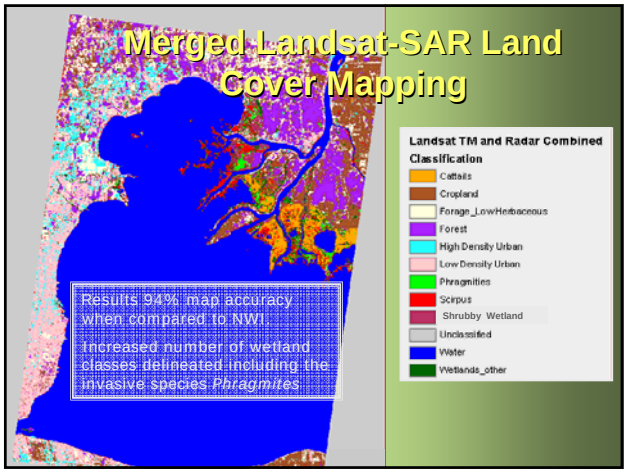

SAR Multi-Sensor Composite of
Lake St. Clair
Lake St. Clair
Multi-sensor L- and C-band radar composite depicts the biomass and flooding differences between the various emergent wetlands in this delta
Radarsat Oct 98
JERS August 98
JERS March 95
Upland Forest
Cattail/Scirpus beds
Wet meadow-sedges
Phragmites dominant
Cattail dominant
Dickinson Island
Harsen's Island
22.7 km
23.6 km
©CSA 1998 ©NASDA 1995-8 ©GD-AIS 2003


Complimentary Landsat and SAR
Landsat ETM (Aug '01) 5,4,3
False Color Composite
Radarsat (Oct '98), JERS (Aug '98), JERS (March '95)
False Color Composite
©CSA 1998 ©NASDA 1995-8 ©GD-AIS 2003

Merged Landsat-SAR Land Cover Mapping

- Methods
  - –Performed separate maximum likelihood classifications on the Landsat and then SAR imagery using multi-date radiometrically calibrated data. This resulted in some overlap of categories but also some unique categories for each individual classification.
  - –Fused resulting categories
    - *Lake St. Clair* Example
      1. Water defined by Landsat alone
      2. *Scirpus* and *Phragmites* were defined by SAR but used Landsat wetland classes for reinforcement
      3. Urban was defined by areas classed as urban in Landsat and urban/forest in SAR.

Merged Landsat-SAR Land Cover Mapping

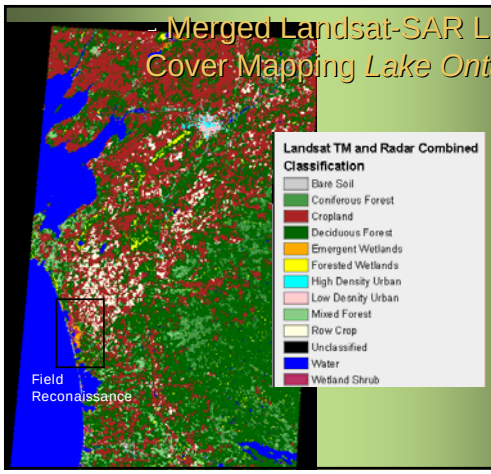


Results 94% map accuracy when compared to NWI

Increased number of wetland classes delineated including the invasive species *Phragmites*

Land Cover Mapping

Merged Landsat-SAR Land Cover Mapping *Lake Ontario*



- National Wetlands Inventory (NWI) 94% overall accuracy
- 89% overall accuracy when compared to Biocomplexity Study

Land Cover Mapping Summary

- Using a combination of SAR and Optical-IR data in wetland mapping and monitoring:
  - Takes advantage of the unique qualities of each sensor
  - Allows a larger range of capabilities
  - Reduces the amount of *in situ* data required when mapping wetlands by creating checks of one dataset against the other (does not eliminate the need)

Recommendation of GLCWC for Landscape Monitoring Protocol:

Use multi-sensor data for wetland mapping, include traditional Optical-IR combined with new technologies such as SAR, Lidar or Thermal data which improve mapping capability

Canadian Peatland Mapping

Application of Hybrid SAR-Optical Wetland Mapping Approach to Alberta Peatlands using Object-based Classification

Canadian Peatland Mapping

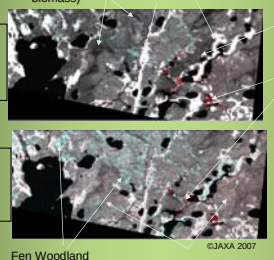
- Input Data: April and August Landsat TM bands 1-5, 7 and 2 dates of PALSAR L-HH, L-HV and 2 dates of Radarsat-I C-HH
- Technique: Object-based classification in Definiens using decision rules and nearest neighbor

Generally bogs and fens are difficult to distinguish from each other, however using multi-date, multi-band SAR allows for distinction in moisture and levels of biomass in these two wetland types

Canadian Peatland Mapping with Hybrid SAR-Optical/IR

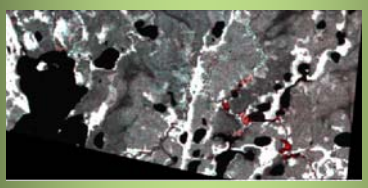
2 Date PALSAR L-HV
July 2007
August 2007

2 Date PALSAR L-HH
July 2007
August 2007



- Using multi-date PALSAR data allows for distinction of fens from bogs due to sensing of variations in soil moisture/water levels

Landsat 5 TM
August 2001
Bands 5,4,3



PALSAR
July-Aug 2007
L-HV

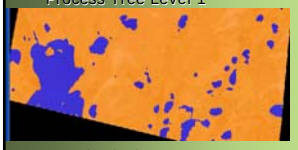
Definiens Segmentation and Classification

Process Tree (thresholds & nearest neighbor classifiers)

Created segmentation of imagery using Landsat and SAR, segments represent areas of similar spectral response in the input imagery

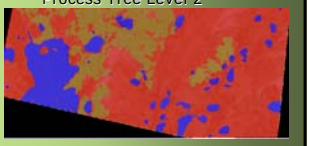
- Classify Water using TM band 5 and Palsar L-HH thresholds
- Everything not classified as water was – Land
  - Land divided into Burn and Non-Burn using nearest neighbor classification of burn/non
    - Non-Burn divided into Upland and Wetland
      - Classify Upland Forest using PALSAR L-HH and use TM band 3 from August
        - Wetland classified Open Fen using L-HV and Landsat
        - NN for Bog, Wooded Fen, Swamp using April TM 4,5,3 and PALSAR HH, and Radarsat

Process Tree Level 1



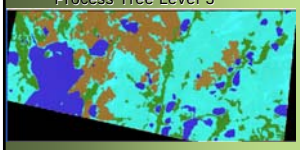
Orange= land, Blue = water

Process Tree Level 2

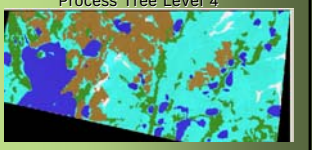


Brown = burn, Red = unburn, blue = water

Process Tree Level 3

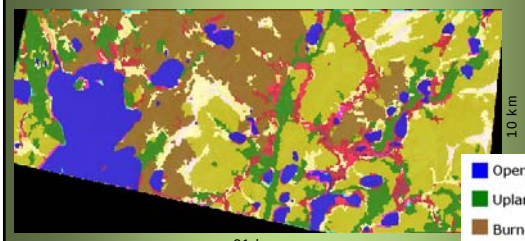


Process Tree Level 4



Brown = burn, Green = upland, Cyan = wetland, blue = water , white = open fen

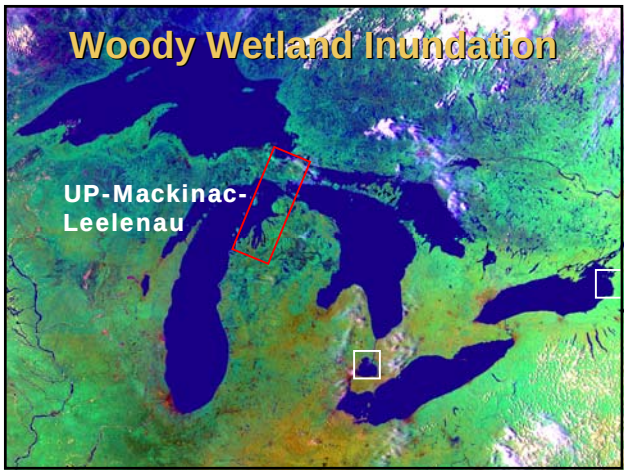
Alberta Peatland Mapping

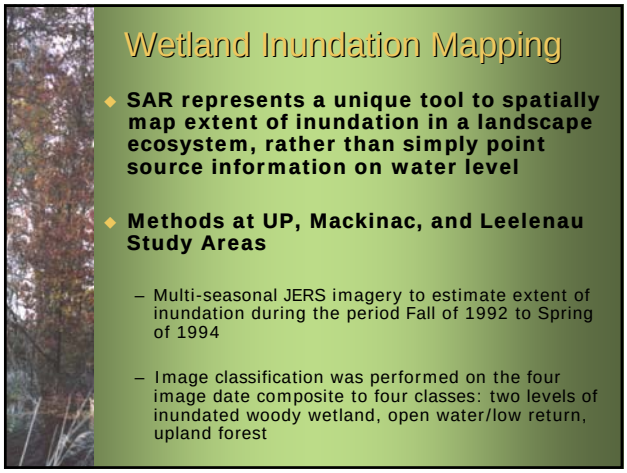


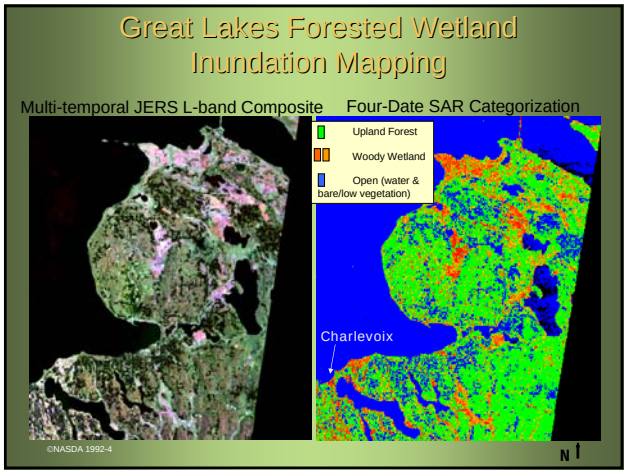
- Open Water
- Upland
- Burned Land
- Bog
- Open Fen
- Open Swamp
- Fen Woodland

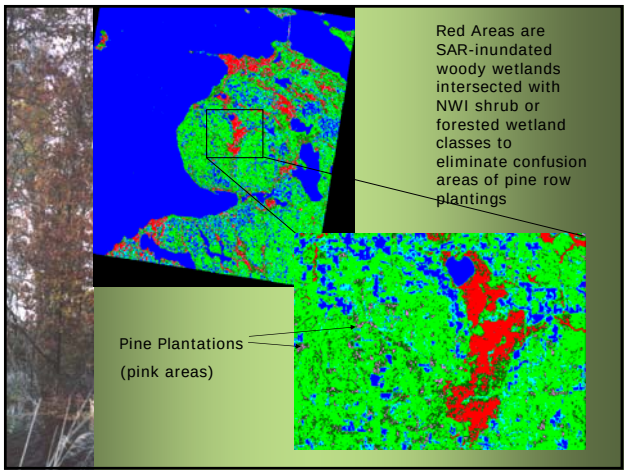
80% overall accuracy when compared to "truth" map created from 1980s air photos and field surveys in 1990s.

Bog: 91% producers accuracy (PA) 77 % Users accuracy (UA): Fen 60% PA and UA

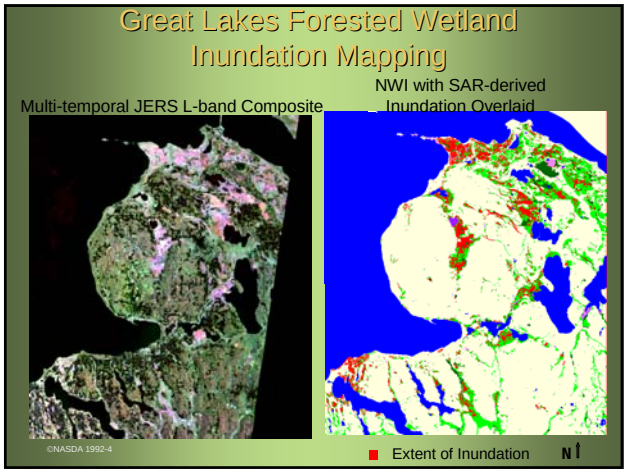

Woody Wetland Inundation
UP-Mackinac-
Leelenau


Wetland Inundation Mapping
SAR represents a unique tool to spatially map extent of inundation in a landscape ecosystem, rather than simply point source information on water level
Methods at UP, Mackinac, and Leelenau Study Areas
– Multi-seasonal JERS imagery to estimate extent of inundation during the period Fall of 1992 to Spring of 1994
– Image classification was performed on the four image date composite to four classes: two levels of inundated woody wetland, open water/low return, upland forest


Great Lakes Forested Wetland Inundation Mapping
Multi-temporal JERS L-band Composite
Four-Date SAR Categorization
Upland Forest
Woody Wetland
Open (water & bare/low vegetation)
Charlevoix
©NASDA 1992-4
N

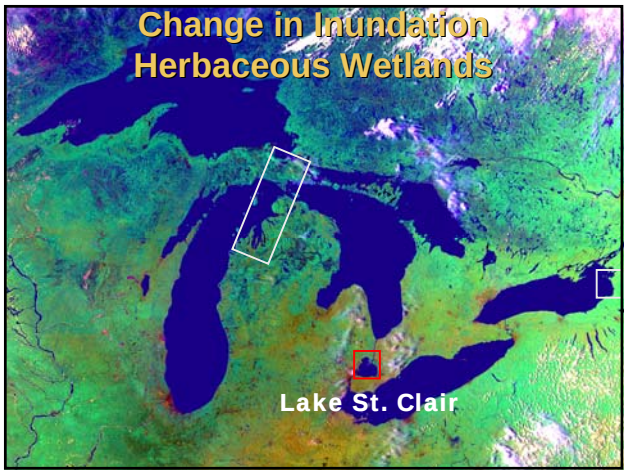


Great Lakes Forested Wetland Inundation Mapping



Great Lakes Forested Wetland Inundation Mapping

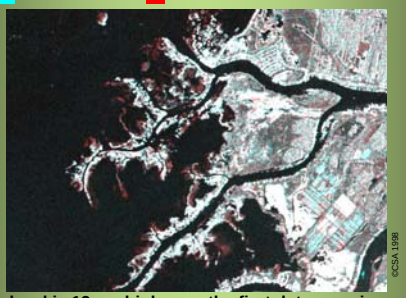
- Data were collected in early 1990s so field truth was not possible
- However,lake levels and rainfall data show that the time period of our imagery represent “normal” conditions. While a single date of imagery would not necessarily capture the “normal” conditions of these years, a time series of imagery from spring, summer and fall do a better job
- These maps can serve as a baseline for future SAR-derived maps



Herbaceous Wetland Change in Inundation

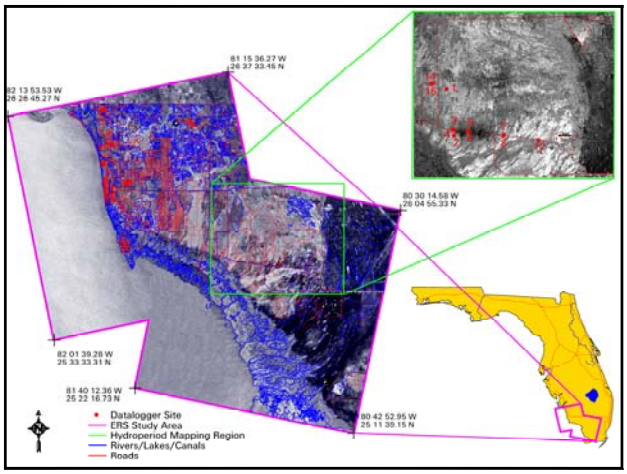
Two date false color composite of Radarsat Imagery *Lake St. Clair*

3 October 1998 27 October 1998

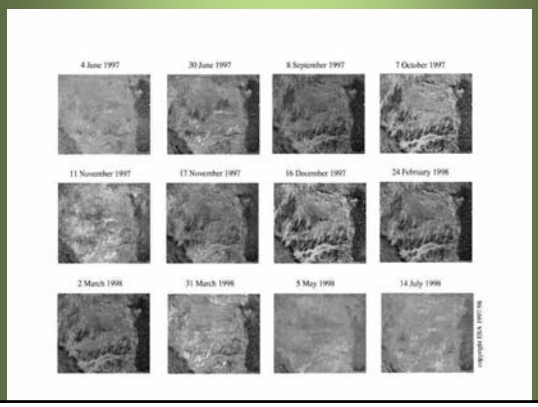


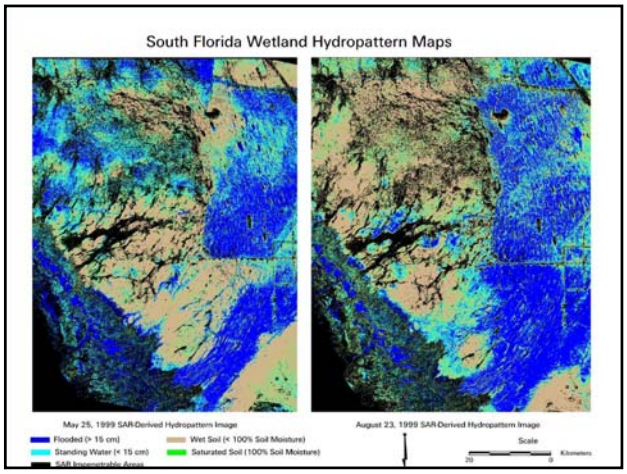
Water level is 19 cm higher on the first date, causing specular reflection (low return-dark). A decrease in inundation on the second date reveals the vegetation causing double bounce scattering (bright return-red).

South Florida Wetland Water Level Monitoring



Time-Series of ERS Images over Big Cypress-Everglades

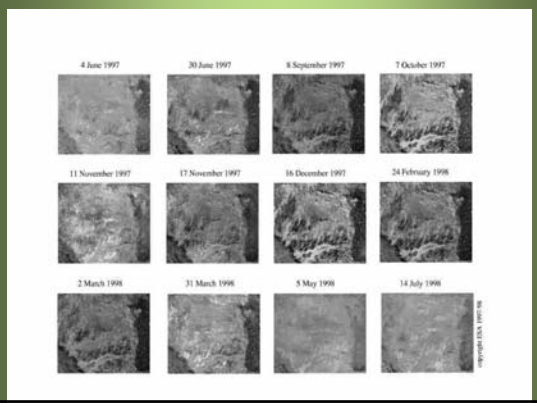


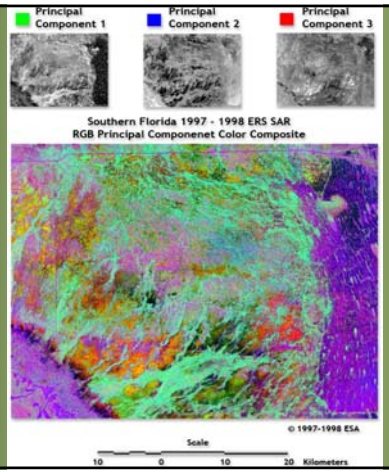


Florida Water Level Mapping

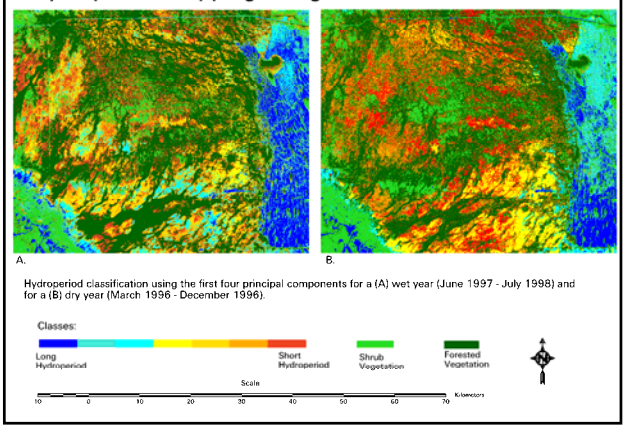
- Created 17 inundation maps, with 70% overall accuracy
- Dry areas can have same backscatter as highly inundated vegetation (phase information will help resolve this issue)
- South Florida Water Management District Hydrologists have had high interest in these maps for the spatial information on extent of inundation
- Differences in biomass also create problems in mapping inundation across a landscape with a single channel SAR
  - —time series analysis allows one to observe changes to a particular location on the landscape over time rather than comparing that location to surrounding areas that have different biomass

Time-Series of ERS Images over Big Cypress-Everglades





Hydroperiod Mapping Using PCA in South Florida



Hydroperiod classification using the first four principal components for a (A) wet year (June 1997 - July 1998) and for a (B) dry year (March 1996 - December 1996).

Inundation Mapping Summary

- Using SAR for mapping extent of inundation
  - Provides a tool for monitoring spatial changes in extent and levels of inundation across a landscape
  - Provides a cost-effective method for monitoring hydrologic change

  GLCWC Recommendation:
  SAR be used in combination with *in situ* data to map inundation patterns and monitor change

- The addition of polarimetric phase information will further improve the water level monitoring capabilities, as well as interferometric analyses

Questions?

Presentation Overview

Overview of Lidar and Its Applications - Dean Gesch, USGS

EROS Training

and Education

Lidar and Its Applications

Dean Gesch (gesch@usgs.gov) & Jason Stoker (jstoker@usgs.gov)
USGS/EROS

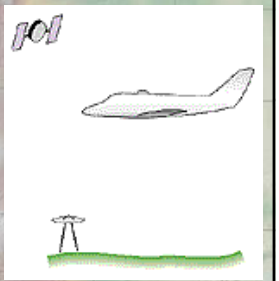
SAR and Water Resources Applications Workshop
September 9-11, 2008

Lidar

- **Light Detection and Ranging**
  - **Laser altimetry**
  - **ALTM (Airborne laser terrain mapping)**
  - **Airborne laser scanning**

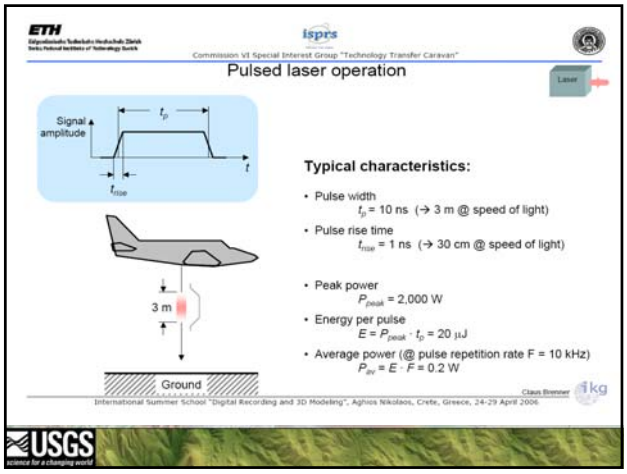
Lidar

- Laser
- IMU (INS)
- GPS
- Scanning Mirror
- On board computer

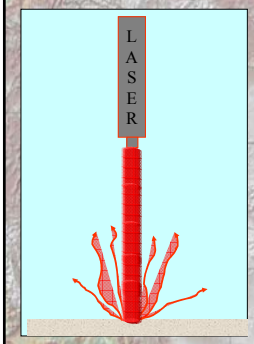


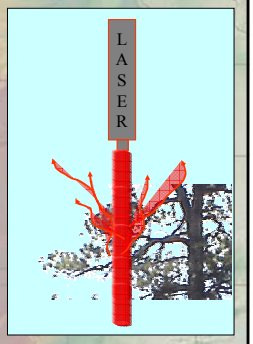
Laser

- Pulse laser
- Records distance to target
  - Time * c / 2
- Laser wavelengths can differ
  - 1064 nm
- 100-150 kHz systems available today



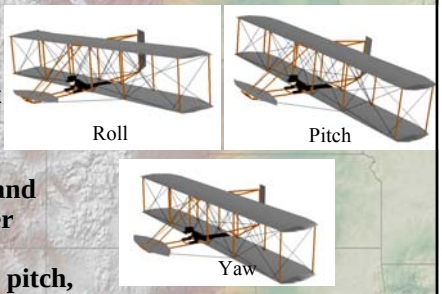
Lidar Laser





IMU

- Inertial Measurement Unit
- Gyroscopes and accelerometer
- Records roll, pitch, yaw of aircraft

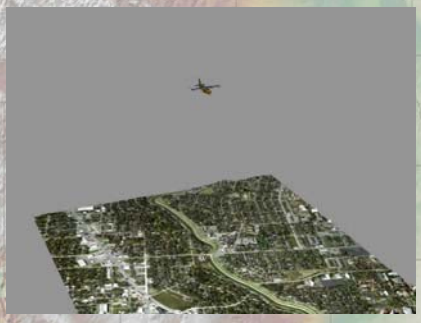


Courtesy of NASA

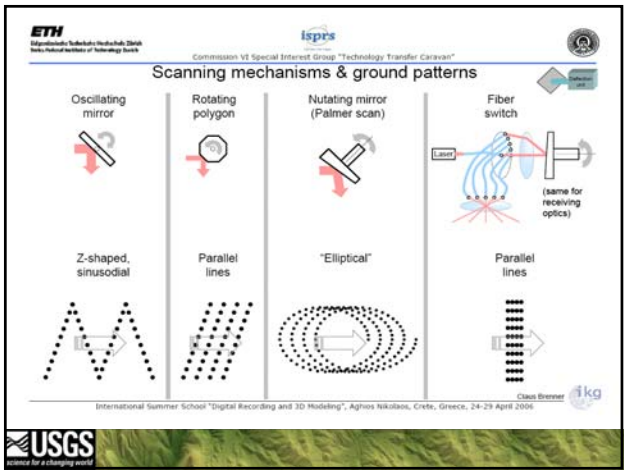
GPS

- Global positioning system
- Differentially corrected
- Provides cm accuracy of aircraft position
- Allows cm accuracy of laser pulse

Scanning Lidar



Courtesy of Dodson & Associates



On-board Computer

- Records data
  - Photon detector (intensity)
  - Laser timing
  - IMU info
  - GPS info
  - Mirror scan angle
- Converts into XYZ
  - Millions of points
- On-board display

USGS science for a changing world

LIDAR Equation

$$\vec{X}_G = \vec{X}_o + R_{\omega,\phi,\kappa}\, R_{\Delta\omega,\Delta\phi,\Delta\kappa}\, \vec{P}_G + R_{\omega,\phi,\kappa}\, R_{\Delta\omega,\Delta\phi,\Delta\kappa}\, R_{\alpha,\beta} \begin{bmatrix} 0 \\ 0 \\ -\rho \end{bmatrix}$$

$\vec{X}_G$ ground coordinates of object point under consideration

$\vec{X}_o$ ground coordinates of GPS antenna phase center

$\vec{P}_G$ offset between laser unit and phase center w.r.t. the laser unit coordinate system

$R_{\omega,\phi,\kappa}$ rotation matrix that needs to be applied to the ground coordinate system until it is parallel to the IMU coordinate system

$R_{\Delta\omega,\Delta\phi,\Delta\kappa}$ rotation matrix that needs to be applied to the IMU coordinate system until it is parallel to the laser unit coordinate system

$R_{\alpha,\beta}$ rotation matrix that needs to be applied to the laser unit coordinate system until it is parallel to the laser beam coordinate system

DPRG Digital Photogrammetry Research Group — Ayman Habib

Error Sources

- Bore-sighting offset error (P_G)
- Bore-sighting angular error ($\Delta\omega$, $\Delta\varphi$, and $\Delta\kappa$)
- Laser range error (ρ)
- Laser beam angular error (α, β)
- Laser range noise (ρ)
- GPS noise (X_o)
- IMU noise (ω, φ, and κ)
- Laser beam angular noise (α, β)

DPRG Digital Photogrammetry Research Group

Ayman Habib

Error Budget

- Detector Bias and gain
  - Diff b/w electronical and mechanical sensor origin
  - Fluctuations in pulse caused by atmosphere
  - Variance caused by SNR, variance of pulse length and variance of sampling frequency
- Pointing Jitter
  - Horizontal position dependent on stability of mirror (tan of terrain slope- high relief, higher error)
- INS (IMU) errors
  - Misalignment and time-dependent gyro-drift

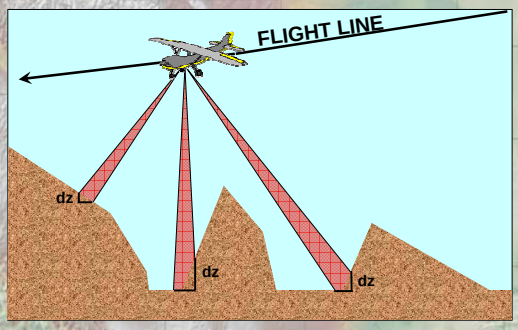
USGS science for a changing world

Error Budget (cont.)

- GPS Errors
  - Orbit Errors
  - Ionospheric and tropospheric delays,
  - Phase ambiguities
  - Multipath returns
- Atmospheric influences
  - Propagation delays
  - Defraction, absorption and scattering
  - Dependent on flying height, moisture

USGS science for a changing world

Slope and flight line effects:



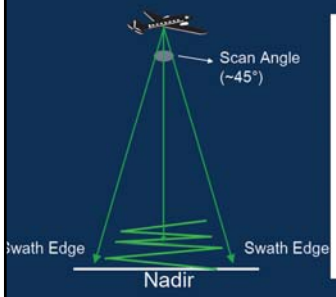
USGS

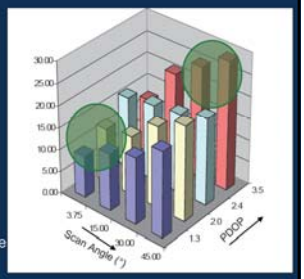
Error Budget (cont.)

- Reflectivity of target
  - Influences SNR and consequently point precision
- GPS and INS integration
  - When use the same clock, errors are minimal
  - When don't, asychronation in the clocks cause positioning errors in the order of the velocity of the aircraft time the sync error

USGS

Effect of GPS and Scan Angle on vertical accuracy



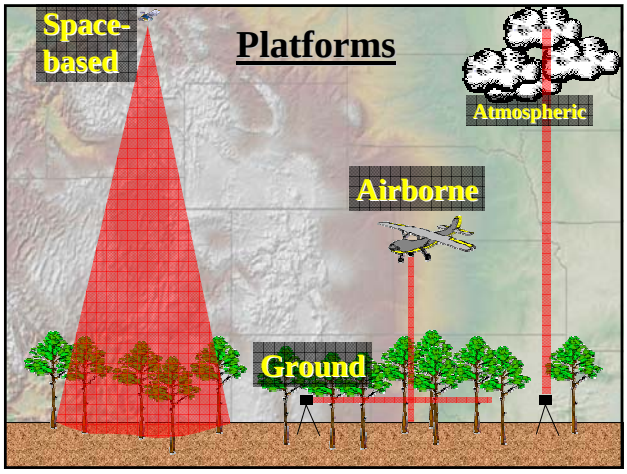


USGS

Courtesy of Amar Nayegandhi

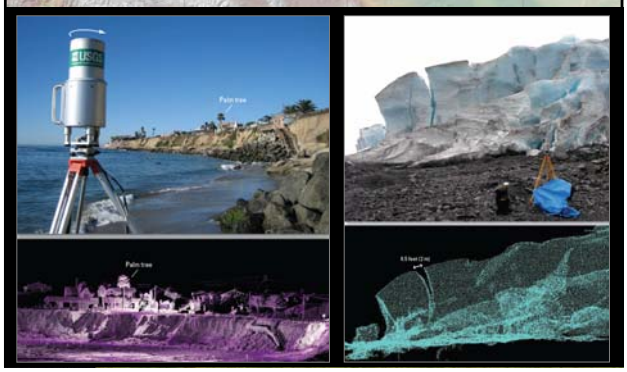
Lidar Differences

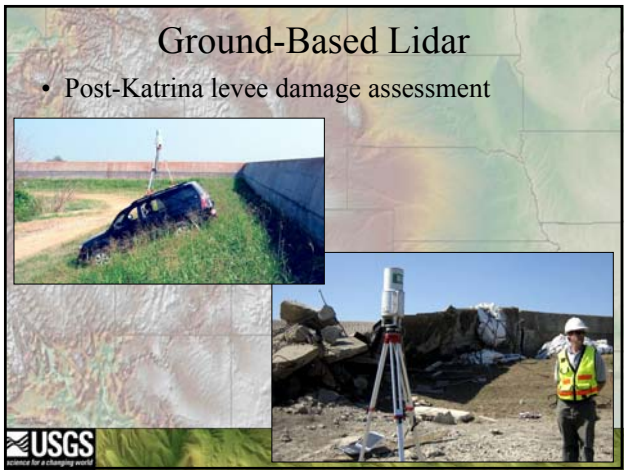
- Platform type
- Profile or scanning
- Single, multiple, or waveform returns
- Footprint Size
- Posting density
- Atmospheric / terrestrial / bathymetric

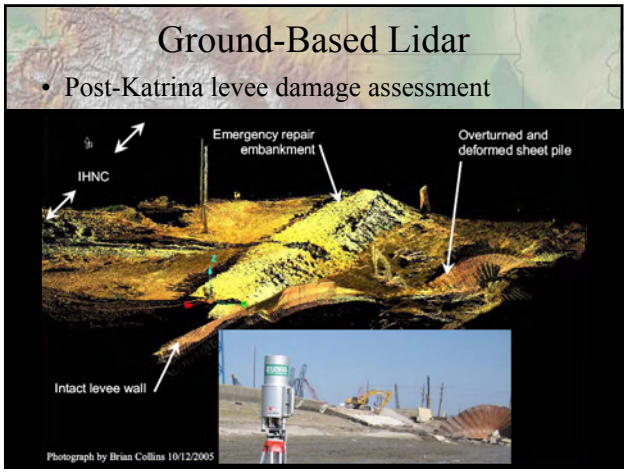


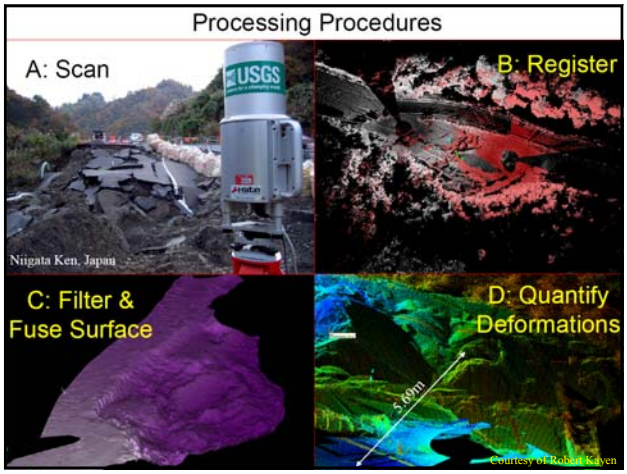
Ground-Based Lidar

- An active research area for the USGS

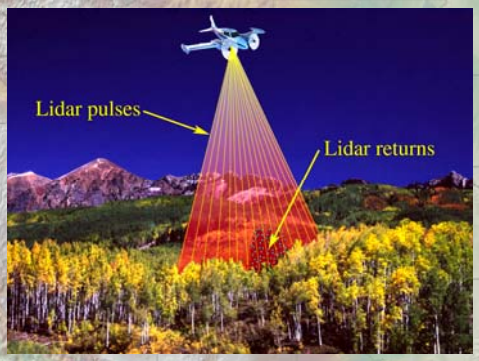



Ground-Based Lidar
• Post-Katrina levee damage assessment
USGS

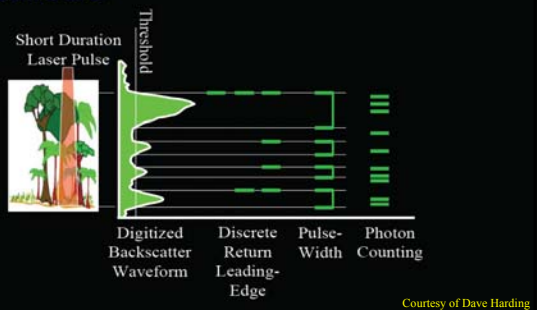

Ground-Based Lidar
• Post-Katrina levee damage assessment
IHNC
Emergency repair embankment
Overturned and deformed sheet pile
Intact levee wall
Photograph by Brian Collins 10/12/2005


Processing Procedures
A: Scan
B: Register
Niigata Ken, Japan
C: Filter & Fuse Surface
D: Quantify Deformations
5.69m
Courtesy of Robert Kayen

Pulses vs. Returns



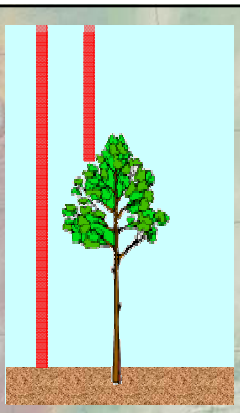
Different Laser Ranging Methods

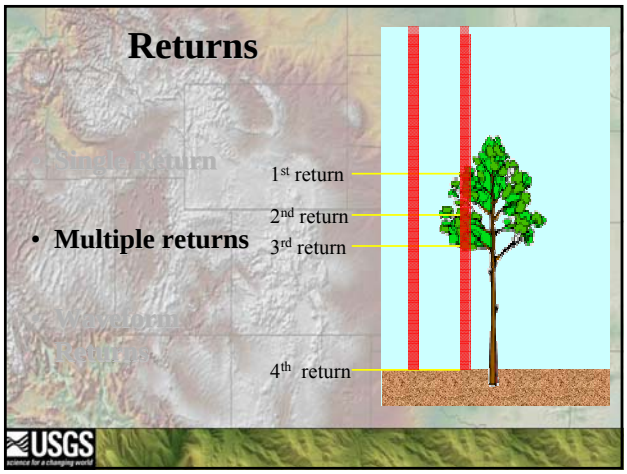


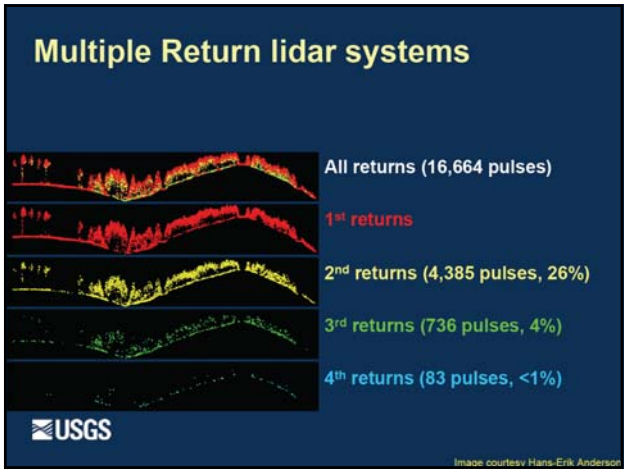
Courtesy of Dave Harding

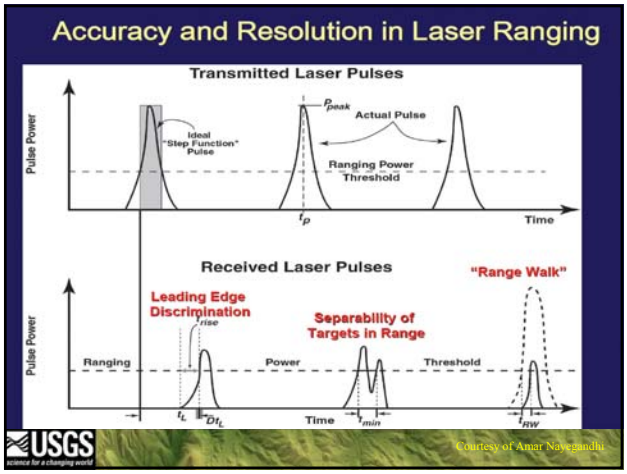
Returns

- **Single Return**
- **Multiple Returns**
- **Waveform Recording**




Returns
Single Return
• Multiple returns
Waveform
1st return
2nd return
3rd return
4th return
USGS


Multiple Return lidar systems
All returns (16,664 pulses)
1st returns
2nd returns (4,385 pulses, 26%)
3rd returns (736 pulses, 4%)
4th returns (83 pulses, <1%)
USGS
Image courtesy Hans-Erik Anderson

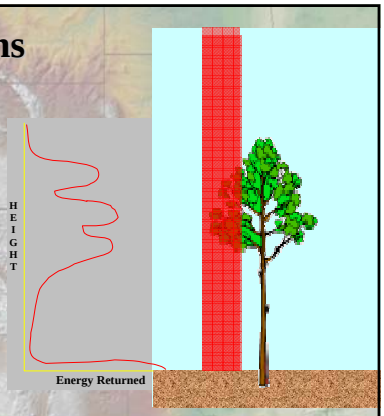

Accuracy and Resolution in Laser Ranging
Transmitted Laser Pulses
Pulse Power
Ideal "Step Function" Pulse
Actual Pulse
Ranging Power Threshold
Time
Received Laser Pulses
"Range Walk"
Leading Edge Discrimination
Separability of Targets in Range
Ranging
Power
Threshold
Time
USGS
Courtesy of Amar Nayegandhi

Intensity

- Intensity = amount of energy reflected for each return
- Different surfaces reflect differently
- Hard to quantify DNs

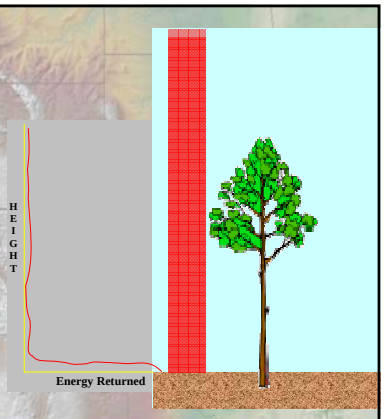
Returns

- Single Return
- Multiple Returns
- Waveform Returns



Returns

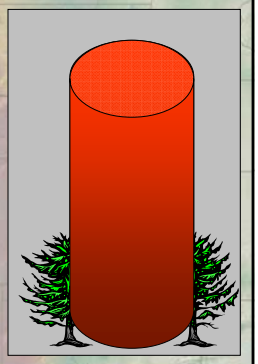
- Single Return
- Multiple Returns
- Waveform Returns



Footprints

Different types of systems:

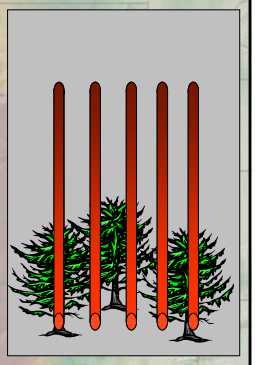
- **Large footprint**



Footprints

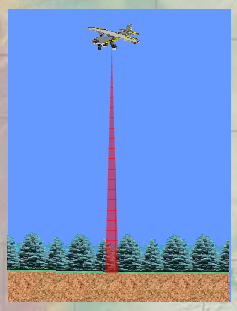
Different types of systems:

- **Large footprint**
- **Small footprint**



Beam Divergence

- Light tends to spread out
- Laser is coherent light, but spreads too
- Beam divergence
- Measured in mrads
- Higher up, the larger the footprint will be



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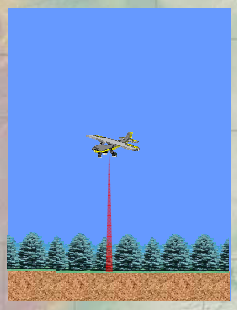


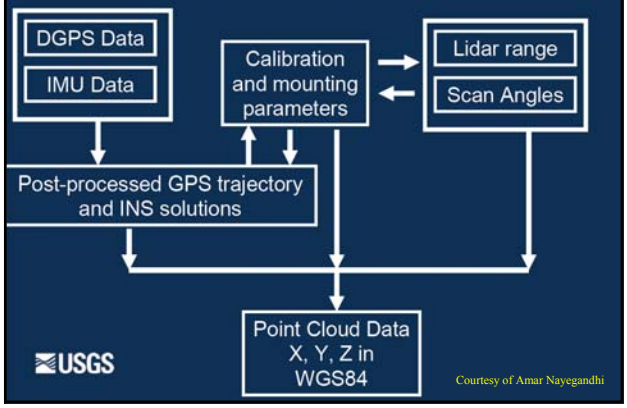
USGS

Posting Density

- **Returns called "postings"**
- **Function of:**
  - **Laser pulse rate**
    - **Hz or kHz**
  - **Flying ht/speed**
  - **Scan angle**
  - **Not regular interval**

USGS

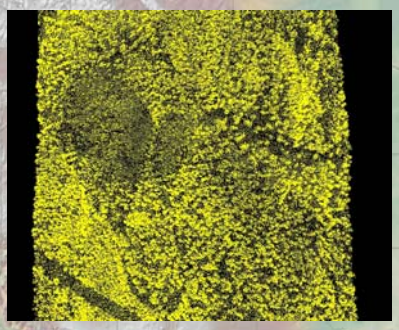
Lidar Data Processing

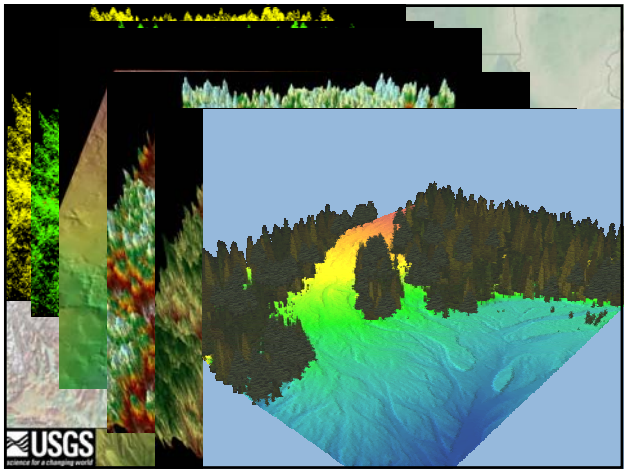


USGS

Courtesy of Amar Nayegandhi

Raw lidar returns





Introduction

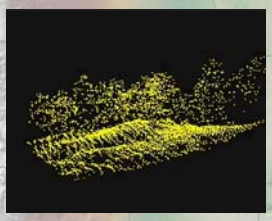
Most commercial systems today are:

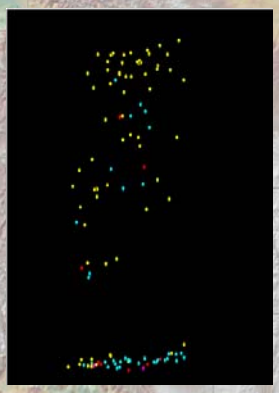
- **Small footprint**
- **Multiple return**
- **Collecting imagery simultaneously**

- **Large footprint continuous waveform operated by NASA**
  - **Some systems sample in the waveform**

Current Lidar Representations of 3D data

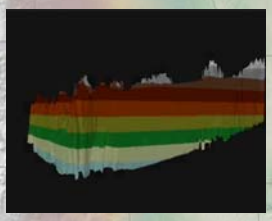
- **Point Cloud**
- Triangulated Irregular Network (TIN)
- Voxel



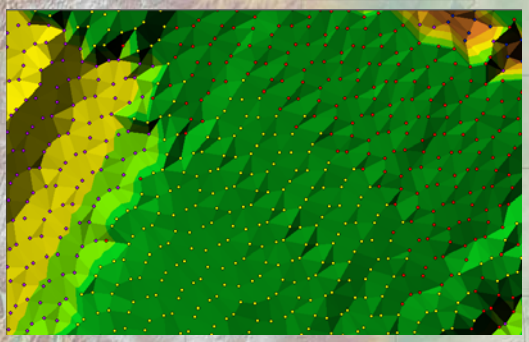


Current Lidar Representations of 3D data

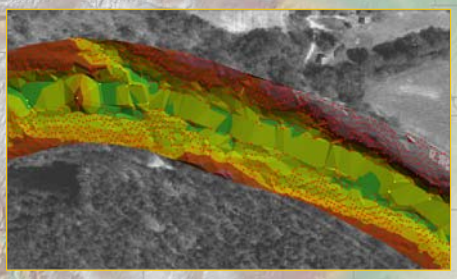
- Point Cloud
- Triangulated Irregular Network (TIN)
- Grid



Converting Points to TIN

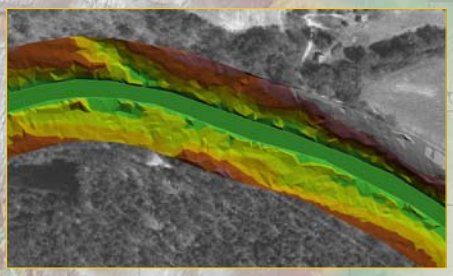


TIN Without Breaklines Not Hydro-Enforced



Courtesy of Dave Maune

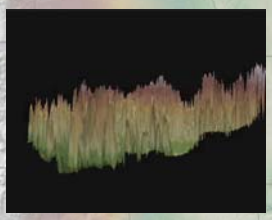
TIN With Breaklines–Hydro-Enforced



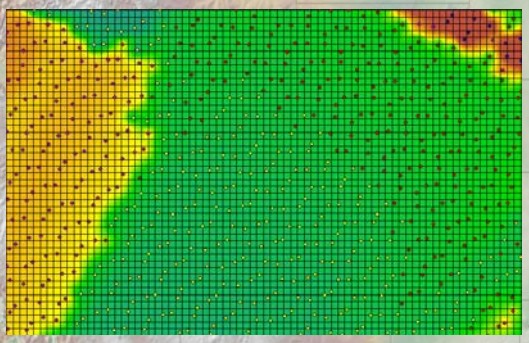
Courtesy of Dave Maune

Current Lidar Representations of 3D data

- Point Cloud
- Triangulated Irregular Network (TIN)
- Raster (Grid)

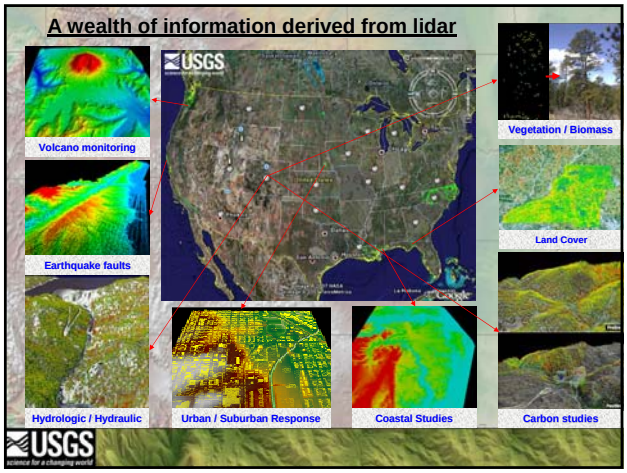


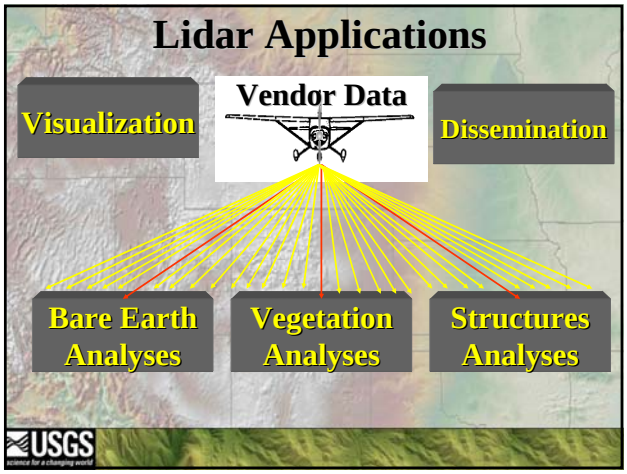
Interpolating a Raster- IDW



Research and Applications

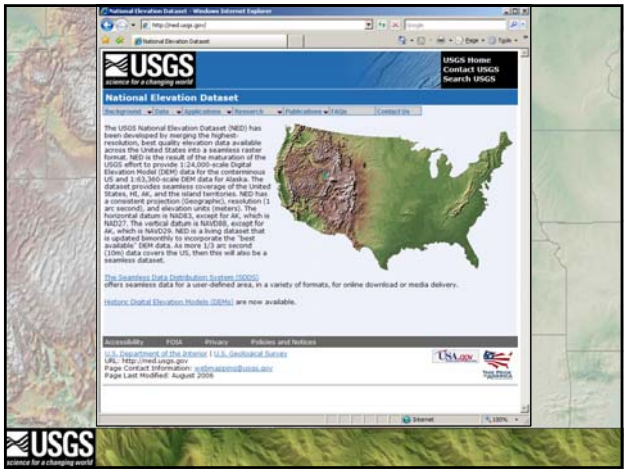
USGS

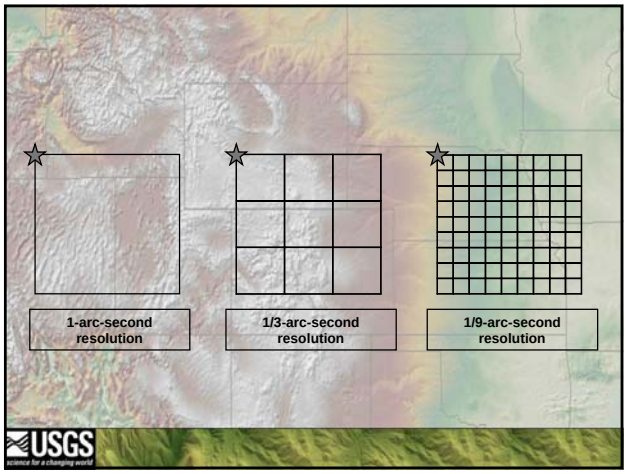


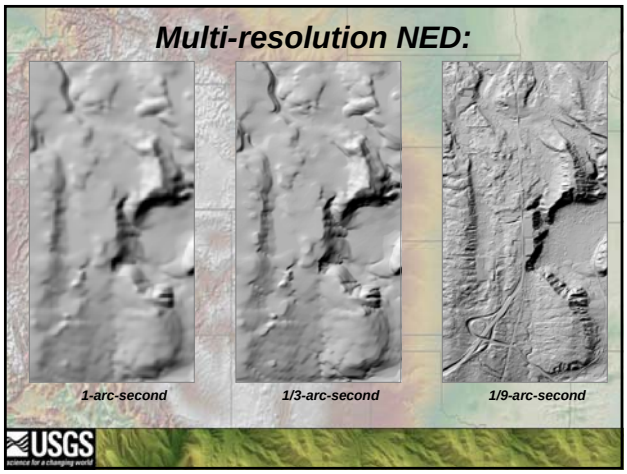


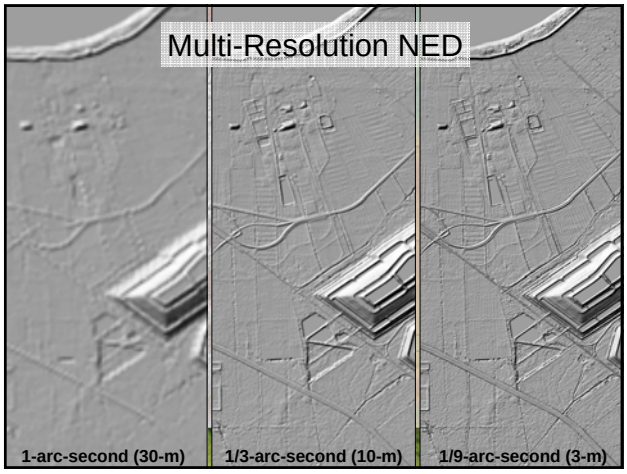
Bare Earth Analysis

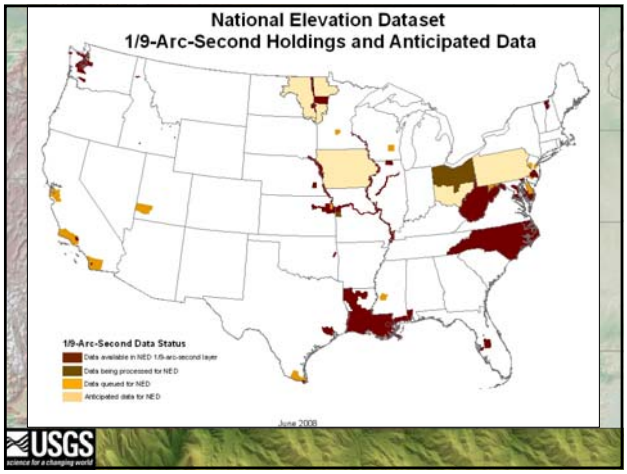
- Primary focus of commercial sector
  - $$$$$
- Technology is become widely accepted
- More cost effective / accurate than photogrammetry

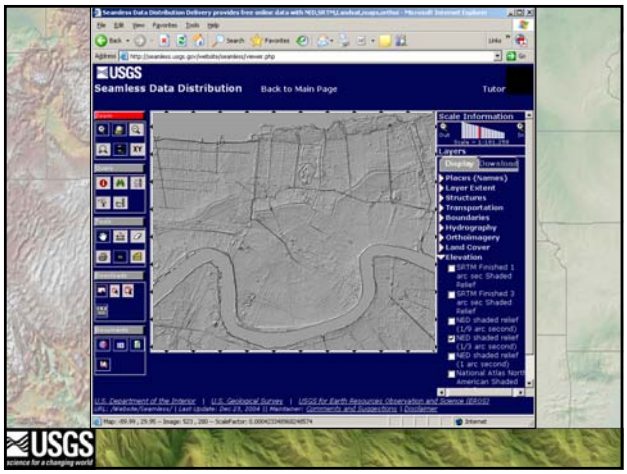


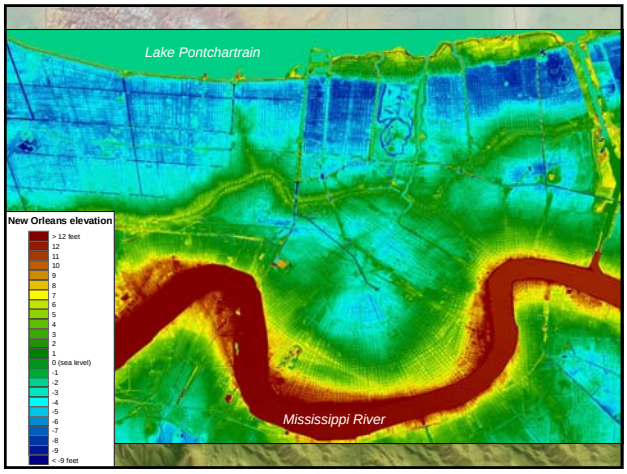


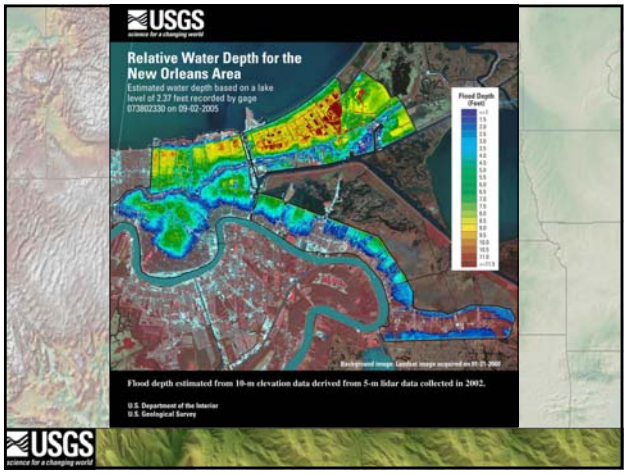

Multi-resolution NED:
1-arc-second
1/3-arc-second
1/9-arc-second
USGS

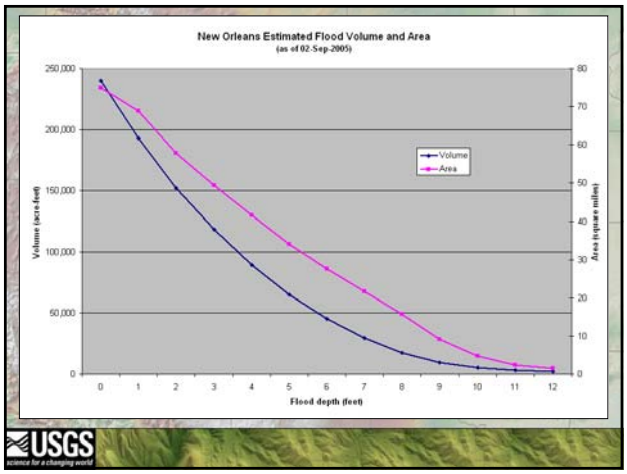

Multi-Resolution NED
1-arc-second (30-m)
1/3-arc-second (10-m)
1/9-arc-second (3-m)

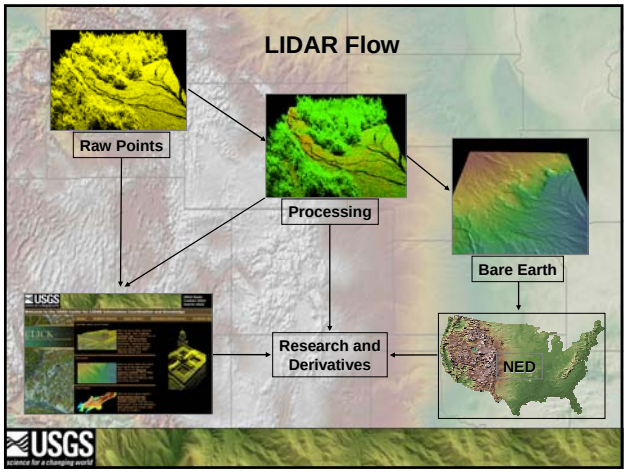

National Elevation Dataset
1/9-Arc-Second Holdings and Anticipated Data
1/9-Arc-Second Data Status
Data available in NED 1/9-arc-second layer
Data being processed for NED
Data queued for NED
Anticipated data for NED
June 2008
USGS


USGS
Seamless Data Distribution
Back to Main Page
Scale Information
Layers
Display
Download
Places (Names)
Layer Extent
Structures
Transportation
Boundaries
Hydrography
Orthoimagery
Land Cover
Elevation
USGS
science for a changing world


Lake Pontchartrain
New Orleans elevation
> 12 feet
12
11
10
9
8
7
6
5
4
3
2
1
0 (sea level)
-1
-2
-3
-4
-5
-6
-7
-8
-9
< -9 feet
Mississippi River

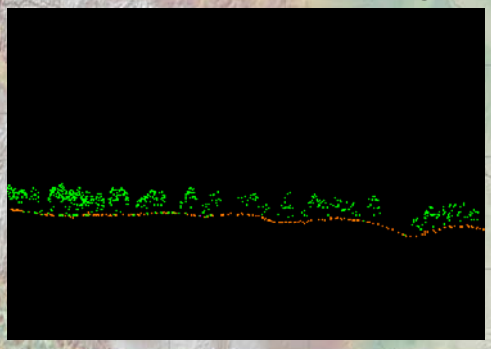

USGS
science for a changing world
Relative Water Depth for the New Orleans Area
Estimated water depth based on a lake level of 2.37 feet recorded by gage 07380233 on 09-02-2005
Flood Depth (Feet)
Flood depth estimated from 10-m elevation data derived from 5-m lidar data collected in 2002.
U.S. Department of the Interior
U.S. Geological Survey
USGS
science for a changing world


New Orleans Estimated Flood Volume and Area
(as of 02-Sep-2005)
Volume (acre-feet)
Area (square miles)
Flood depth (feet)
Volume
Area
USGS
science for a changing world

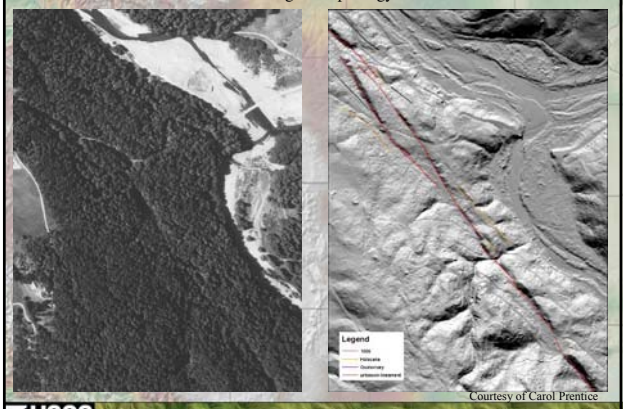

LIDAR Flow
Raw Points
Processing
Bare Earth
Research and Derivatives
NED
USGS
science for a changing world

Welcome to the USGS Center for LIDAR Information Coordination and Knowledge
CLICK
USGS
science for a changing world

Manual Post-Processing

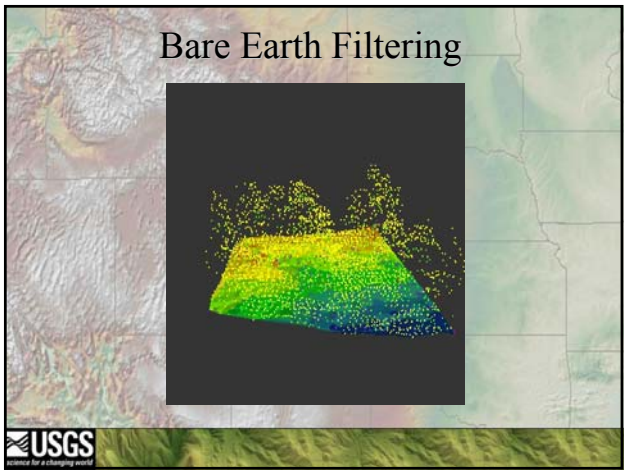


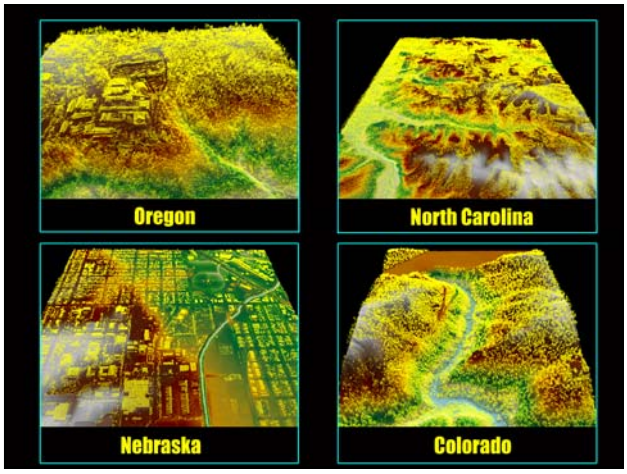
Northern San Andreas LIDAR: fault geomorphology

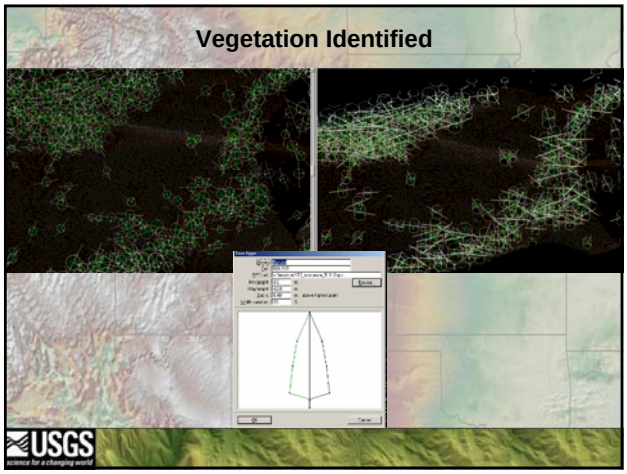


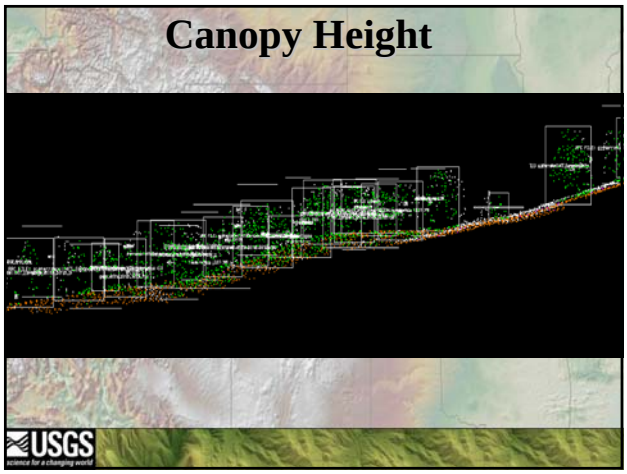
Courtesy of Carol Prentice

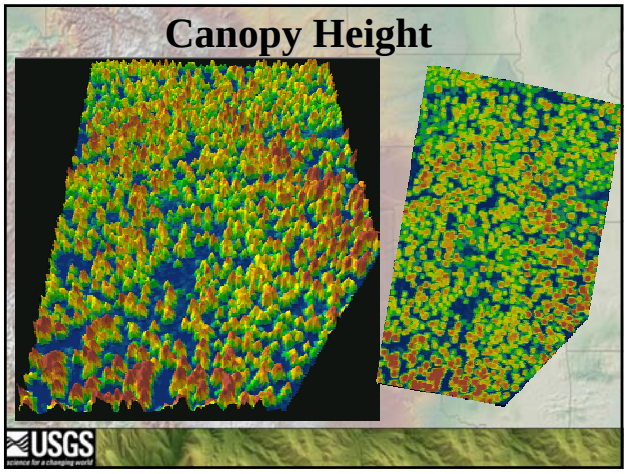
Vegetation

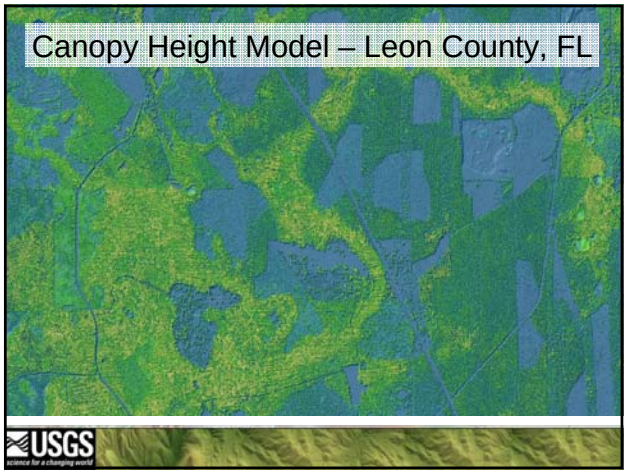

Bare Earth Filtering
USGS


Oregon
North Carolina
Nebraska
Colorado

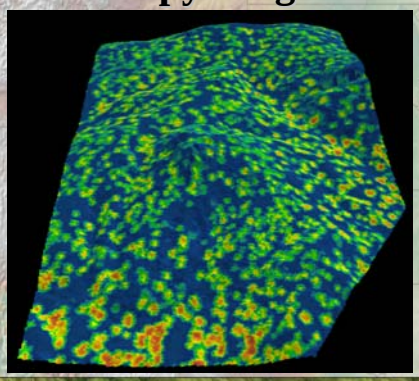

Vegetation Identified
USGS

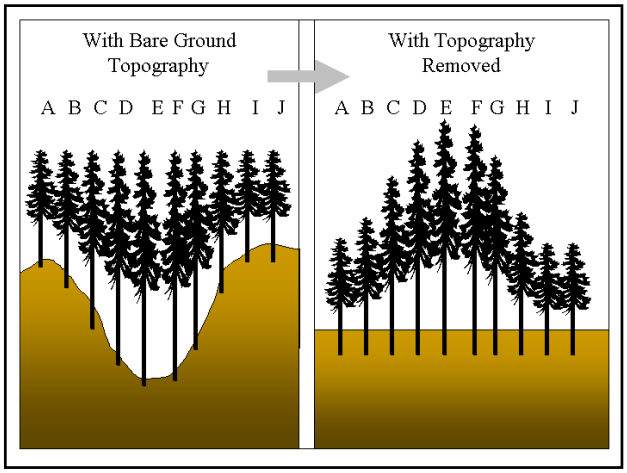

Canopy Height
USGS


Canopy Height
USGS


Canopy Height Model – Leon County, FL
USGS

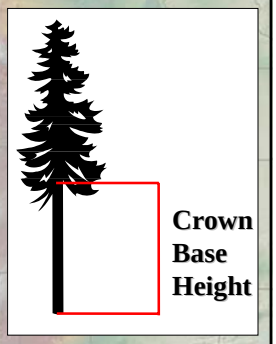
Canopy Height

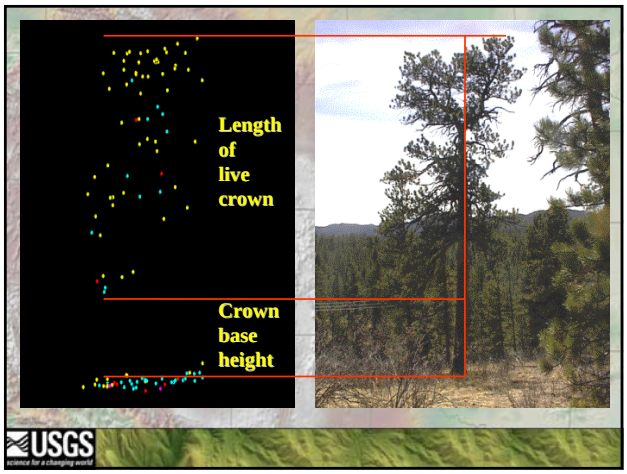




Crown Base Height

- Distance from the ground to the lowest needle-bearing branch
- Important in fire modeling
- Surface fire / crown fire

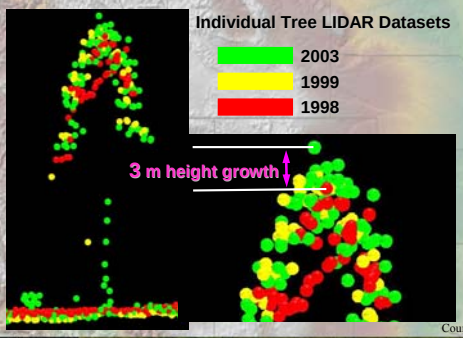




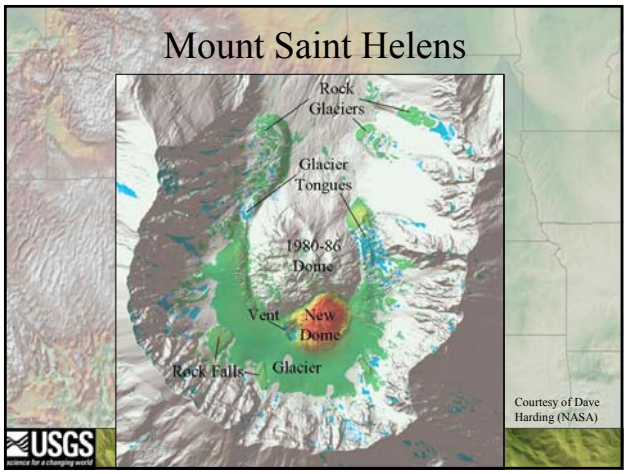
Multi-temporal LIDAR

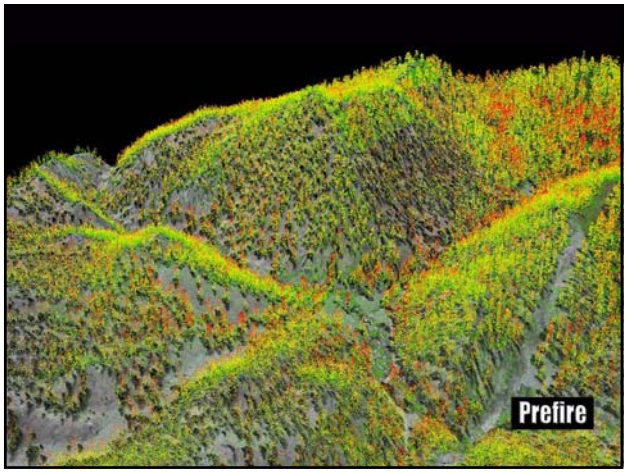
- As LIDAR collections increase, there will be more availability to use LIDAR for monitoring change detection purposes

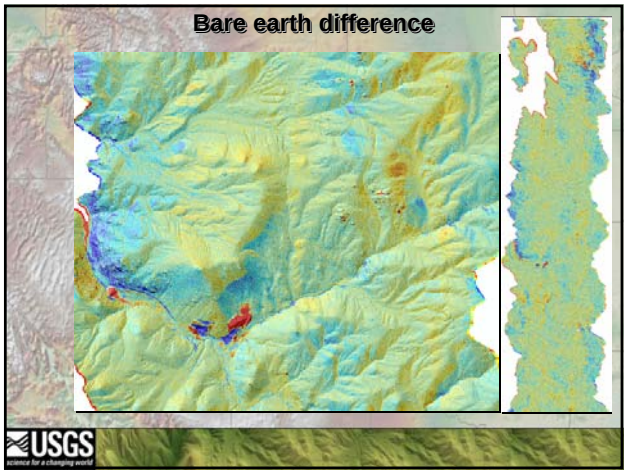
Monitoring Growth with LIDAR

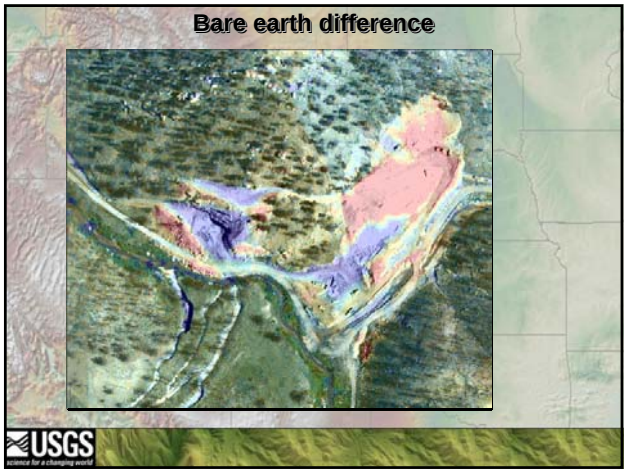


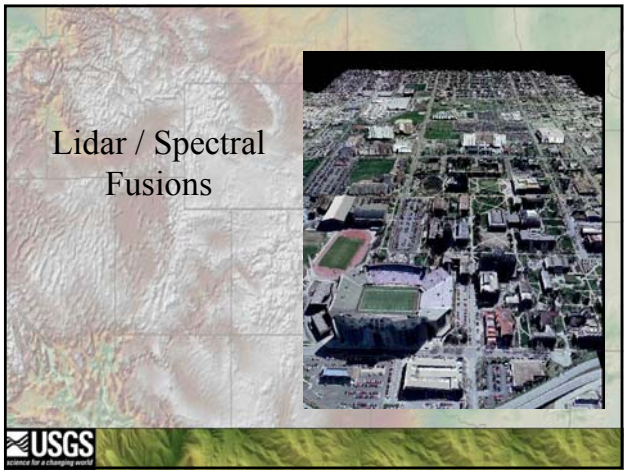
Courtesy of Hans-Erik Andersen

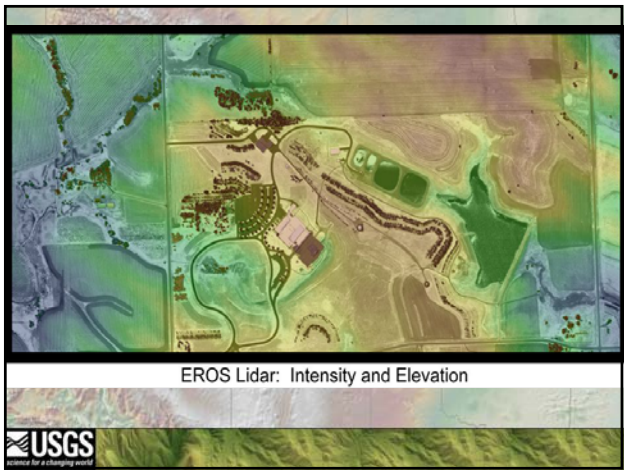

Mount Saint Helens
Rock Glaciers
Glacier Tongues
1980-86 Dome
Vent
New Dome
Rock Falls
Glacier
Courtesy of Dave Harding (NASA)
USGS

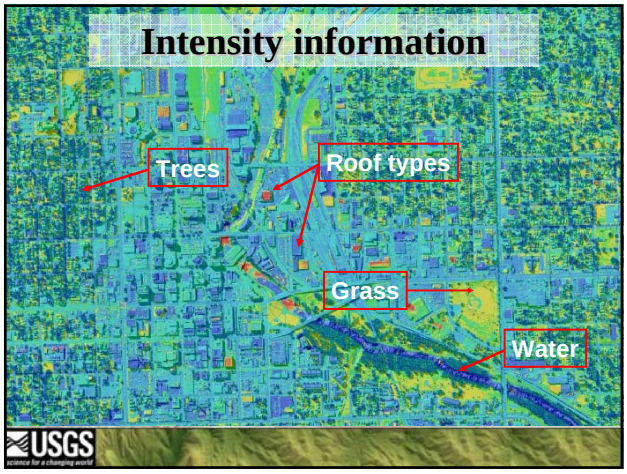

Prefire

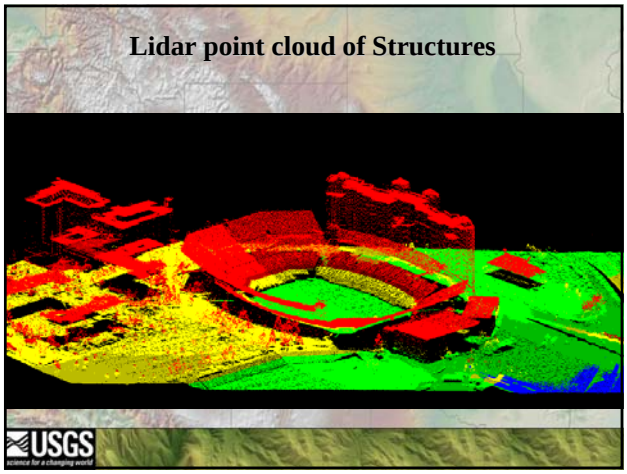

Bare earth difference
USGS

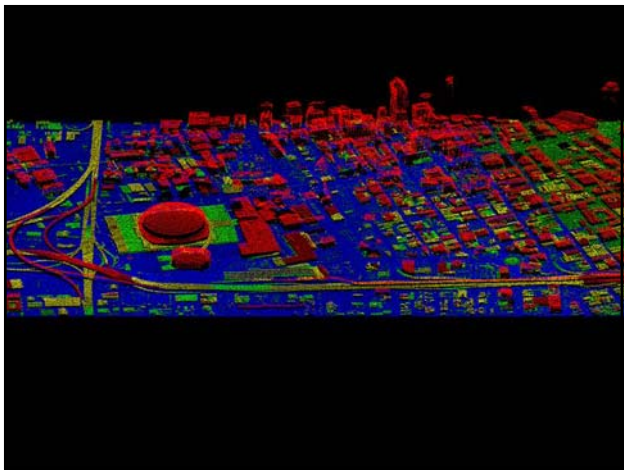

Bare earth difference
USGS


Lidar / Spectral
Fusions
USGS


EROS Lidar: Intensity and Elevation
USGS


Intensity information
Trees
Roof types
Grass
Water
USGS


Lidar point cloud of Structures
USGS



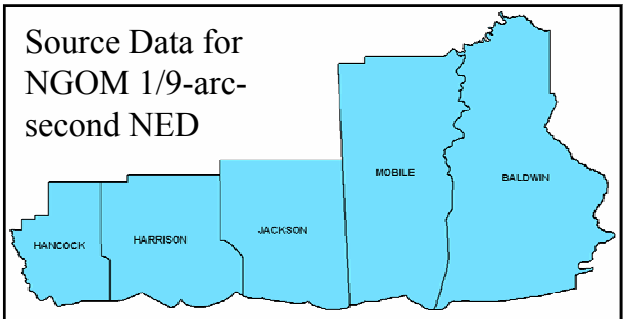
Feature Extraction using Lidar

National Lidar Initiative

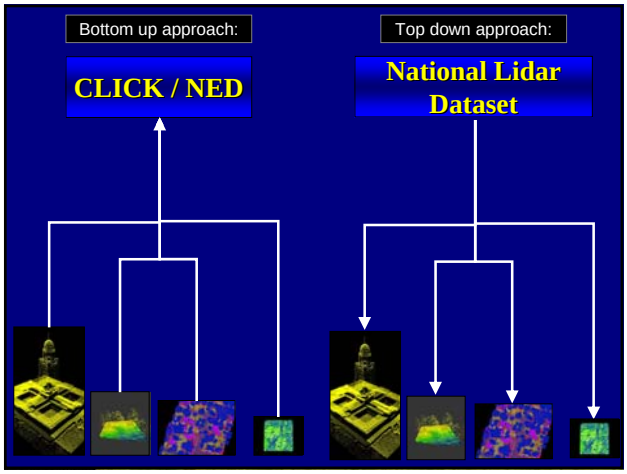
- There is a growing demand for a consistent national-level high-resolution lidar survey
- USGS is being looked to as the leader by other agencies in planning and managing this effort
- Two initial meetings hosted by the USGS to lay the groundwork for a national collection
  - Feb. 2007, Reston, VA
  - May 2008, Reston, VA

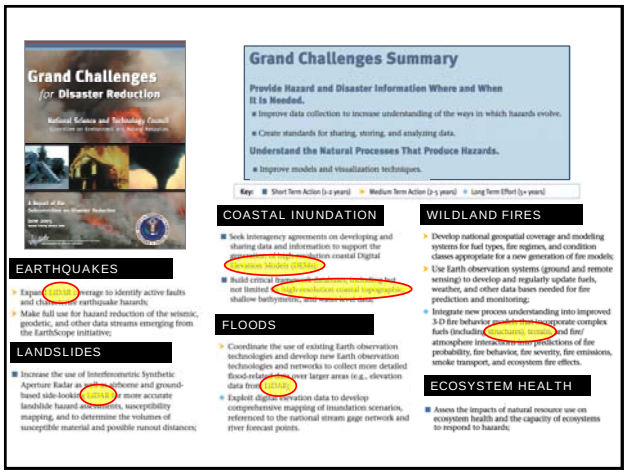
Difficulties with a bottom up approach - Gulf Coast example

Source Data for NGOM 1/9-arc-second NED



Area	Format	Projection	Elevation Units	Metadata?
Louisiana	5-m DEM (raster)	UTM	Feet	Yes
Hancock Co., MS	LAS binary (points)	MS State Plane (m)	Feet	Yes
Harrison Co., MS	ASCII XYZ (points)	MS State Plane (ft)	Meters	No
Jackson Co., MS	LAS binary (points)	MS State Plane (m)	Feet	Yes
Mobile Co., AL	LAS binary (points)	AL State Plane (ft)	Feet	Partial
Baldwin Co. AL	Shapefile (MPBL)	AL State Plane (ft)	Meters	Partial





Lidar and CLICK

- For further information, see:
  - "CLICK: The New USGS Center for Lidar Information Coordination and Knowledge" in the June 2006 issue of *Photogrammetric Engineering & Remote Sensing*
  - "Report of the First National Lidar Initiative Meeting, February 14-16, 2007, Reston, Va." USGS Open-File Report 2007-1189
  - CLICK Web site: lidar.cr.usgs.gov
    - References on SAR – lidar comparisons

Presentation Overview

Hydrologic Derivatives from Lidar - Sandra Poppenga, USGS

EROS Training

and Education

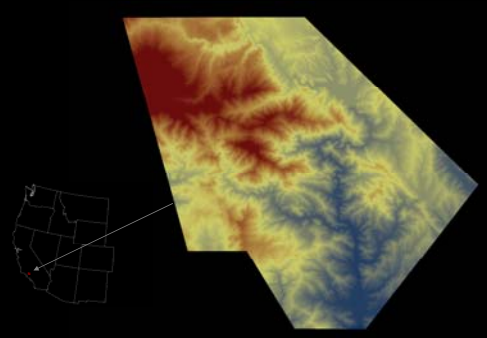
Hydrologic Derivatives from Lidar-derived Digital Elevation Models

U.S. Department of the Interior
U.S. Geological Survey

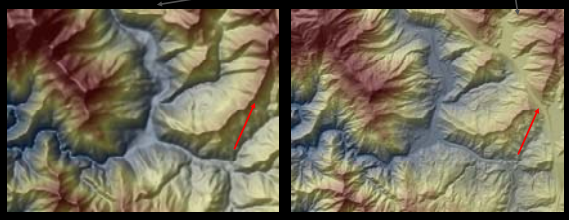
Purpose

- Produce derivatives from lidar (1 meter)-derived Digital Elevation Models.
- Produce hydrologic derivatives for characterizing surface flow on the landscape.
- Conduct terrestrial monitoring within a watershed.

Lidar-derived Digital Elevation Model (1m)



DEM comparison (30m vs 1m) improved elevation data

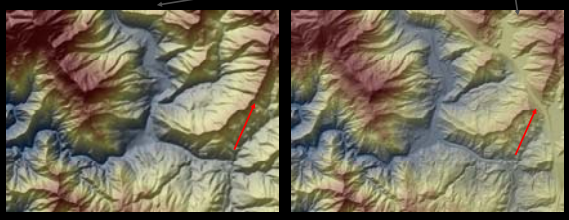


30m DEM derived from NED

1m DEM derived from LiDar

USGS

DEM comparison (10m re-sampled vs 1m lidar)



10m DEM derived from NED

1m DEM derived from LiDar

USGS

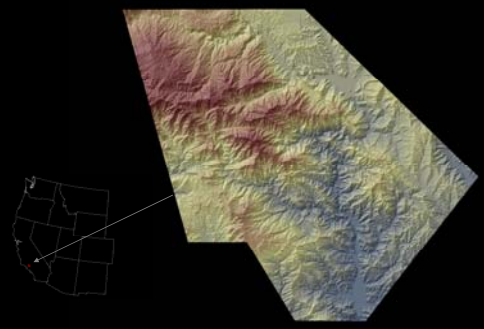
DEMs (30, 10, & 1m)

USGS

Importance of improved elevation data

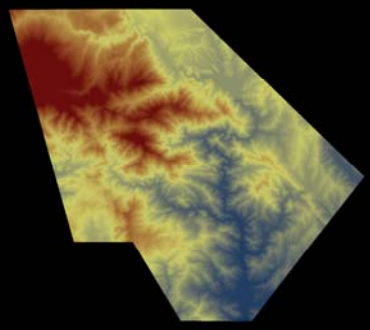
USGS

Lidar-derived hydrologic derivatives



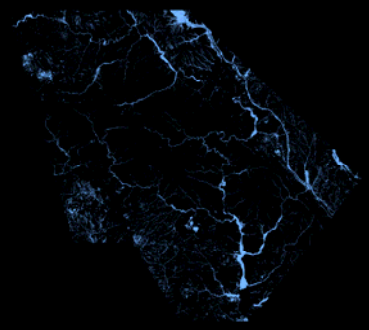
USGS

Hydrologic analysis
Characterize surface flow on the landscape



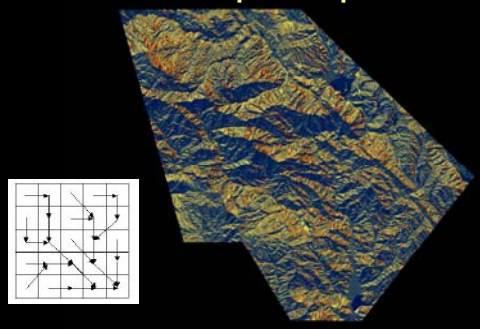
USGS

Sinks (depressions) are filled to create overland flow



USGS

Flow direction - water would flow out of each cell to its steepest slope



USGS

Flow accumulation- number of upslope cells flowing to a location

USGS

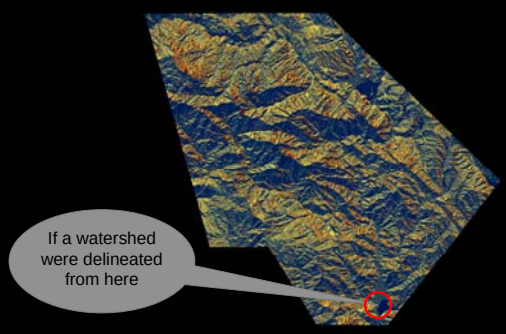
Characterize surface flow

USGS

Surface flow comparison
30m at 5000 and 250 thresholds vs.
1m DEM derivatives

USGS

Delineate a watershed



USGS

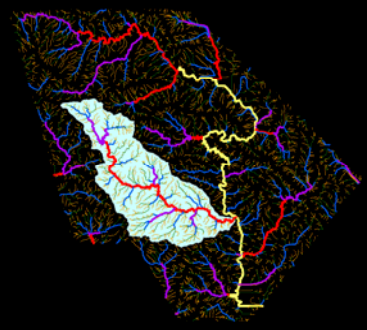
Watershed boundary beyond the lidar footprint

USGS

Watershed delineation (with surface flow)

USGS

Some larger watersheds within study area where we have lidar data



USGS

Terrestrial Monitoring
Land Cover change within a watershed

USGS

Terrestrial Monitoring
Land Cover change within a watershed

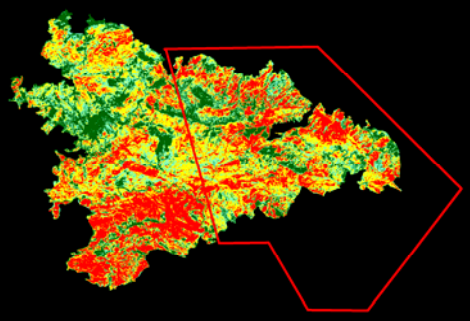
USGS

A few notes on the Day Fire

- The fire started on Labor Day, September 4, 2006 in Los Padres National Forest
- Burned over 658 km^2
- Cost over $73 million
- At one point had 4,000+ active firefighters
- Contained on October 2, 2006
- Lidar data used for debris flow monitoring research

USGS

Monitoring Trends in Burn Severity



USGS

Topographic Science

- National Elevation Dataset (NED)
  http://ned.usgs.gov
- Elevation Derivatives for National Applications (EDNA)
  http://edna.usgs.gov
- Light Detection and Ranging (lidar)
  http://lidar.cr.usgs.gov
- Topographic Change
  http://topochange.cr.usgs.gov/

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