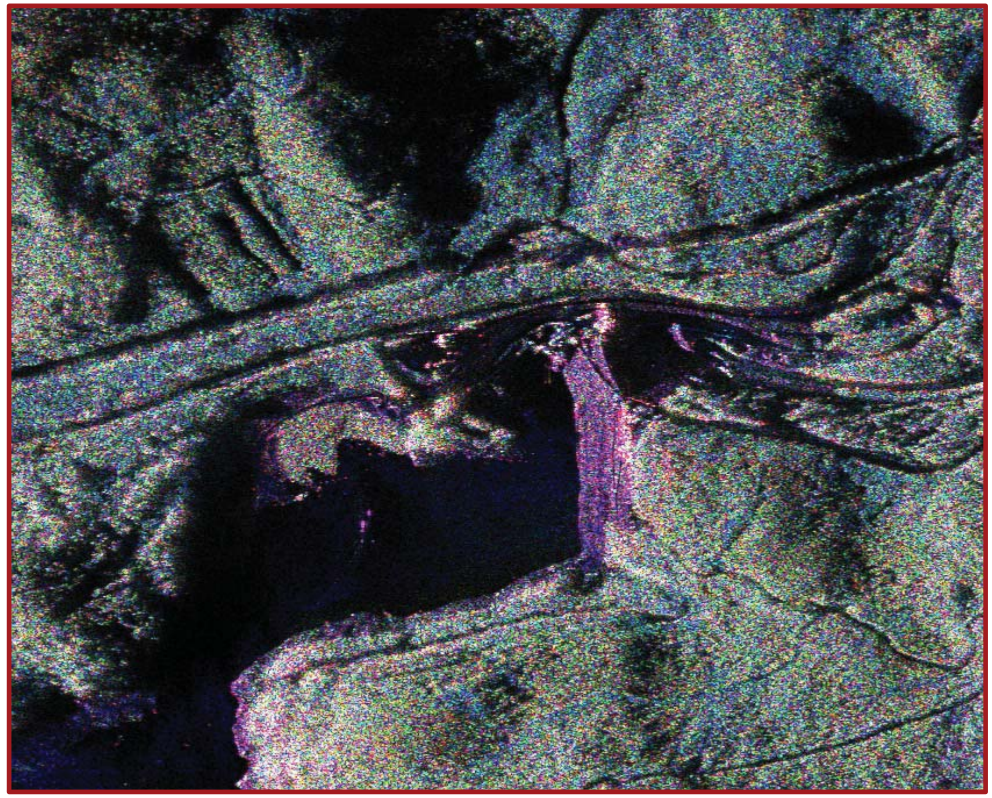
Monitoring Critical Infrastructure with Radar Remote Sensing

A Case Study of the Howard A. Hanson Dam and the Sacramento Delta Levees



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October 14, 2011

A Dam Safety Program Using Remote Sensing

- **FEMA and the USACE currently monitors thousands of dams and thousands of miles of levees throughout the United States.**

- **Remote sensing can augment ground-based and visual surveys by:**
  - **providing *consistent monitoring* across all sites**
  - **enabling *rapid data collection* over large areas to give a "snapshot" of conditions at many sites at the same time**
  - ***detecting* areas that *change* by small amounts or in subtle ways**
  - **informing a *targeted monitoring program* that can *identify potential problem spots* and/or provide continual monitoring of those sites to identify when/how they change**
  - **imaging areas that are *difficult* to *access* on the ground**

Outline of Presentation

- **Overview of Radar Remote Sensing**
- **Surface Change Detection with Differential Interferometric Radar Processing**
- **Study of the Howard A. Hanson Dam**
- **Study of the Sacramento-San Joaquin Levees**
- **Other Examples of Radar Remote Sensing for Surface Change Detection, Hazard Mitigation, and Emergency Response**

Overview of Radar Remote Sensing

Radar Remote Sensing

Radar remote sensing is used to support a wide range of science investigations including geology, vegetation mapping and biomass measurement, archeological research, soil moisture mapping, and cold land processes. It is also used to support applications such as monitoring aquifer discharge/refill, land subsidence, landslides and debris flows, land use classification, and, more recently, emergency response for a wide variety of natural or technological disasters.

L-band Radar can…

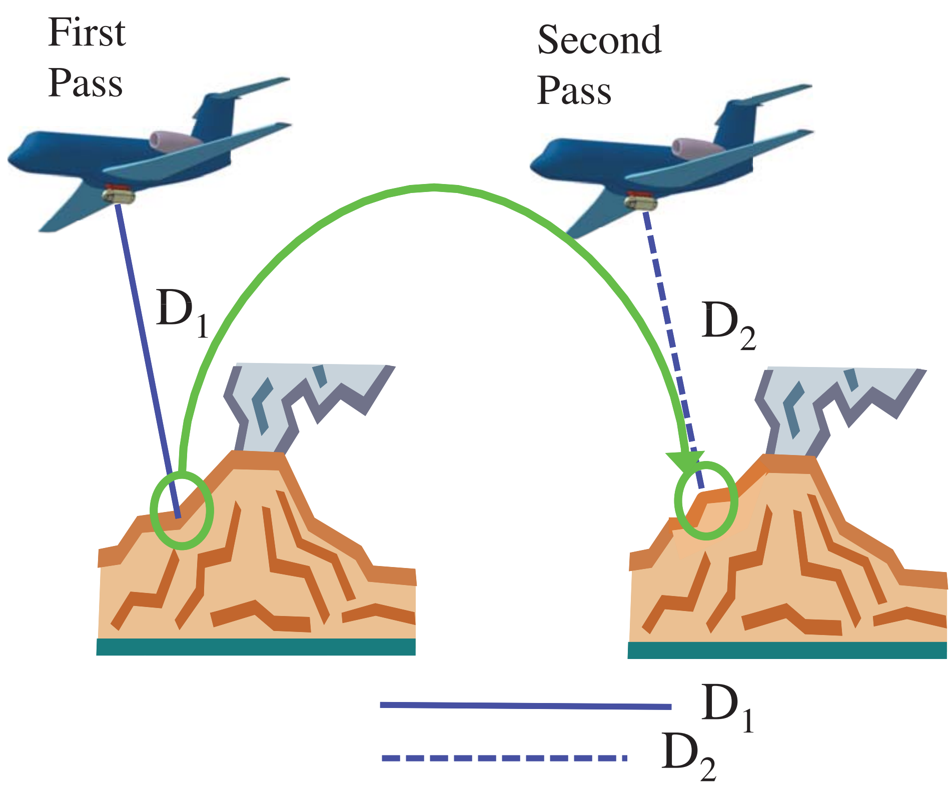
1) See through clouds, smoke, haze.
2) Image the surface of the Earth day or night in any light conditions.
3) Tell where there is standing water.
4) Determine the type of surface based upon physical and electrical characteristics.
5) Determine whether the surface changed properties (i.e., seep developed, equipment was moved, water level dropped)
6) Detect changes in hard targets that don't move a lot.
7) Detect very small scale (few millimeters) change in the position of hard targets.

L-band Radar cannot…

1) Take a photograph.
2) Identify a specific object and find it elsewhere in the scene if it is moved a long distance.
3) See below the surface by more than a few centimeters and then only when the surface is dry.
4) Reliably detect and quantify ground-level change of objects below large trees.
5) Do chemistry – radar can differentiate objects based upon physical properties (i.e., upright, dielectric properties) but not chemical properties (chlorophyll content, i.e., poison ivy vs. raspberry bush).

Radar Remote Sensing – Differential Interferometry

Radar Data Processing for Change Detection



Surface deformation causes the distance to the feature on the ground to change, which is measurable as a change in phase of the radar return.

$$\Delta\phi = \frac{4\pi}{\lambda}(D_2 - D_1)$$

$\lambda =$ wavelength of radar

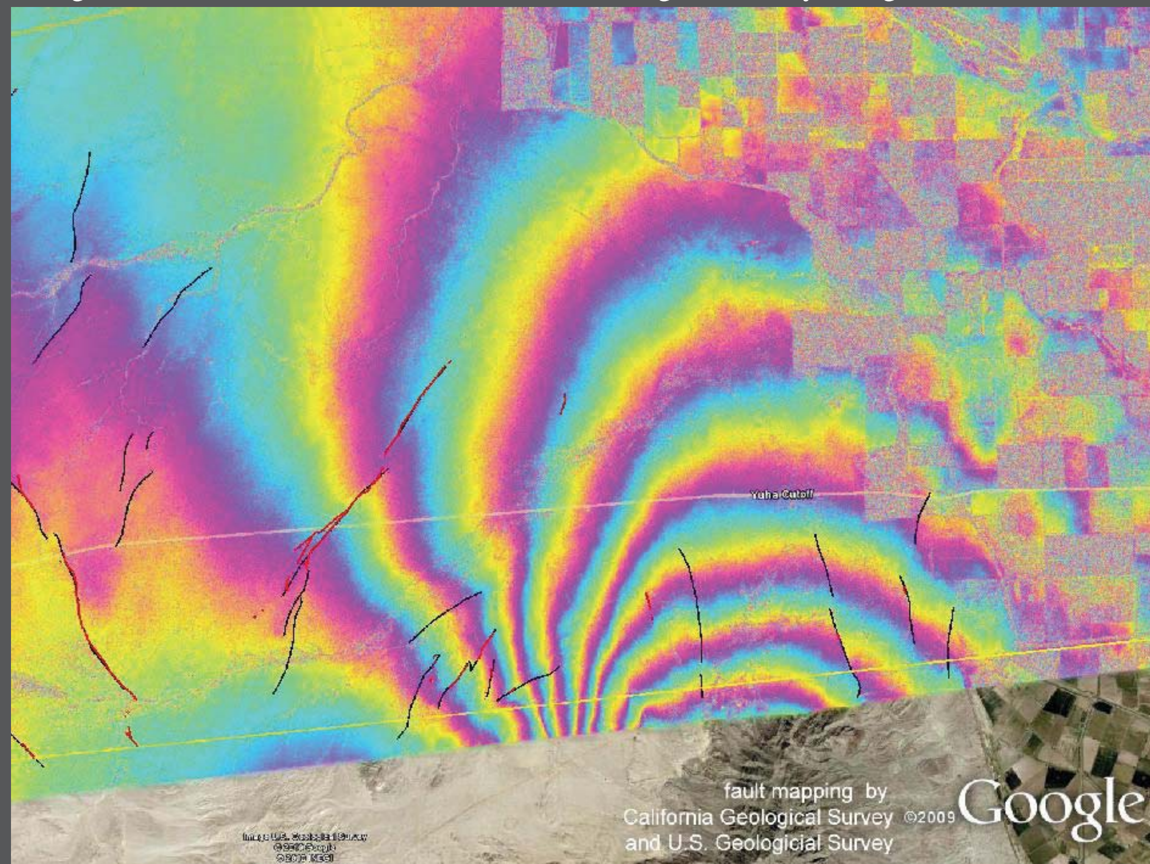
EXAMPLE: Using SAR to measure a volcano's surface deformation: The radar measures the distance D_1 to a point on the volcano on the first pass and the distance D_2 on a second pass taken after the volcano has undergone some deformation of the surface. The change in surface location can be measured to ~0.5 cm (1/4 inch) level at L-band.

Example: Earthquake Fault Slip

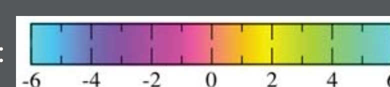
Baja Earthquake, April 2010

This UAVSAR DifInSAR image, covering the time period from October 21, 2009 to April 13, 2010, shows ground deformation that is largely a result of the April 4, 2010 earthquake in Baja California. Black lines indicate interpreted faults, and red lines show where surface rupture was confirmed by geologists in the field.

Image credit: NASA JPL/USGS/California Geological Survey/Google

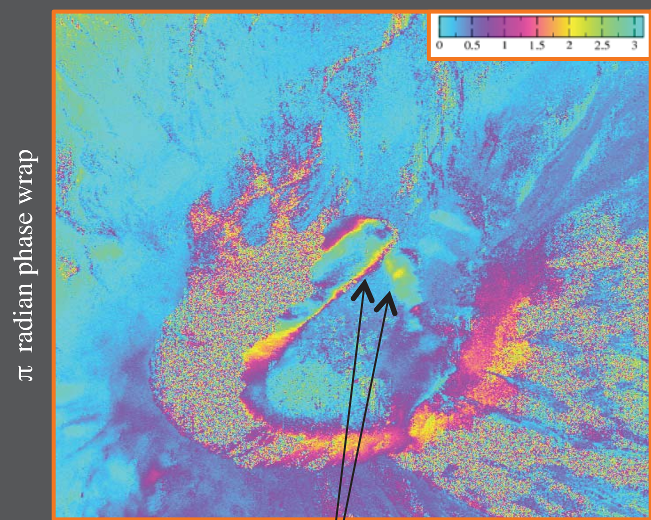


Relative surface shift in centimeters:

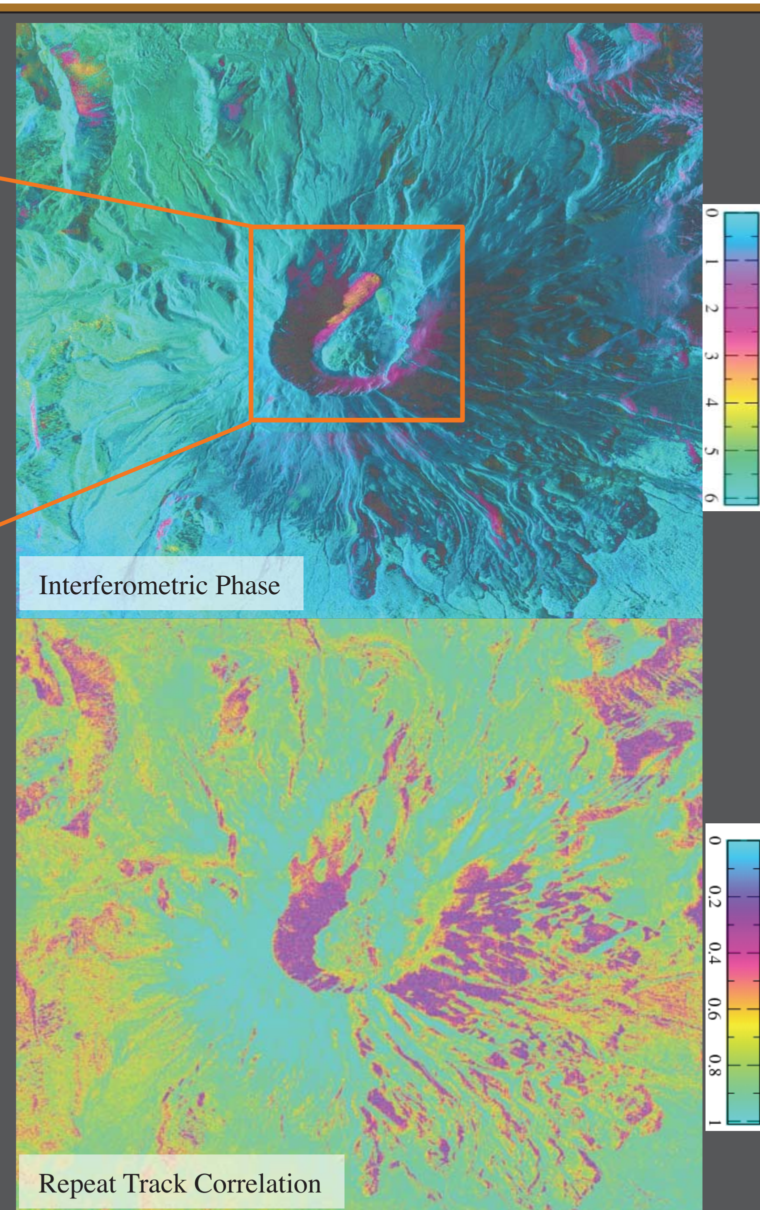


Example: Glacier Movement

Mt. St. Helens Repeat Track Interferometry



We can readily detect motion of the glaciers within the Mt. St. Helens caldera even with only a 4 hour repeat time. In this case, the glaciers are moving at a rate of ~0.5 m/day.



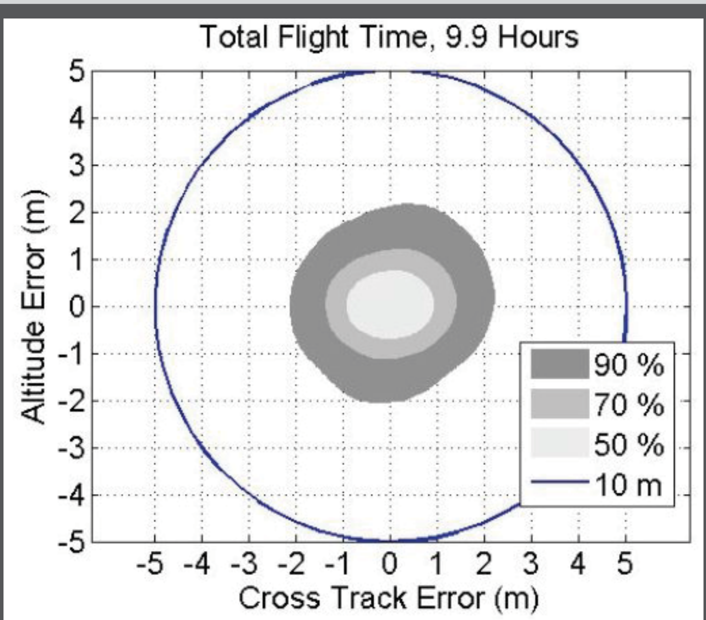
UAVSAR

An Airborne L-band Radar for Repeat Track Interferometry

The UAVSAR system combines control of the radar instrument with the aircraft flight path and is designed for DifInSAR. UAVSAR has several unique features to allow high precision differential interferometry from an airborne platform:

1. Precision autopilot to maintain the flight track within a 10 meter tube around the desired track.
2. Phased array antenna plus adaptive steering to maintain pointing direction of the radar beam.

Parameter	Value
Frequency	L-Band 1217.5 to 1297.5 MHz (23.8 cm wavelength)
Bandwidth	80 MHz
Resolution	1.67 m Range, 0.8 m Azimuth
Polarization	Full Quad-Polarization
ADC	12 bit ADC; 180 MHz sampling frequency
Waveform	Nominal Chirp/Arbitrary Waveform
Antenna Aperture	0.5 m range/1.5 m azimuth (electrical)
Azimuth Steering	Greater than ±20°
Transmit Power	> 3.1 kW



Monitoring the Howard A. Hanson Dam in 2009 and 2010 with the UAVSAR Radar

Radar Imaging of the Howard A. Hanson Dam for Change Detection

Jet Propulsion Lab [Cathleen Jones]

The Howard Hanson Dam developed two sink holes and a seep in early 2009. The Army Corp of Engineers installed a grout curtain to mitigate the problem in the latter half of 2009.

On November 4, 2009 the Howard Hanson Dam was imaged by the UAVSAR radar for the first time shortly after the fall pool lowering. A repeat flight was done a year later, on November 9, 2010, to determine whether high resolution radar could be used to detect changes on the dam face.

Four flight lines were collected to image the upstream and downstream faces of the dam and its abutments from several directions.

Goal of study: Explore the use of state-of-the-art radar instruments and processing techniques to monitor the dam for changes following the grout curtain installation.

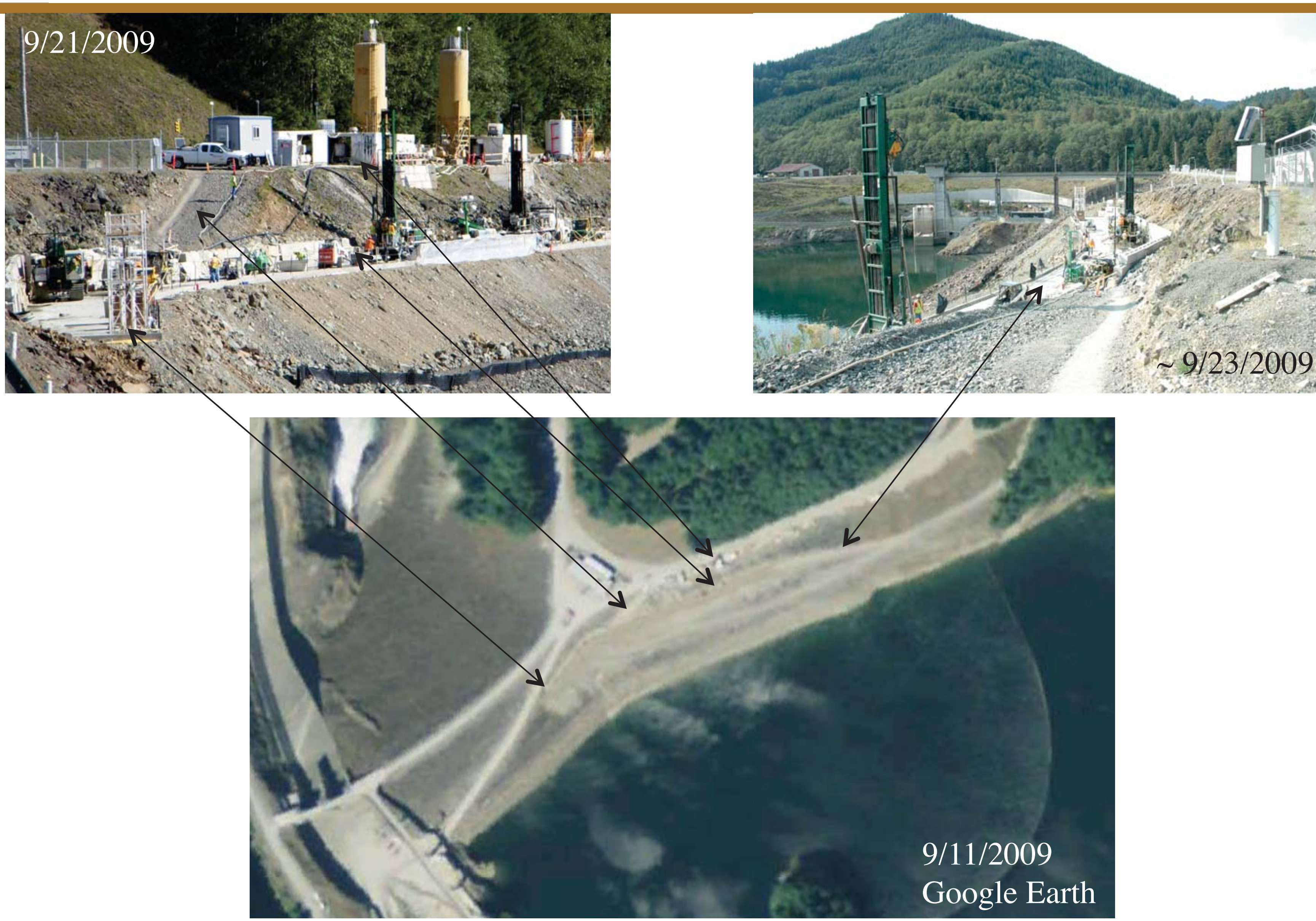
Howard Hanson Dam

GROUT CURTAIN INSTALLATION, SUMMER 2009

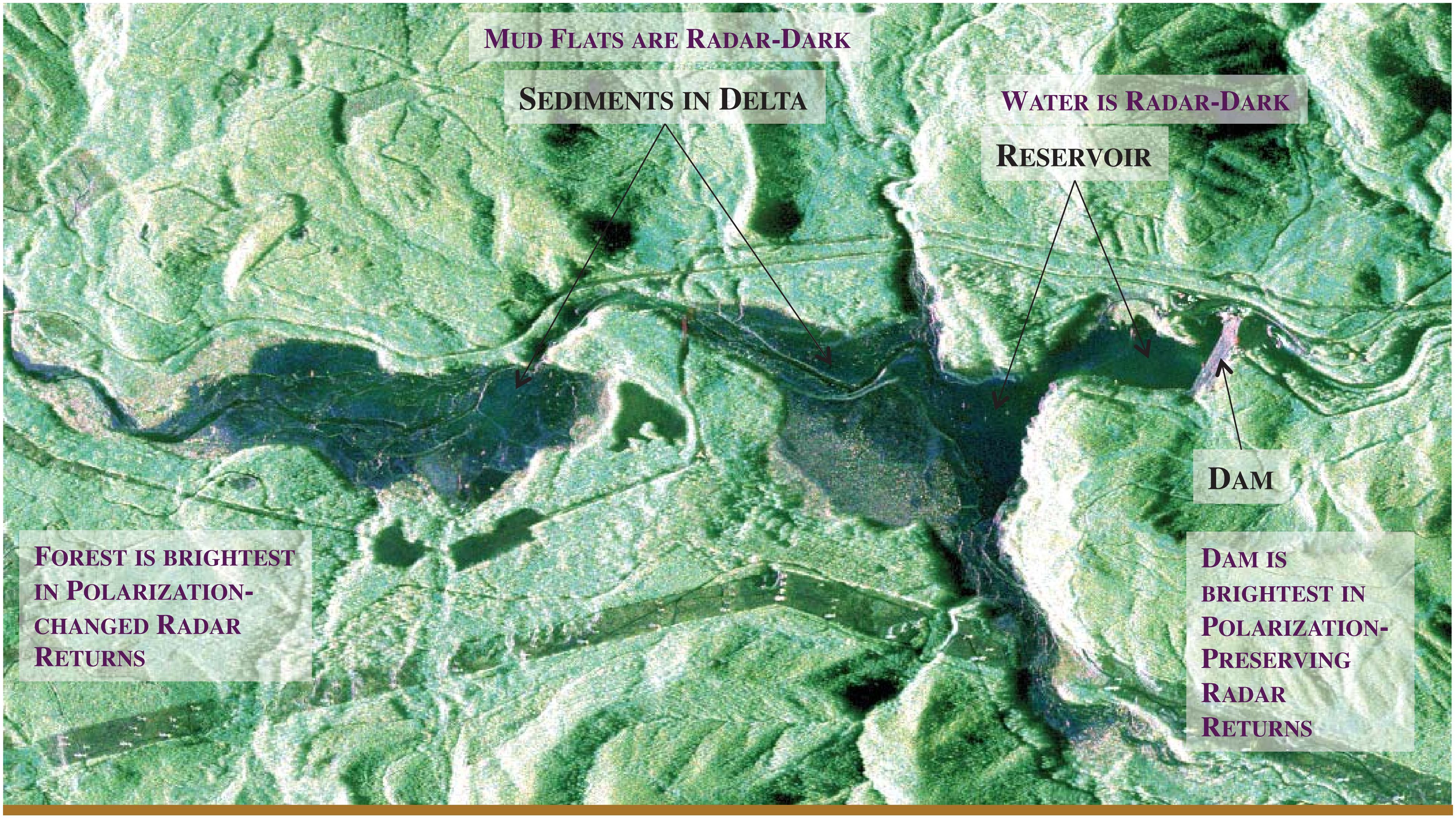
from Howard Hanson Dam Update, Seattle District, USACE

Grout Curtain Construction

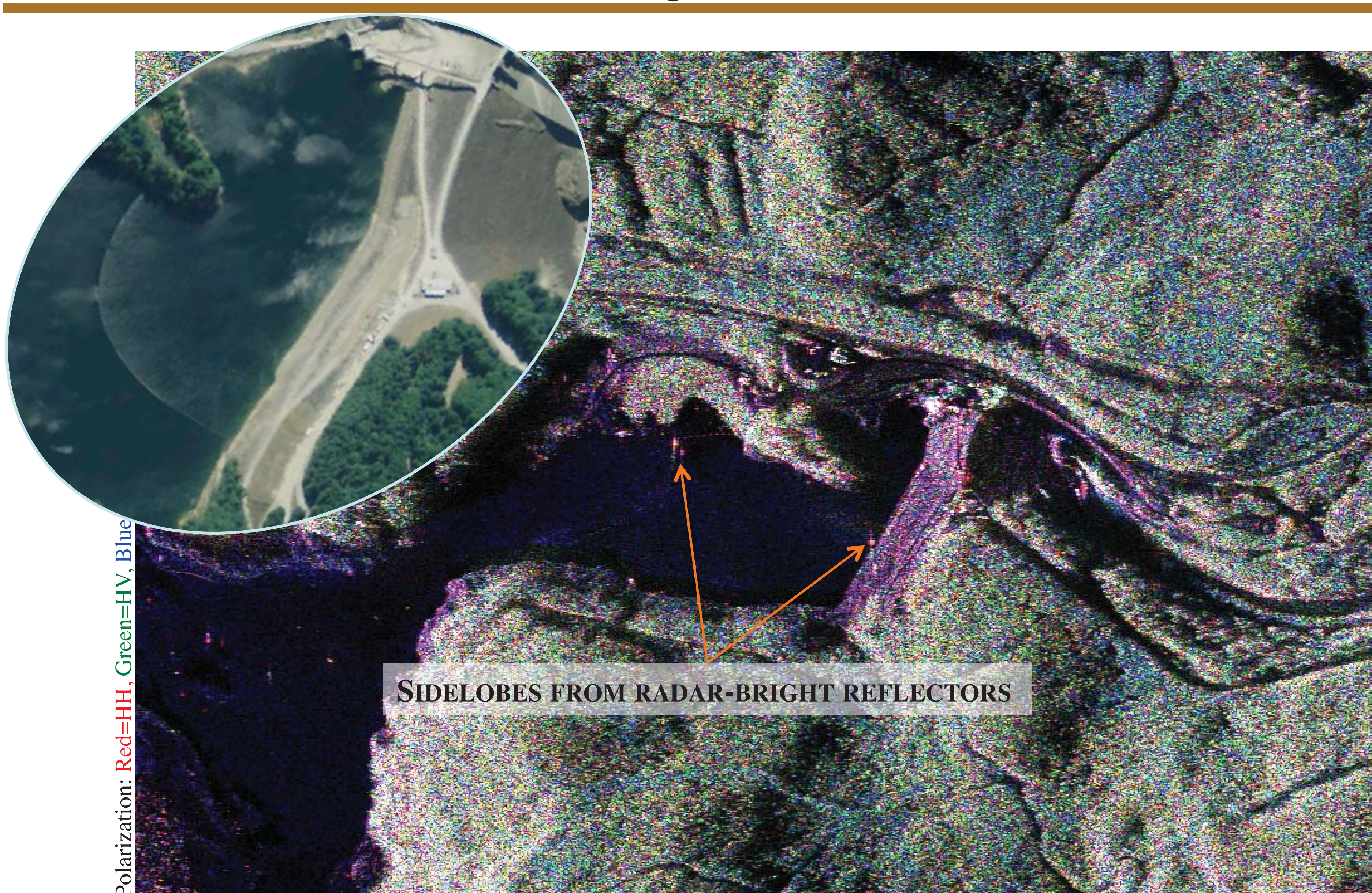
Construction Equipment Location



UAVSAR POLSAR image of dam, reservoir, and delta:



PolSAR Images of Upstream Dam Face and Right Abutment
UAVSAR Overflight #1 - Nov. 4, 2009



Polarization: Red=HH, Green=HV, Blue

PolSAR Images of Dam Face and Right Abutment

Images from the two UAVSAR flight lines looking at the Howard Hanson Dam from different directions:

Downstream Face of Dam
@ Aircraft Heading 200°

UAVSAR image; pixel resolution = 7m x 7m

Upstream Face of Dam & Right Abutment
@ Aircraft Heading 40°

Polarization: Red=HH, Green=HV, Blue=VV

Analysis for change detection of the UAVSAR radar data imaging Howard Hanson Dam

November 2009 to November 2010

1. Changes in the radar signal return power

Detects changes in the *type* of surface, i.e., land to water (water level, extent) or water to mud flat (sediment transport).

More or less a gross change detection, generally will not be confused by changes in vegetation senescence or soil moisture.

Detects change at the scale of the radar ground resolution.

2. Changes in the correlated amplitude and phase of the radar return (coherence between returns on the repeat passes)

Detects more subtle changes in the scattering surface and changes at a scale smaller than the radar resolution, i.e., vegetation growth, soil moisture.

Detects change at a scale smaller than the radar resolution, i.e., shifts of the gravel on a road caused by vehicles, rocks moved in a melted snow drifts.

Indicates whether the surface has changed, but doesn't indicate what caused the surface to change.

3. Changes in the interferometric phase of the radar return (DifInSAR)

Highly accurate measurement of surface motion under conditions where the surface properties didn't change, i.e., pre-slide slumps, earthquake fault slips, glacier movement

Is sensitive to small changes in soil moisture when the radar can penetrate below a surface (<40% volumetric soil moisture for L-band radar).

Combine with coherence to identify areas where accurate measurements of deformation can be made.

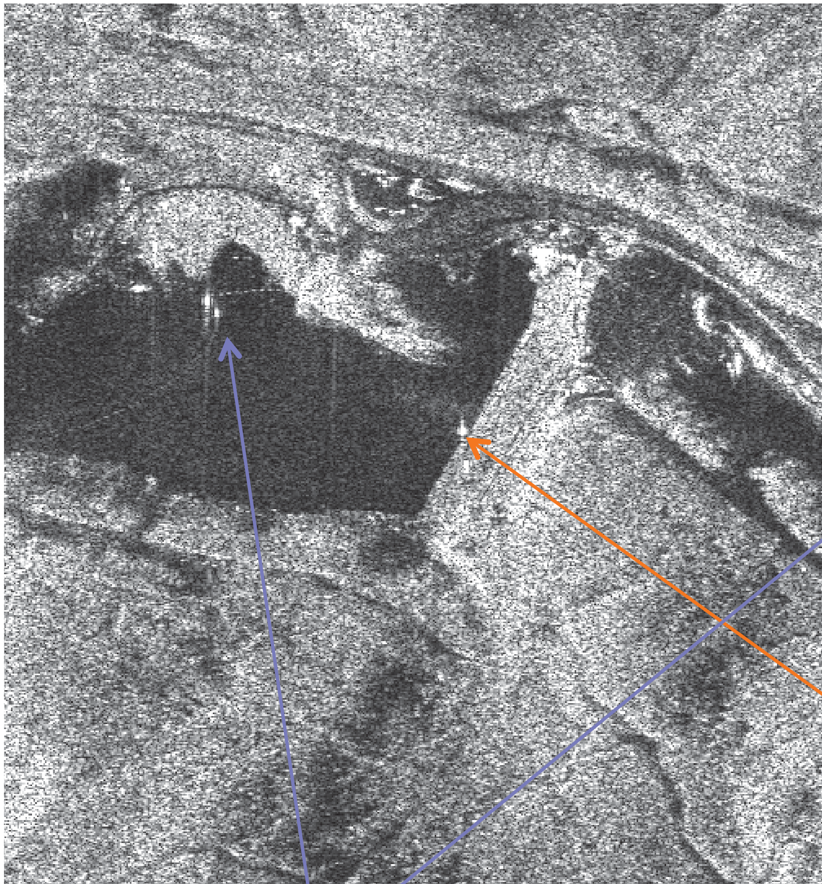
UPSTREAM SIDE OF THE DAM EMBANKMENT AND RIGHT ABUTMENT

UAVSAR FLIGHT LINE HEADING: 40°

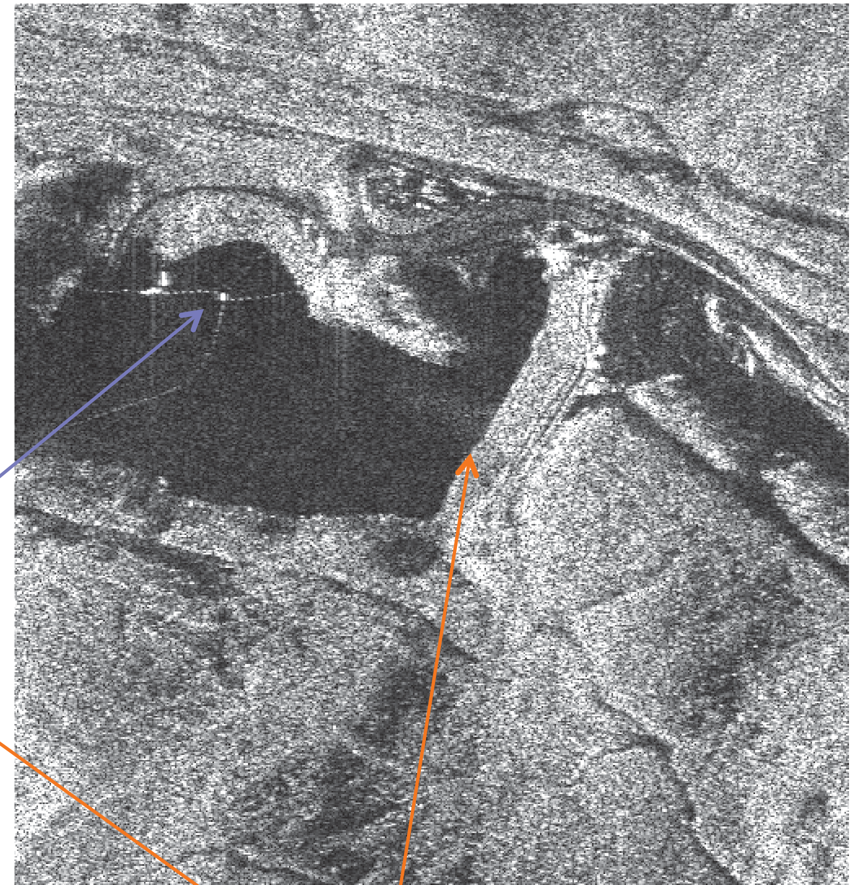
November 2009 to November 2010

Reservoir Comparison 2009 vs. 2010 – Radar Return Power

November 4, 2009



November 9, 2010

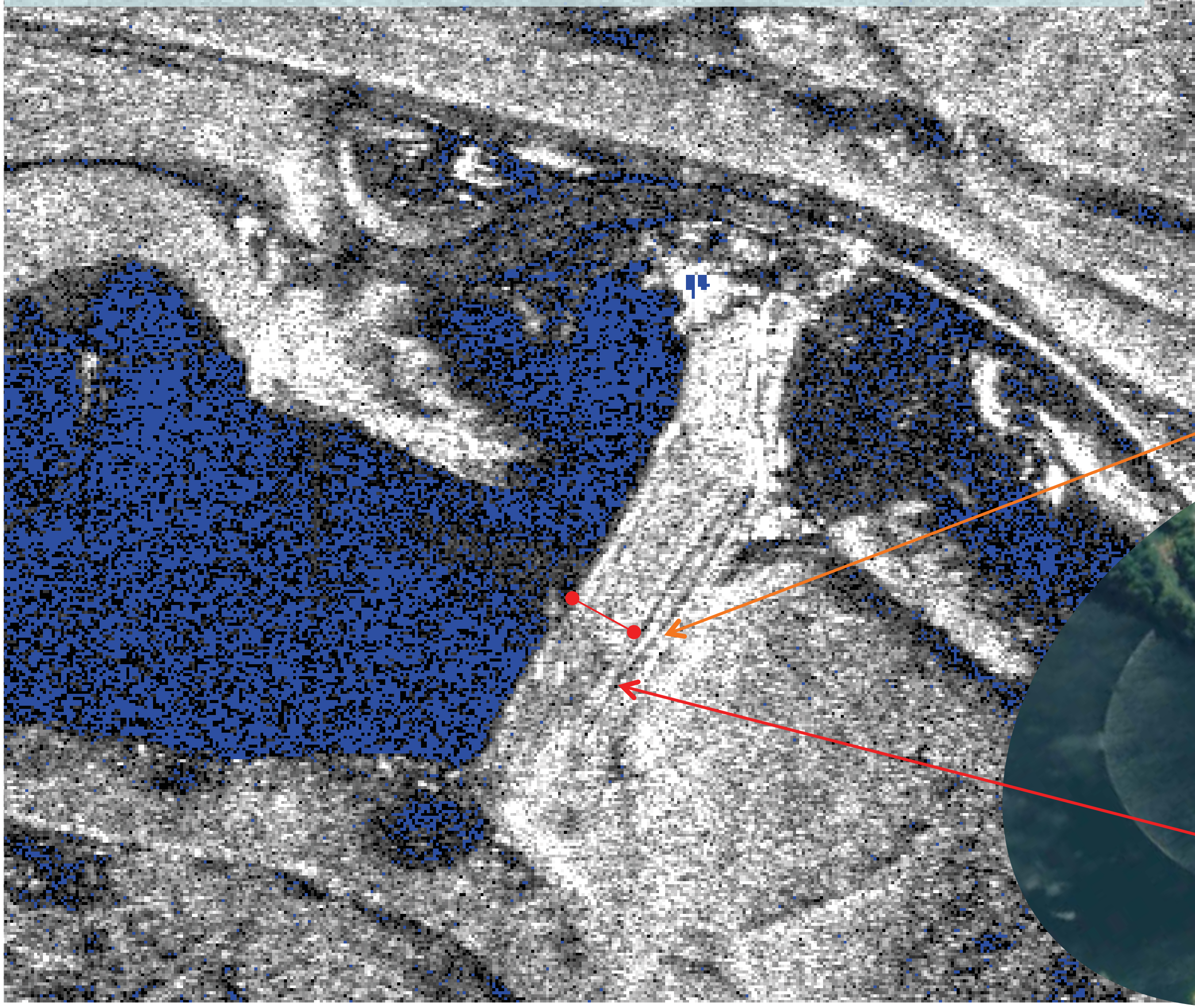


The buoys and restrictive barriers moved.

The bright reflector in the water near dam face is gone in 2010.

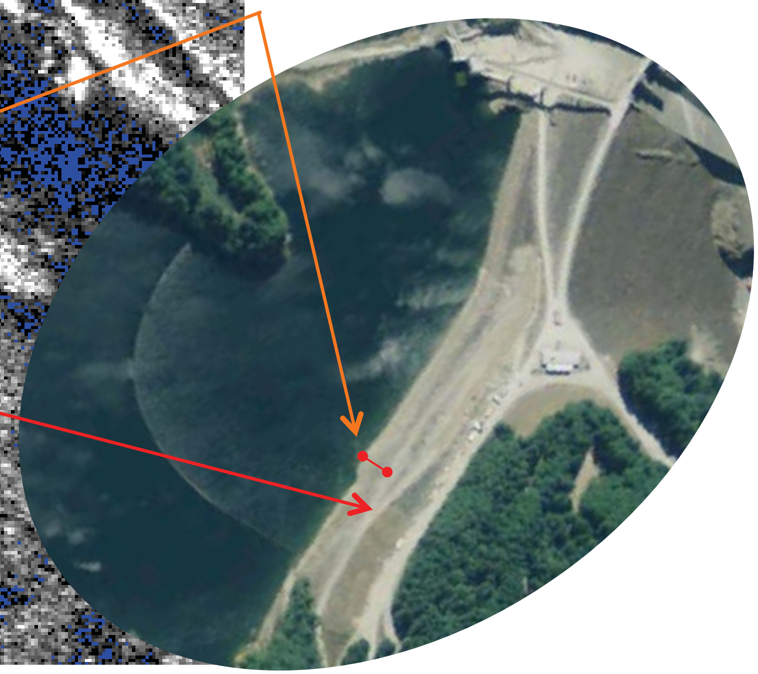
UAVSAR – Upstream Face of Howard Hanson Dam Radar Return Power

Radar return power with low values (blue) masked to show upstream face:

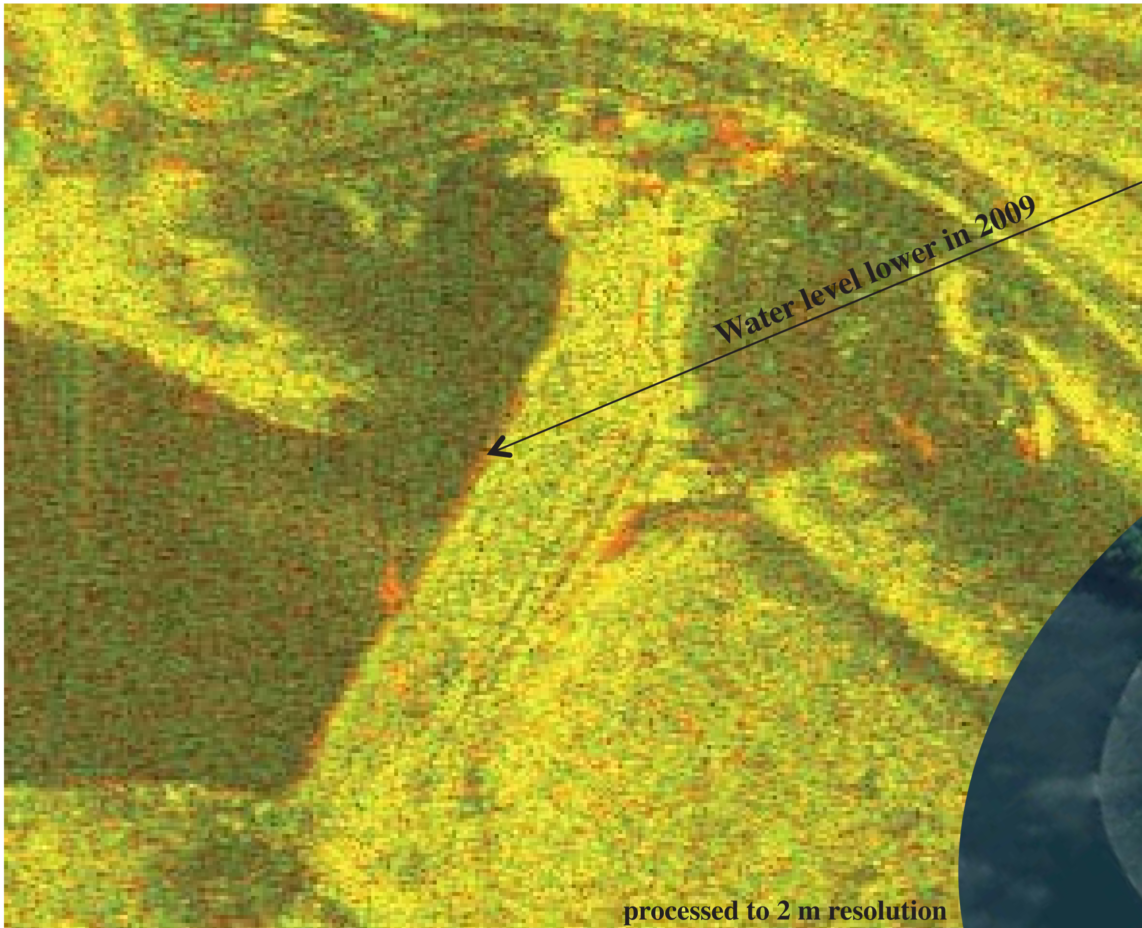


Date	Pool Level
Google Earth 9/11/2009	1136 ft
UAVSAR flight 11/4/2009	1076 ft
Difference	- 60 ft

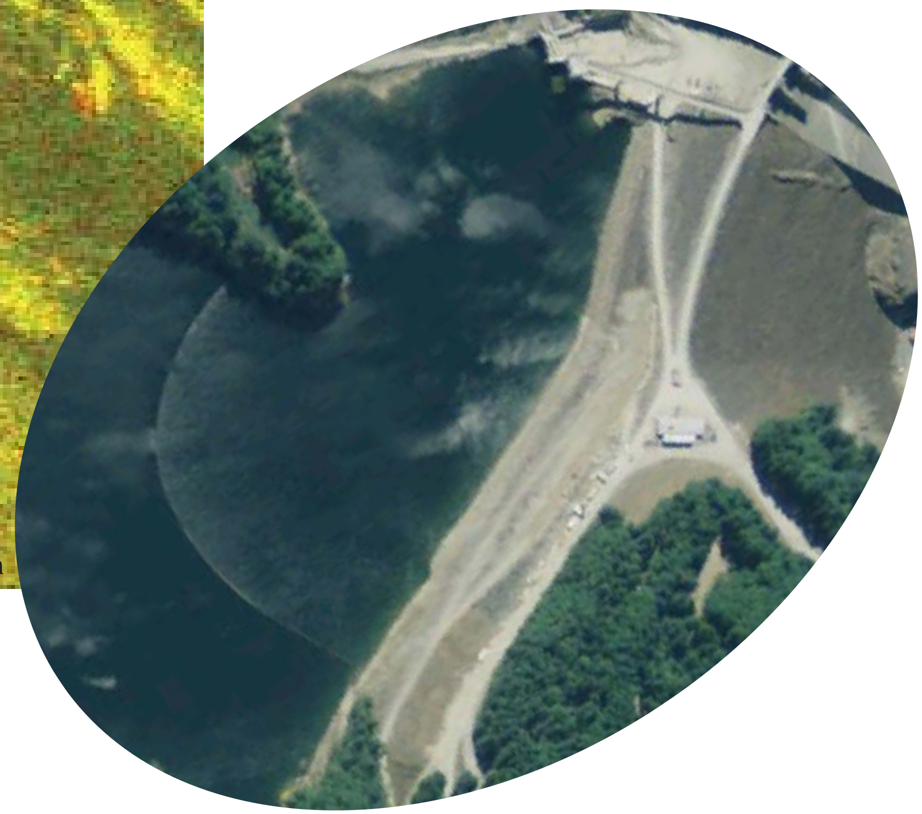
The water level in the pool was much lower in November 2009 and 2010 than in early September 2009 when the Google Earth image was made.



Change in the UAVSAR Radar Return Power
Nov. 2009 to Nov. 2010



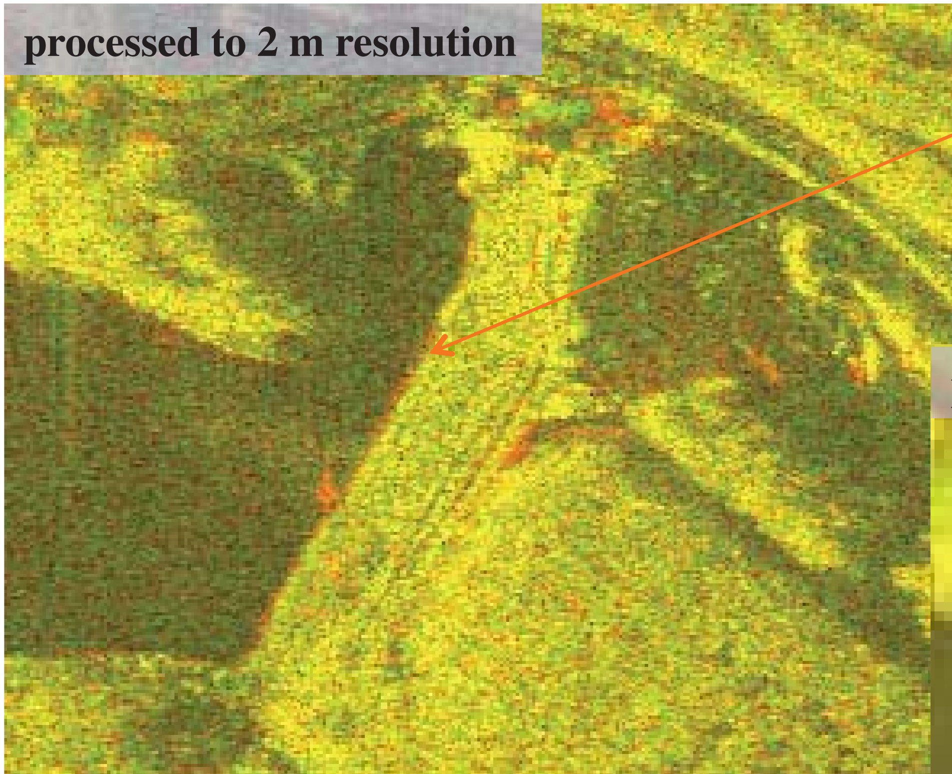
Date of Flight	Pool Level
11/4/2009	1076 ft
11/9/2010	1080 ft
Difference	+ 4 ft



Red = Brighter in 2009
Green = Brighter in 2010
Yellow = same in 2009 and 2010

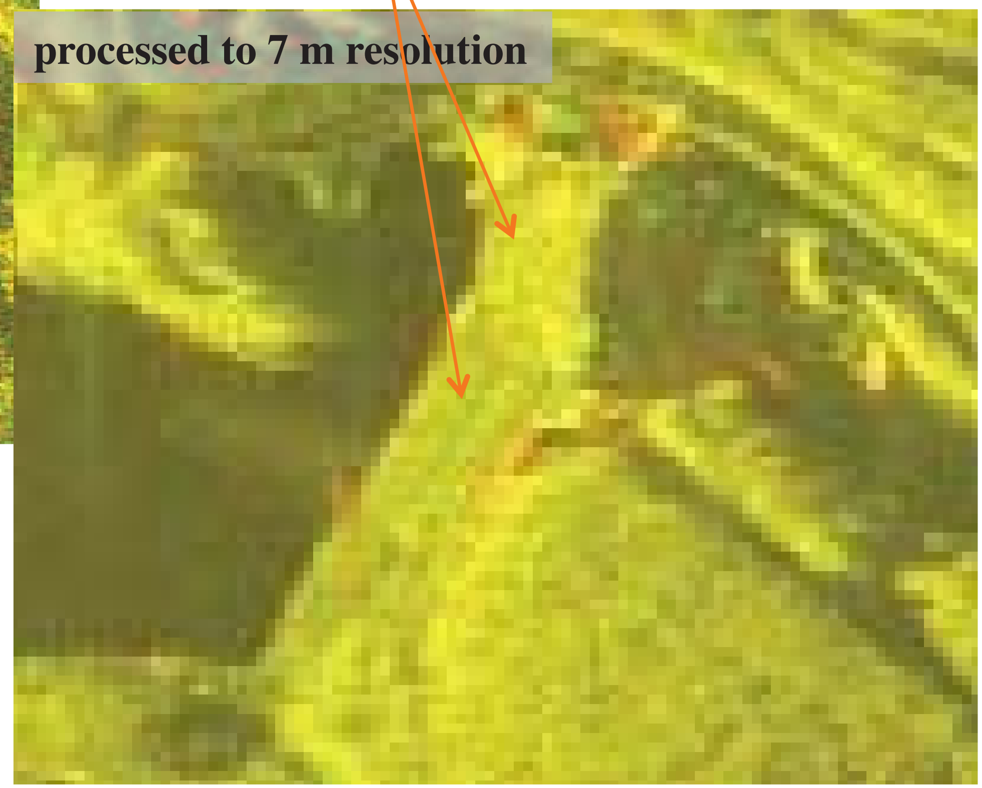
Radar Data - Effect of Processing Resolution
Return Power Change

Radar data can be processed to different resolutions, trading off between resolution and noise.



High resolution – resolve significant changes that occur in a localized area better.

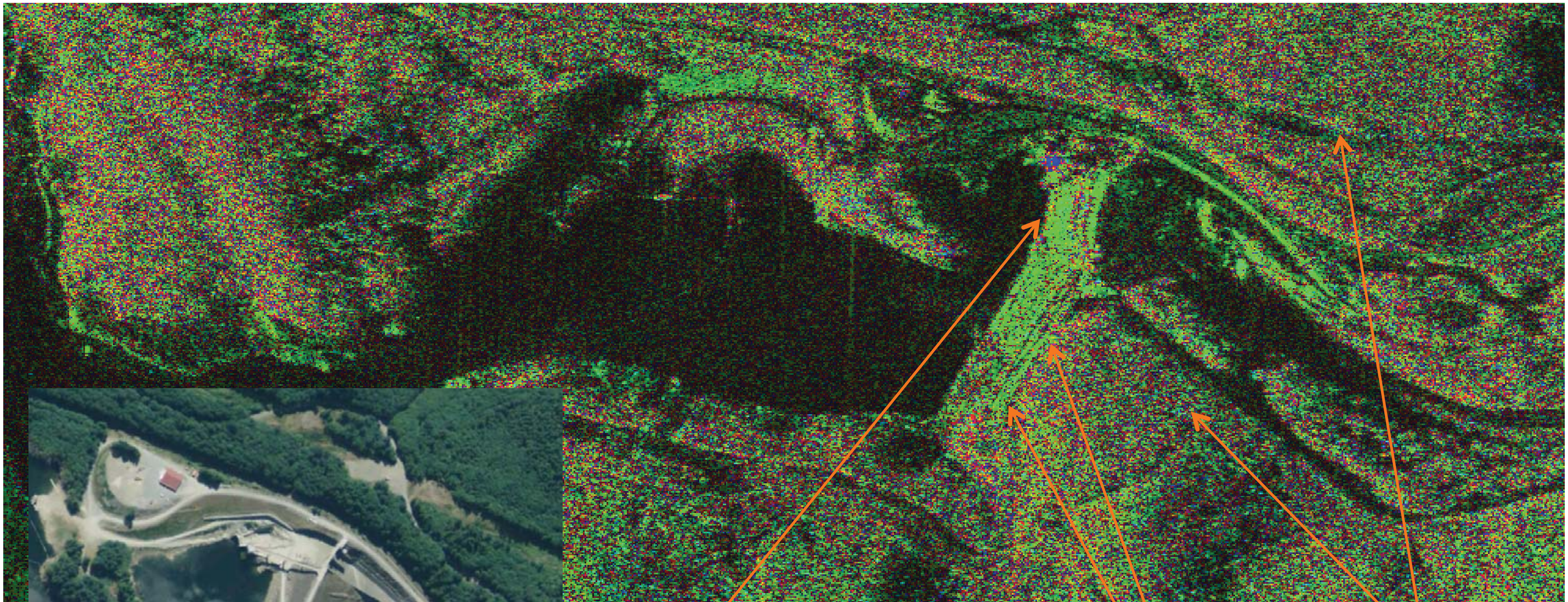
Low resolution – see general trends better



Red = Brighter in 2009
Green = Brighter in 2010
Yellow = same in 2009 and 2010

UAVSAR Nov. 2009 to Nov. 2010
Radar Data Processed for Change Detection – Phase and Correlation

Homeland Security

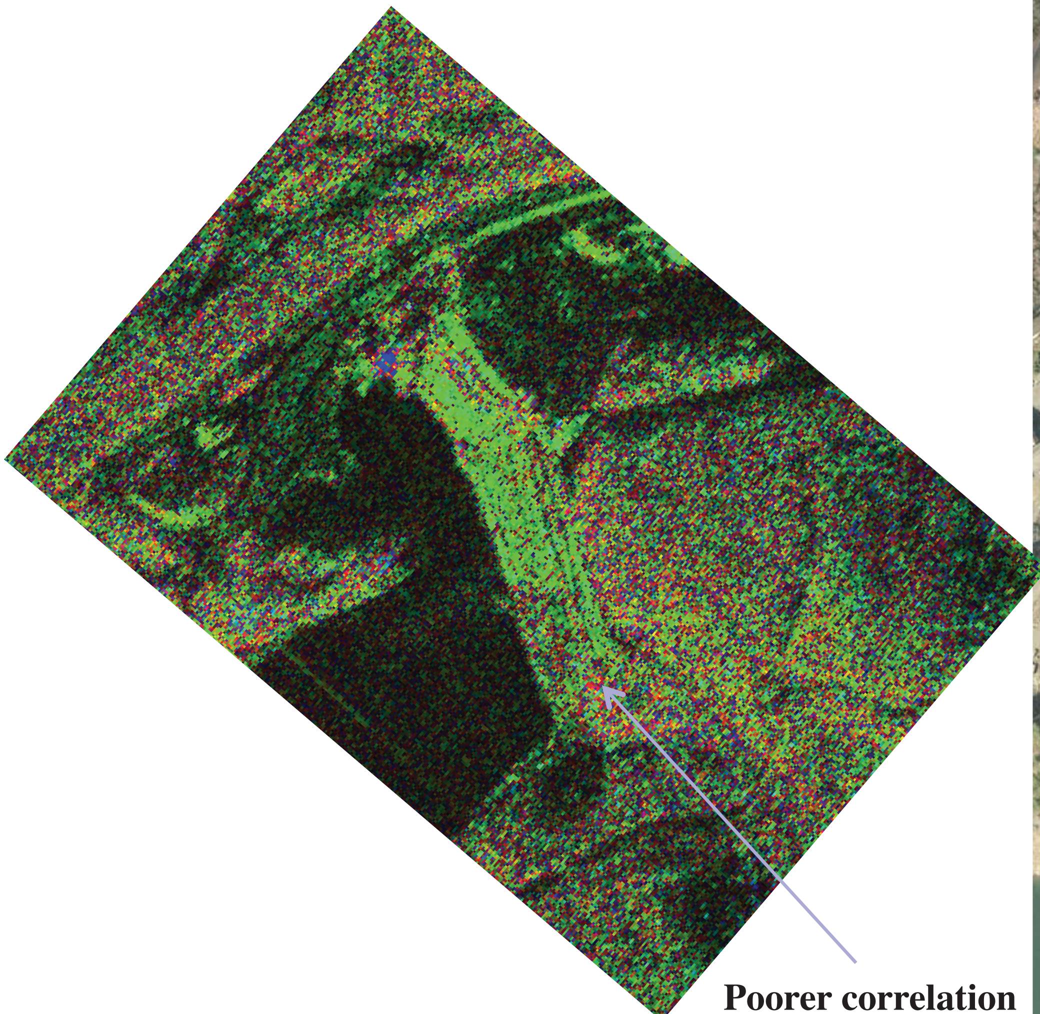


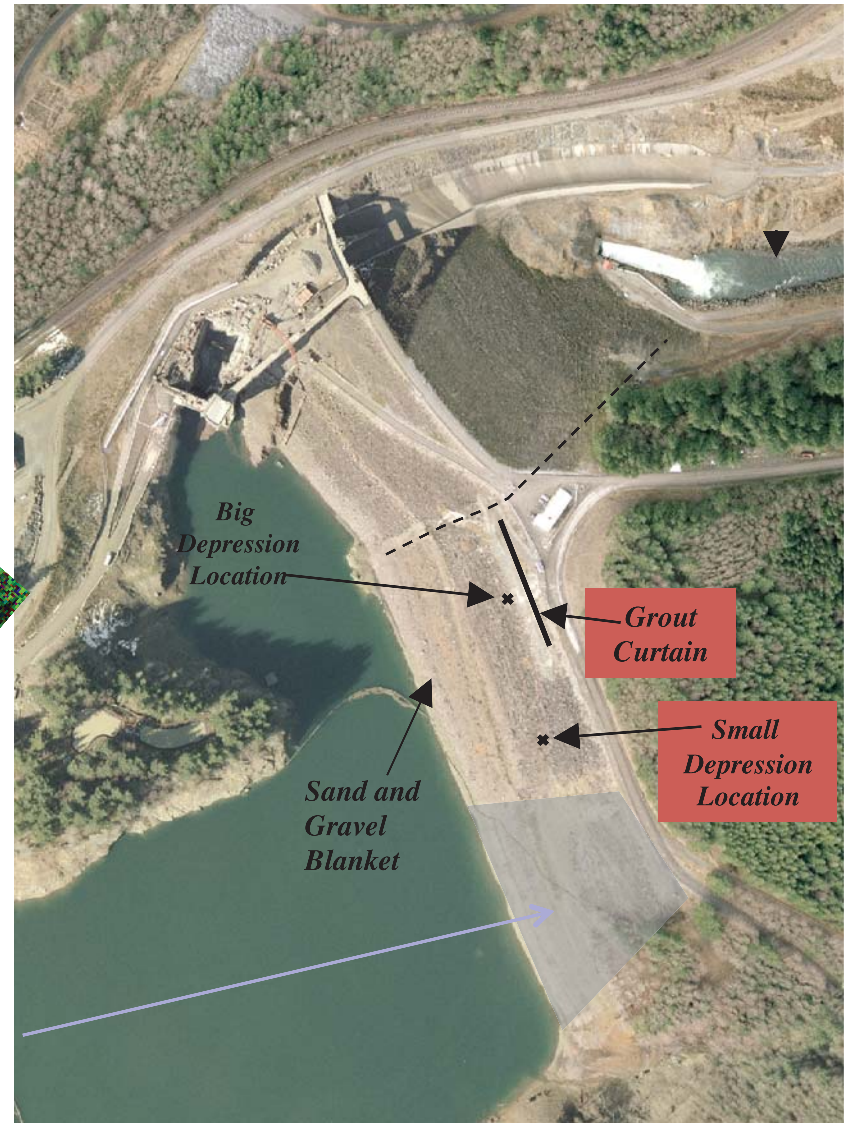
The dam embankment shows no measurable change except very near the roads and waterline.

Forested areas are totally decorrelated.

The area of the right abutment below where the grout wall was installed shows less change than the eastern section of the embankment.

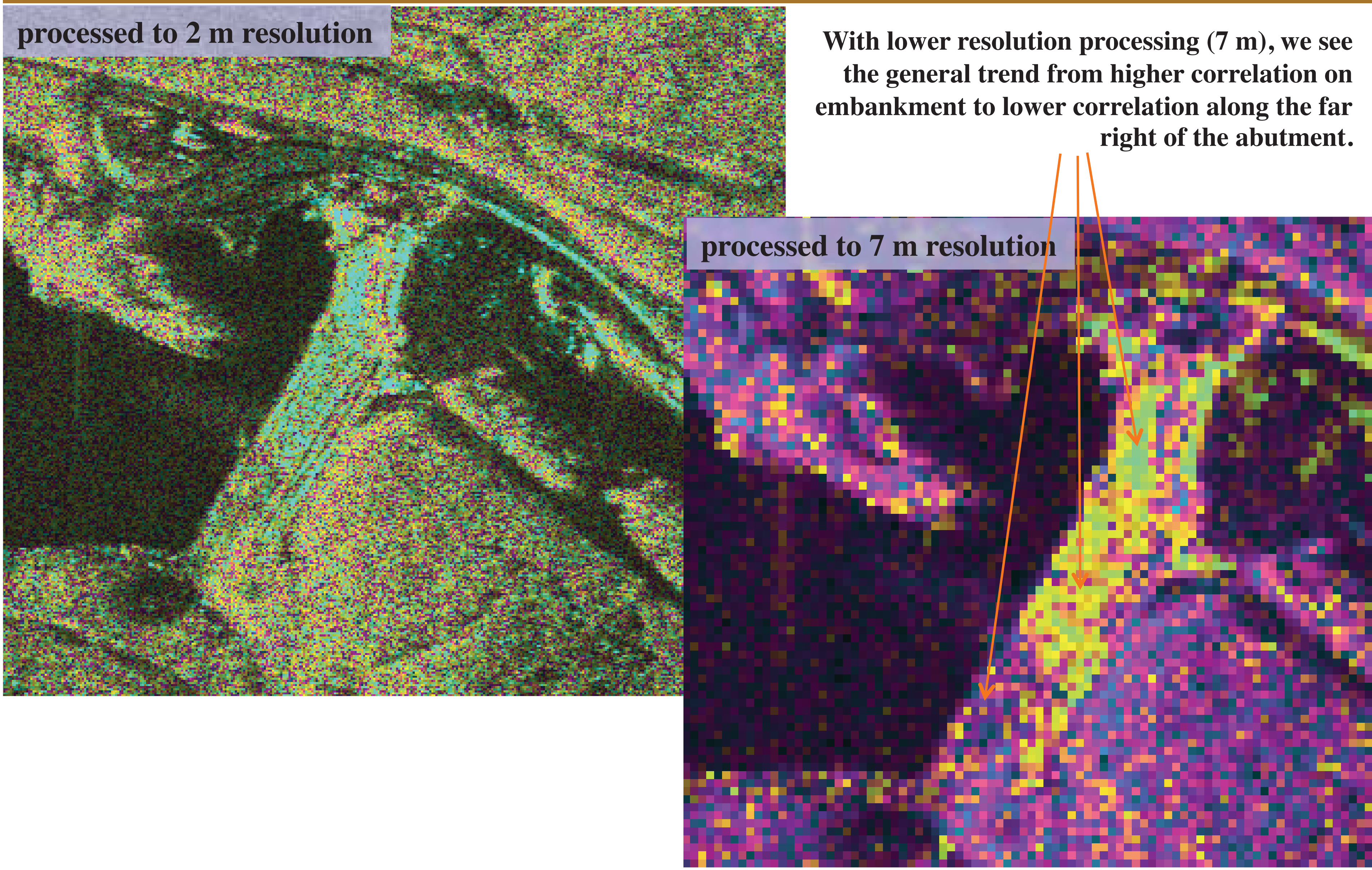
Howard Hanson Dam
Grout Curtain Location





Poorer correlation
=> changed more

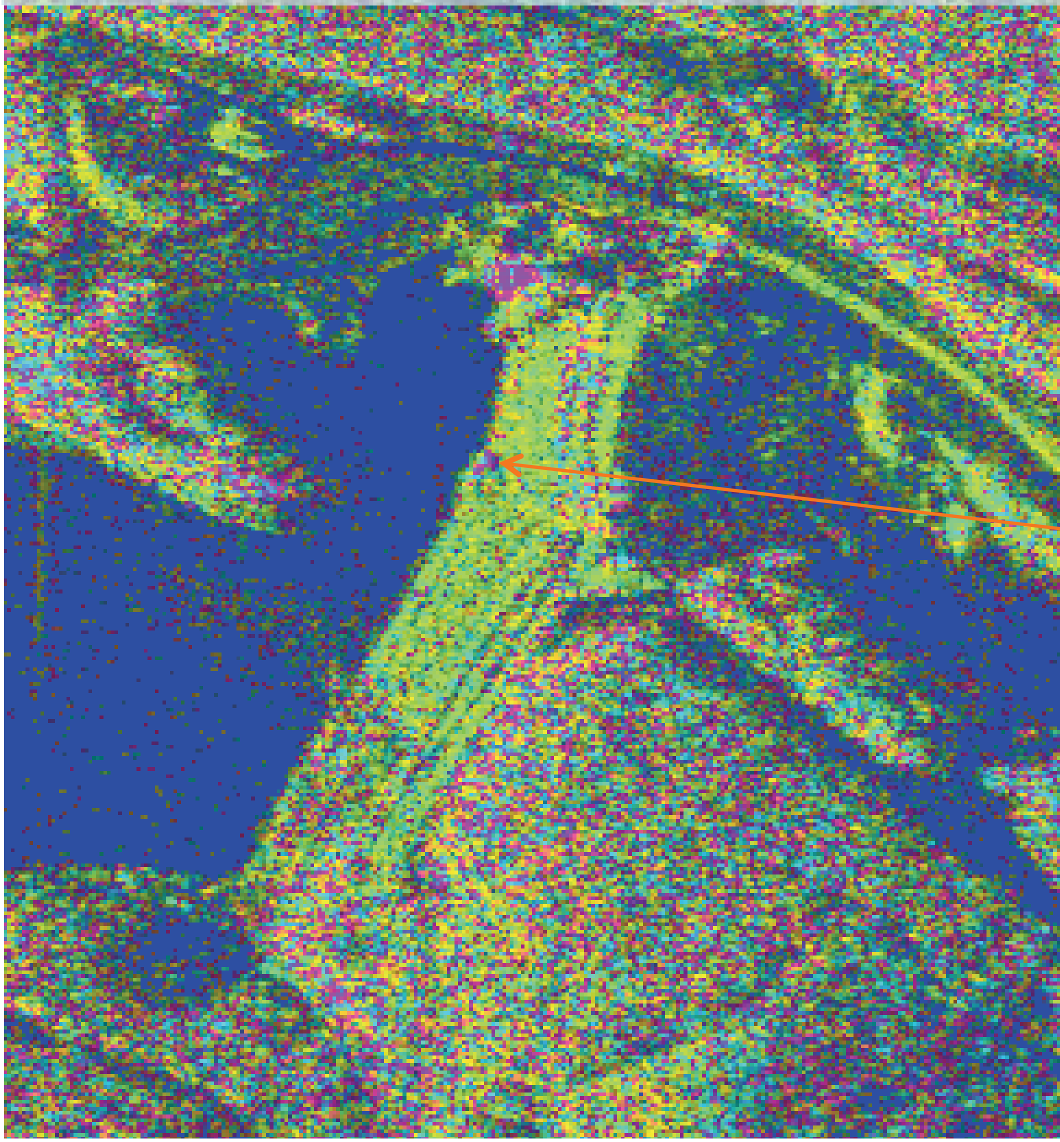
UAVSAR Nov. 2009 to Nov. 2010
Radar Data Processed for Change Detection - Correlation

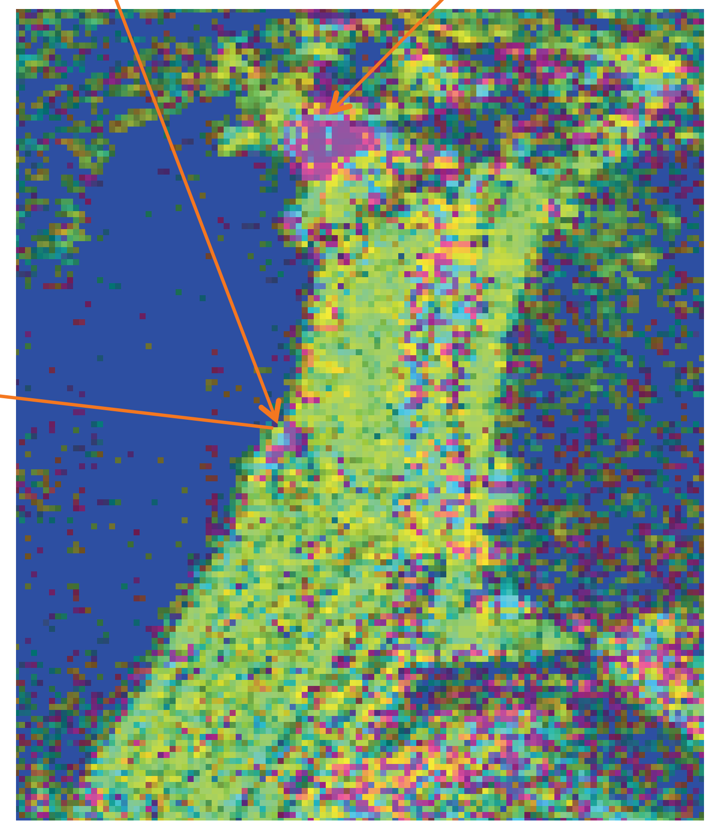


With lower resolution processing (7 m), we see the general trend from higher correlation on embankment to lower correlation along the far right of the abutment.

UAVSAR Nov. 2009 to Nov. 2010
Radar Data Processed for Movement – Interferometric Phase

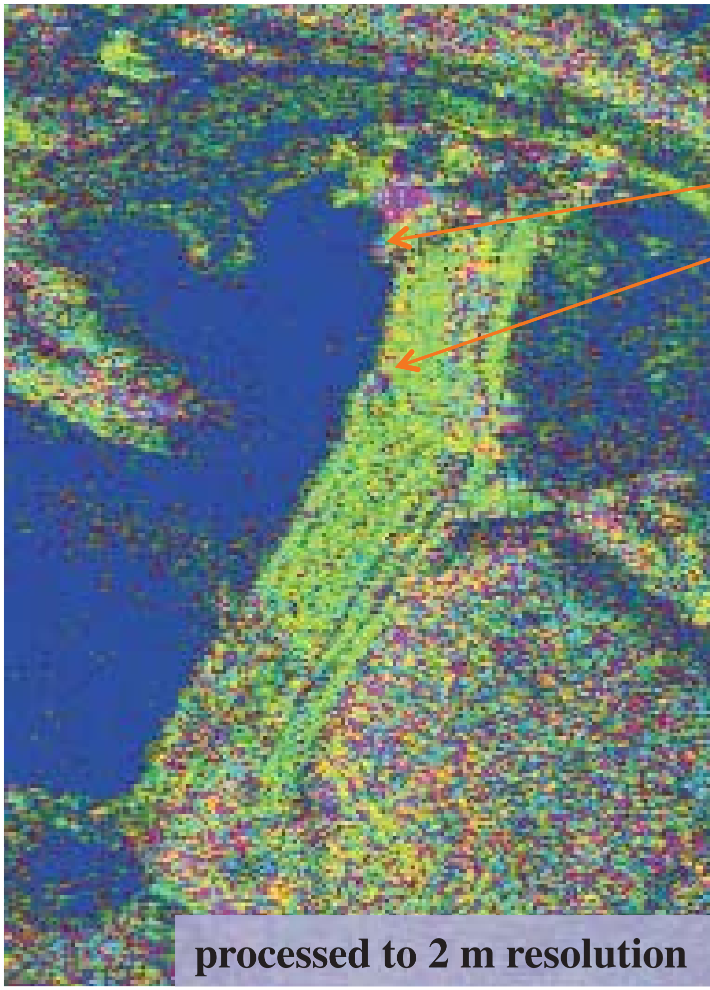
Phase with low values masked (blue) to see upstream face:

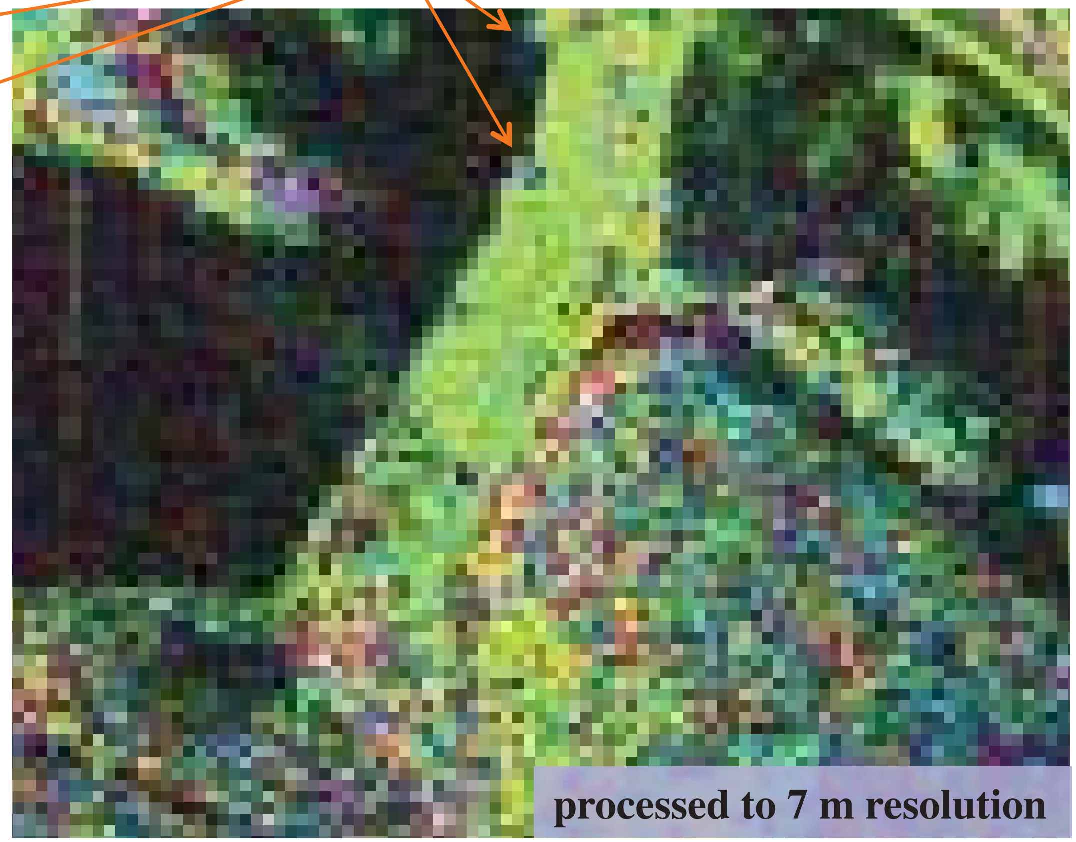




UAVSAR Nov. 2009 to Nov. 2010
Radar Data Processed for Movement – Interferometric Phase

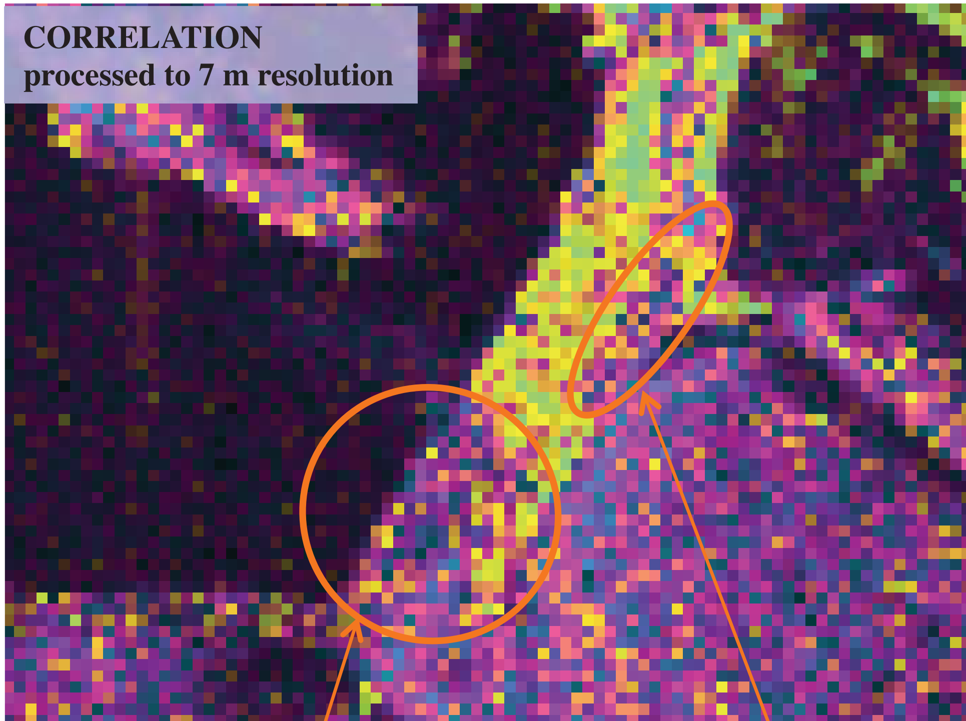
With lower resolution processing (7 m), noise is reduced, allowing us to confirm locations most likely to have really shifted.

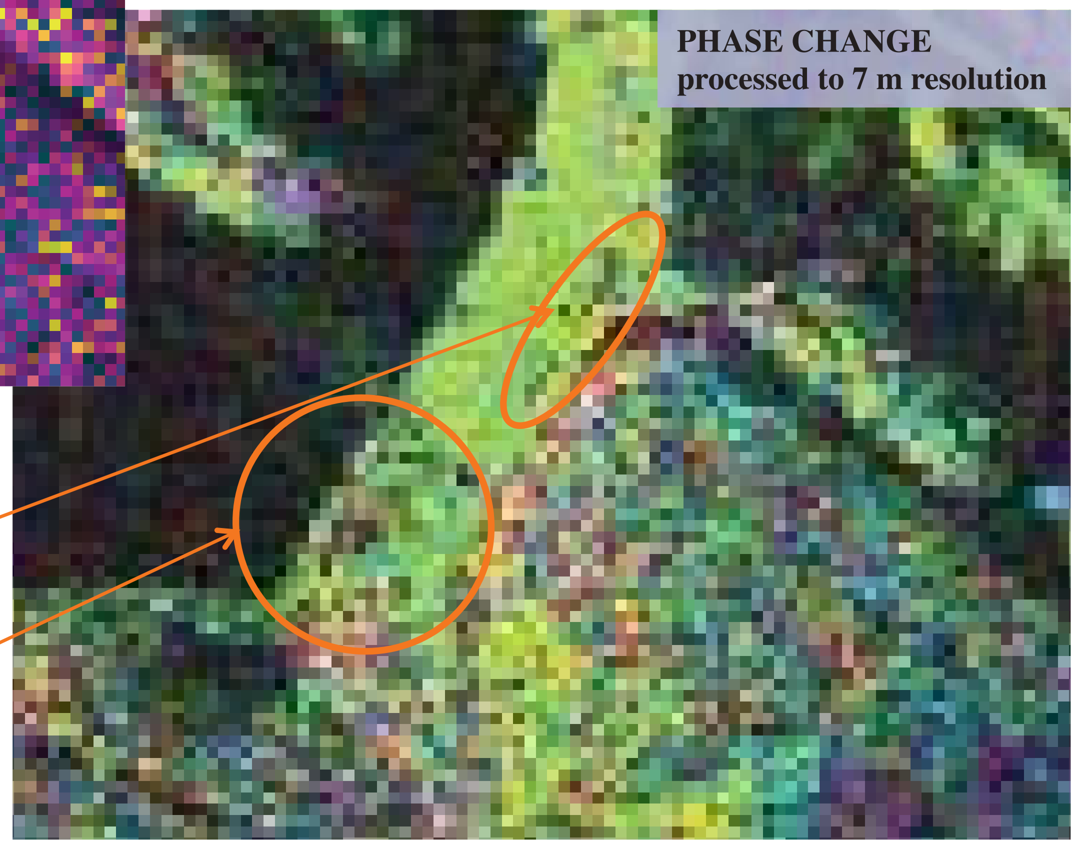




UAVSAR Nov. 2009 to Nov. 2010
Identification of Areas with Most/Least Change

RADAR DATA CAN INFORM GROUND OBSERVATIONS TO FOCUS ON AREAS SHOWING THE MOST CHANGE.





Equipment Movement?

Vegetation? Rock movement? Moisture?

Conclusions

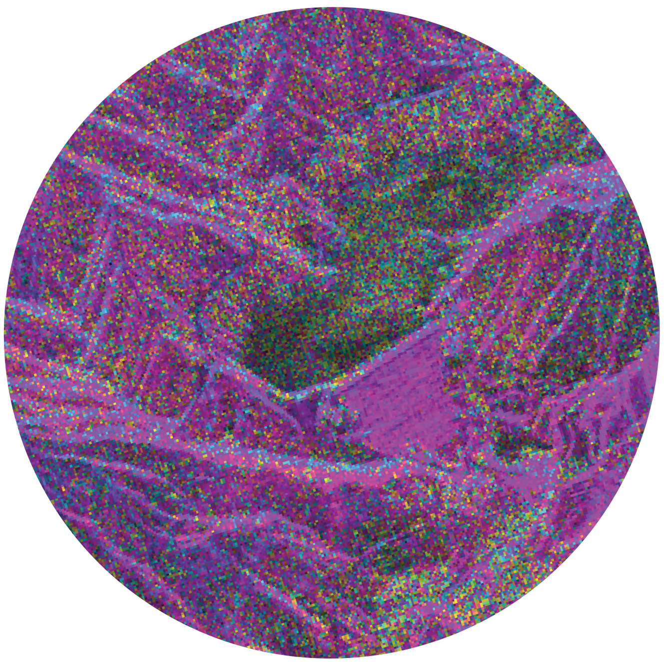
1. For the Howard A. Hanson dam, no major movement or seepage were noted on either face or on the upstream right abutment.
2. The radar coherence in this study was limited by the year repeat time and by the movement of equipment during the group wall installation.

Recommendations:

- Equipment movement and relocation adds significant noise to the radar images so we should create a baseline of the dam faces before major work is done or several times after equipment removal.
- Image dams more frequently and especially before/after major changes.
- Tailor acquisitions to weather patterns in region and to pool raising/lowering, especially for detection of seepage.

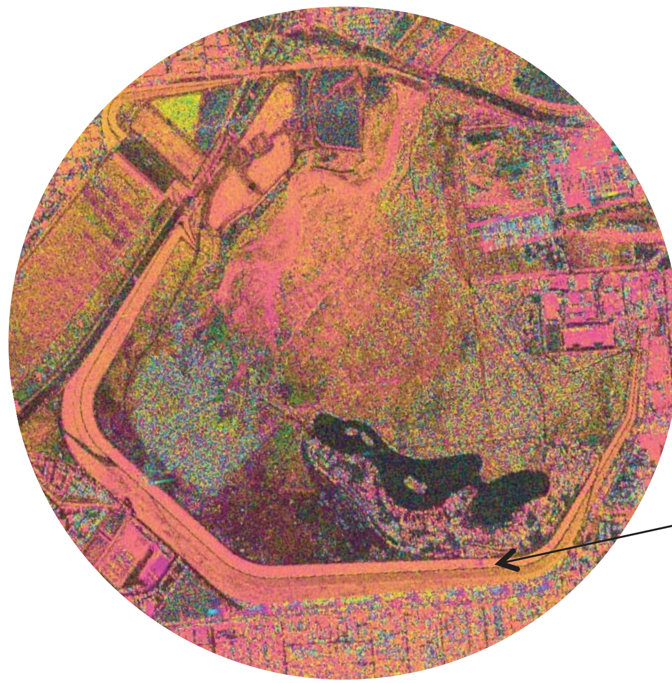
Other Dams – Los Angeles County

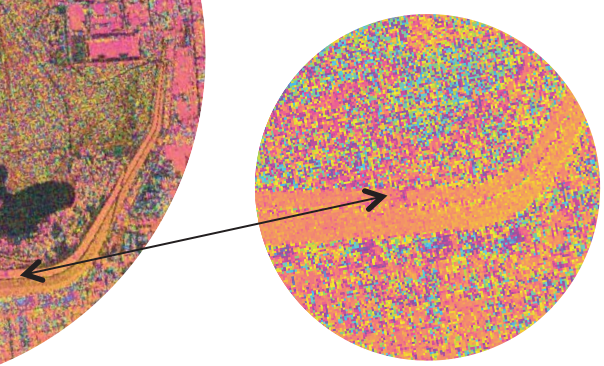
San Gabriel Dam
391 days
9/18/2009 to 10/14/2010



Santa Fe Dam
391 days
9/18/2009 to 10/14/2010

Very high correlation is maintained over 13 months because of no vegetation, little access, and low precipitation.

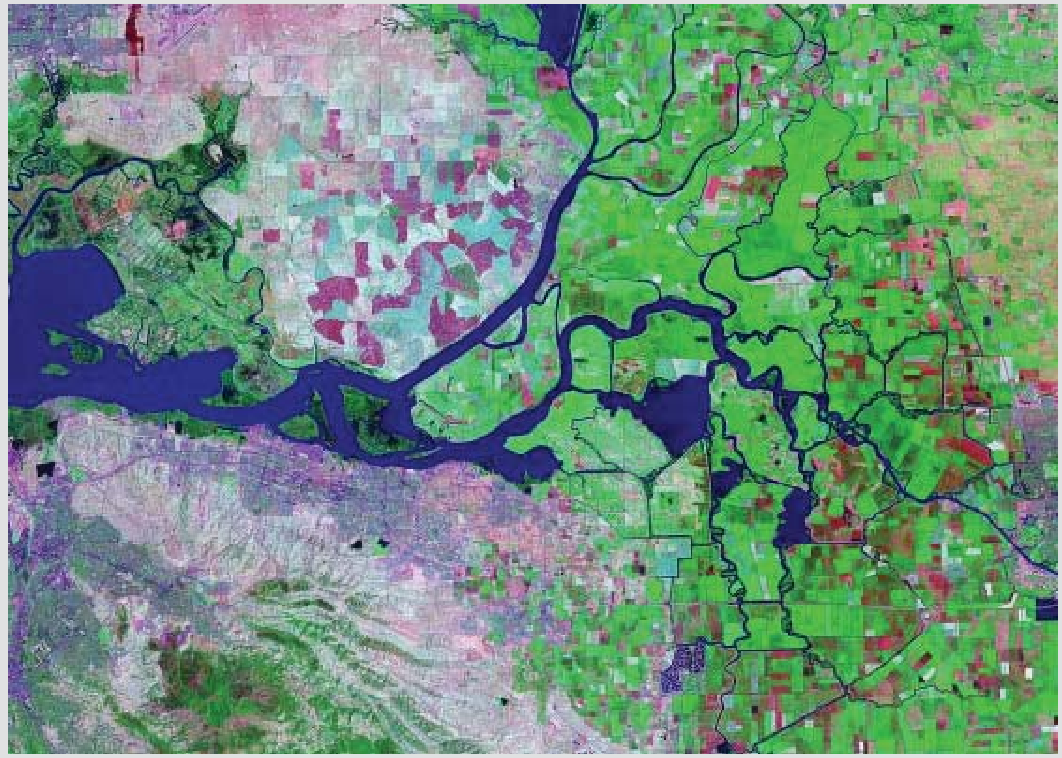




Monitoring the Levees of the Sacramento-San Joaquin Delta with the UAVSAR Radar

The Sacramento-San Joaquin Delta

Critical Infrastructure: The Levees



- Over 60 reclaimed islands surrounded by 1100 miles of levees
- Most islands lie below mean sea level.
- Collects run-off from approximately 2/3 of the state via the Sacramento and San Joaquin rivers.
- Supplies water to ~2/3 of the residents of California and to almost all of the agriculture of the Central Valley.

The delta is the most critical water resource in California.

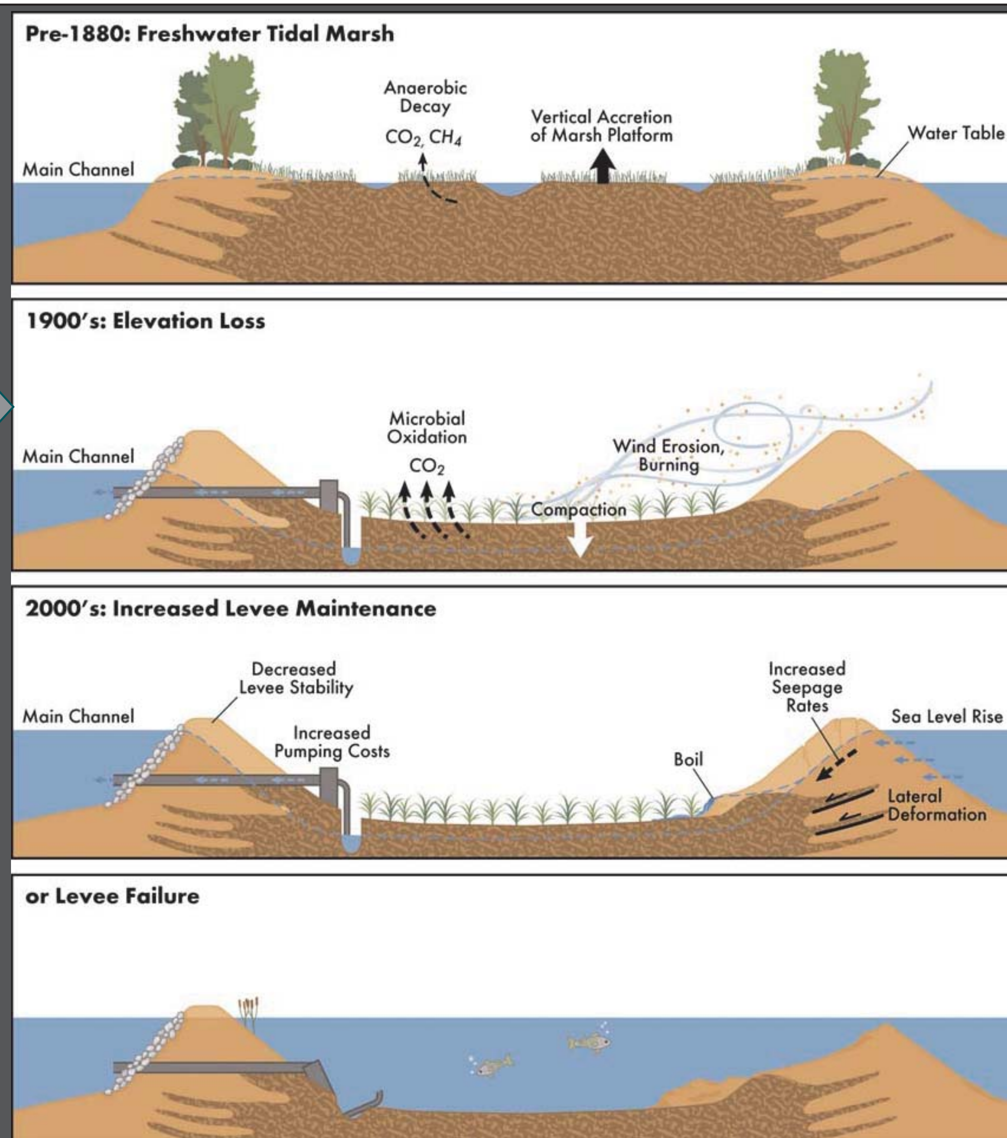
The Delta at Risk

SUBSIDENCE MECHANISMS

Levees are at risk from constant hydrostatic pressure because of subsidence.

Conceptual diagram illustrating evolution of Delta islands due to levee construction and island subsidence.

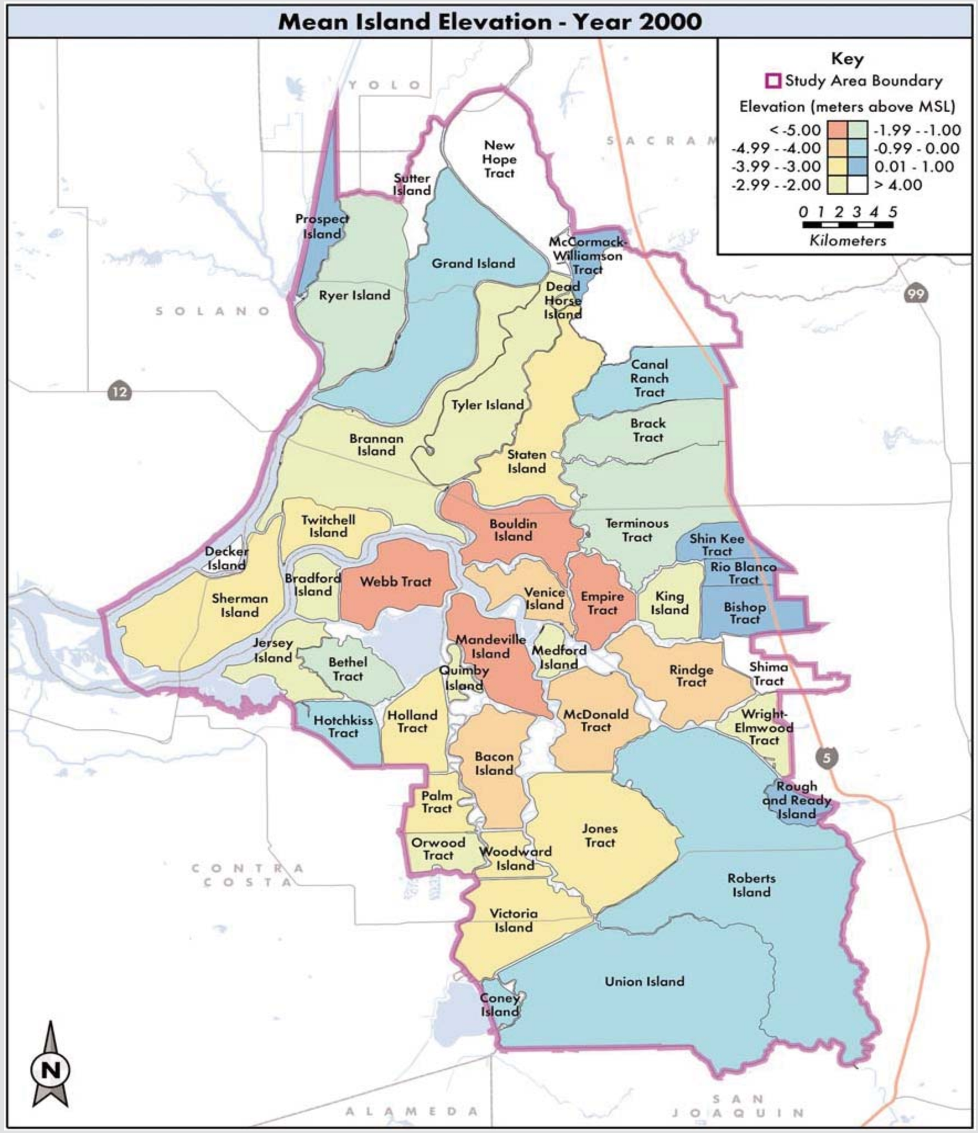
Subsidence rates and the dominant subsidence mechanism varies from island to island with the soil type. In high peat soils, the dominant subsidence mechanism is aerobic microbial oxidation, which releases CO_2 as a by-product.



From Mount and Twiss, 2004

Subsidence in the Sacramento-San Joaquin Delta

AN ONGOING AND LONG-TERM ISSUE



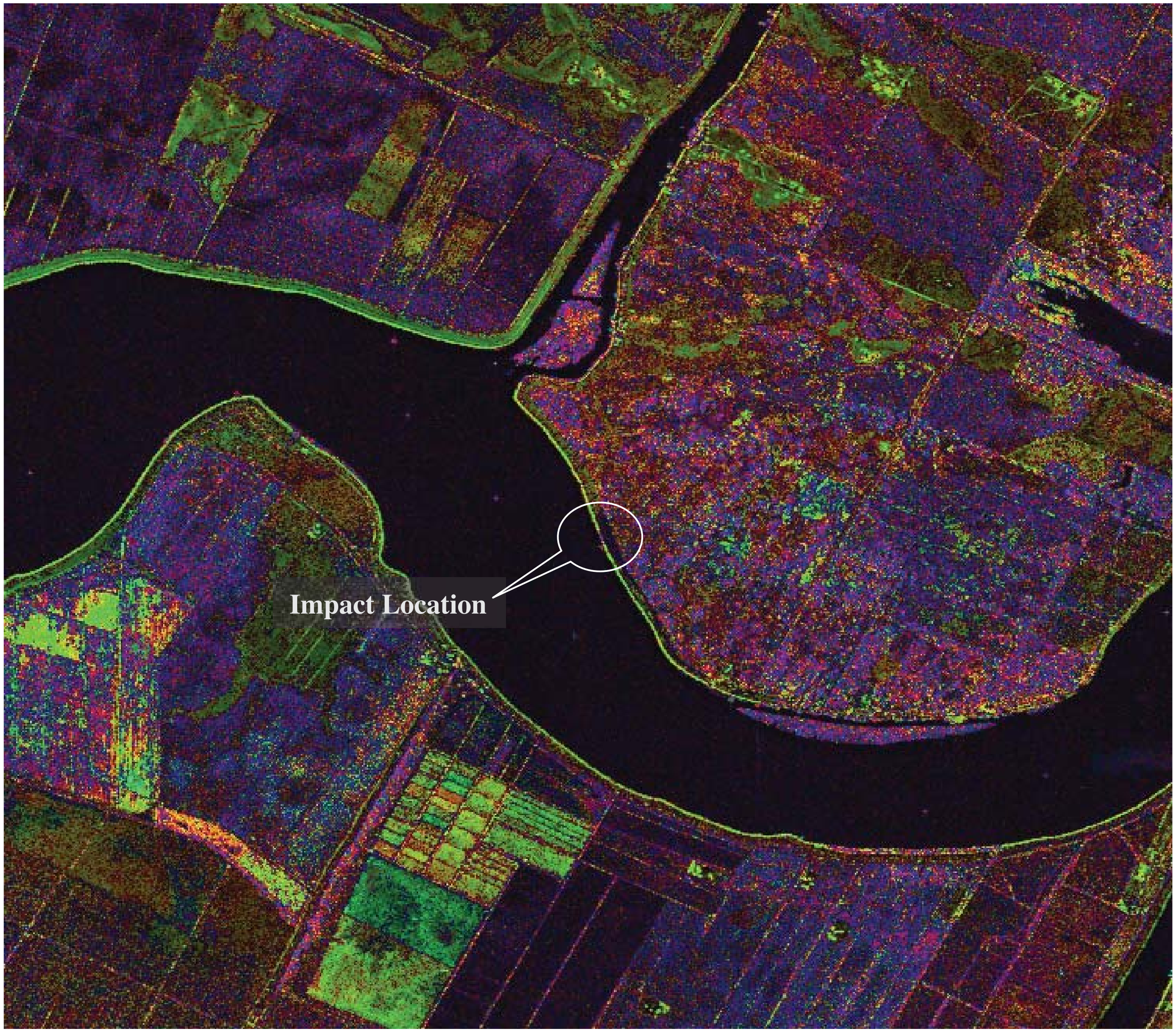
From "Subsidence, Sea Level Rise, and Seismicity in the Sacramento – San Joaquin Delta," Jeffrey Mount and Robert Twiss, San Francisco Estuary & Watershed Science, March 2005.

Example: Levee Monitoring

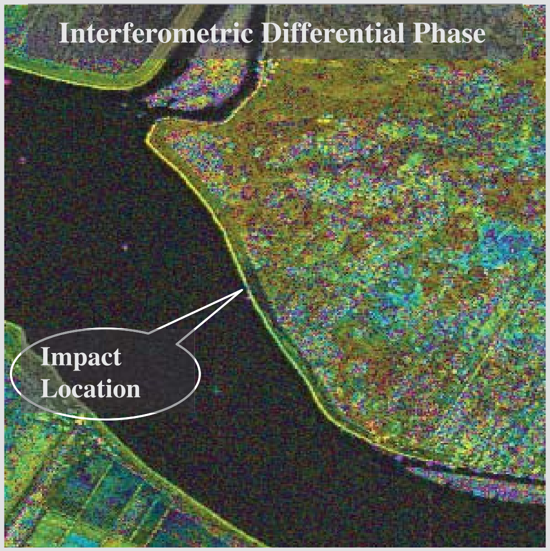
Sacramento San-Joaquin Delta

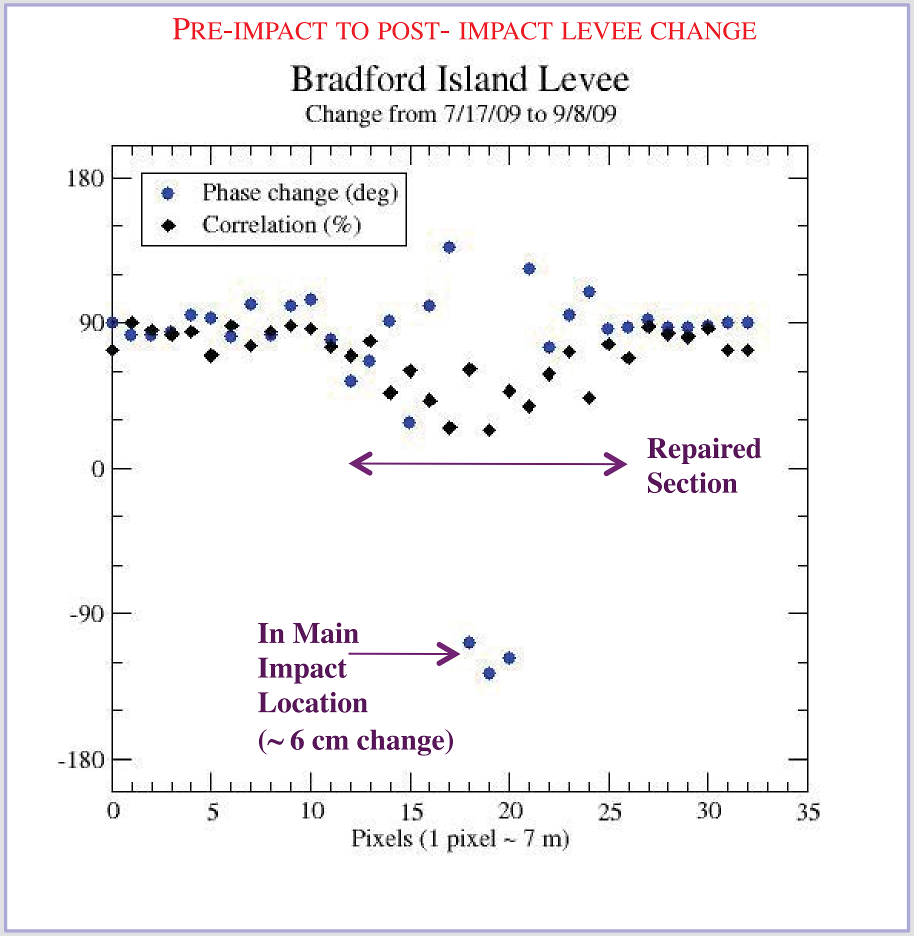
On August 28, 2009 a ship rammed the north levee on Bradford Island. This image was made from an interferogram between UAVSAR data collected on July 17 and Sept. 10, so evidence of the impact and repair are seen in the data.

The plot shows a false color map overlaying the differential phase and correlation between the two data sets.



Bradford Island Levee Damage





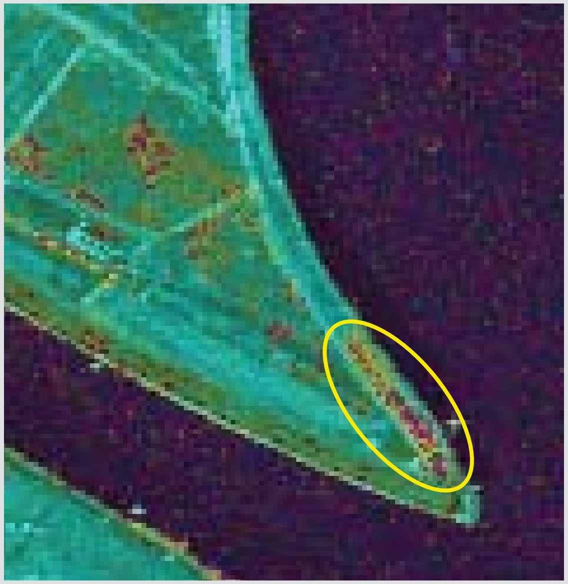
Seep Detection Behind Levees

Twitchell Island – Seep Formation

A seep through the levee developed between July 2010 and June 2011. This is detected in the repeat pass interferometric correlation, measured with the UAVSAR L-band radar, which saw no change behind the levee during the high/low tidal cycle in 2010, but detected a large change the following year.

July 2010

June 2011

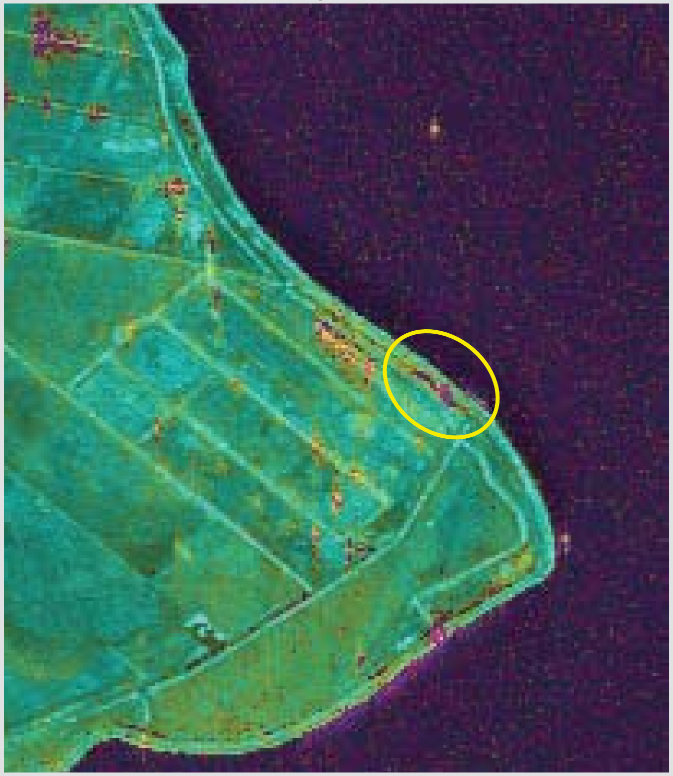


Seep Detection Behind Levees

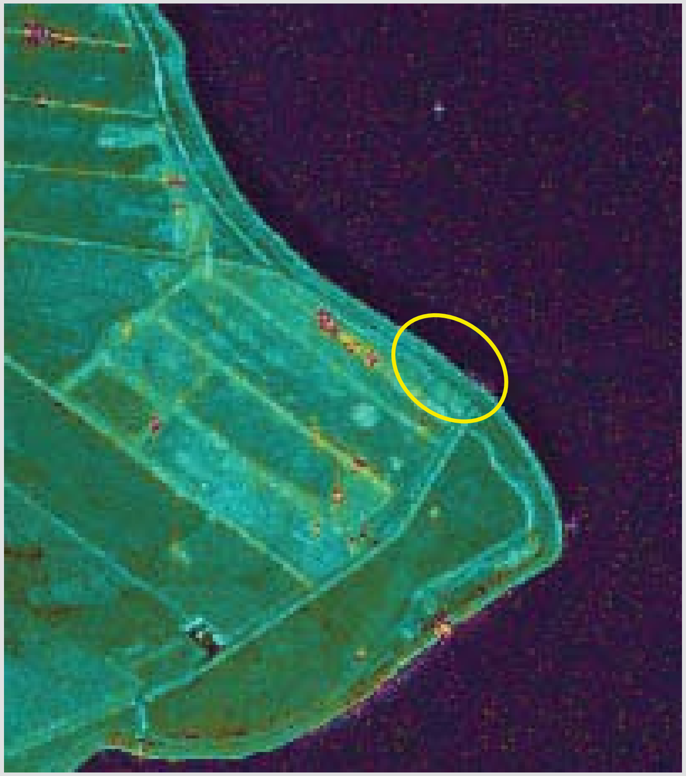
Twitchell Island – Levee Repair

A seep that had been present in 2010 was repaired in May 2011. The seep was identified using the repeat pass interferometric correlation in 2010 but not seen following the repair in 2011.

July 2010



June 2011



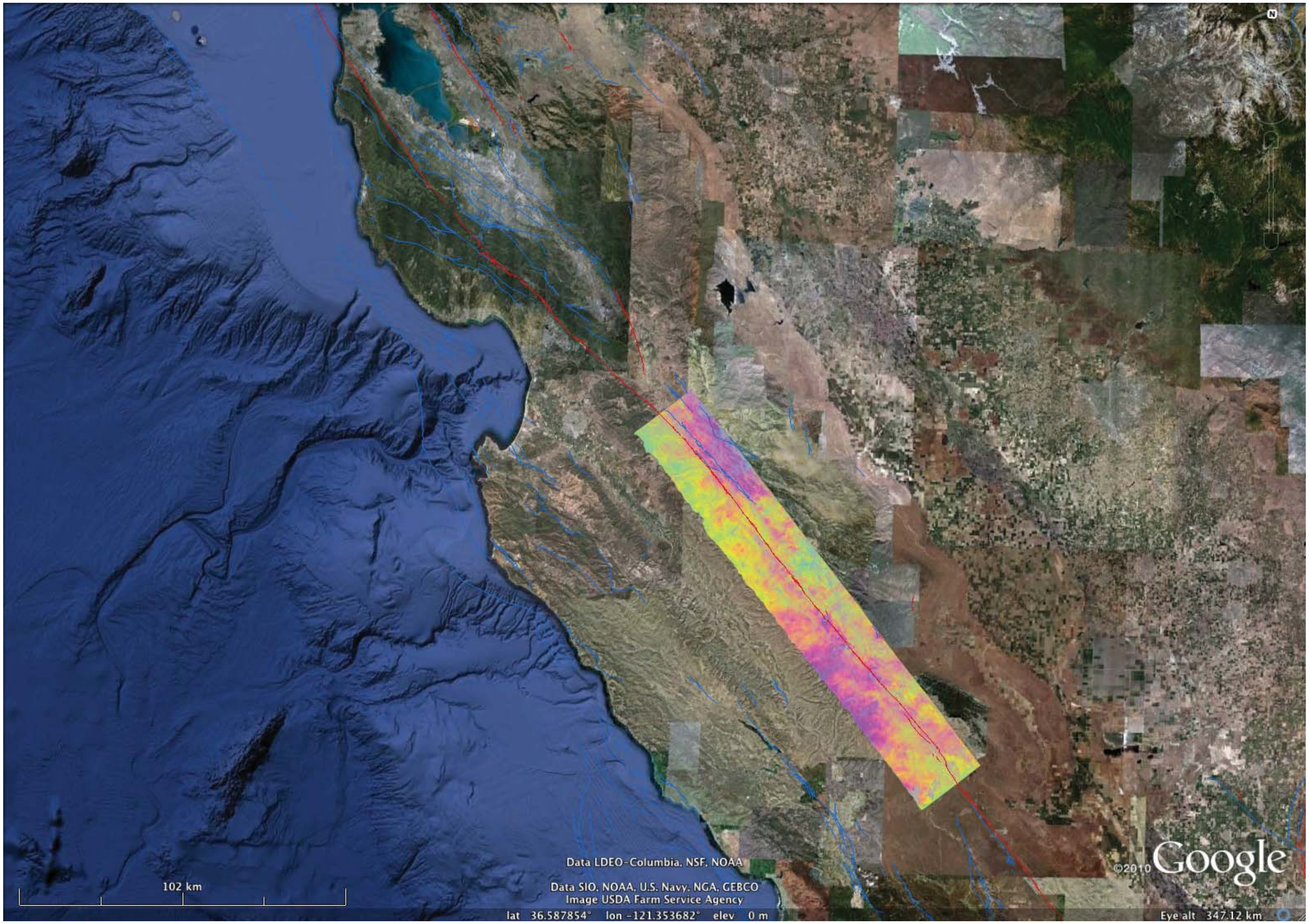
Other Examples of the Use of Radar Remote Sensing for Surface Change Detection and Rapid Response Applications

All-Weather Flood Monitoring

Mississippi River, Spring 2011

Landslide Detection

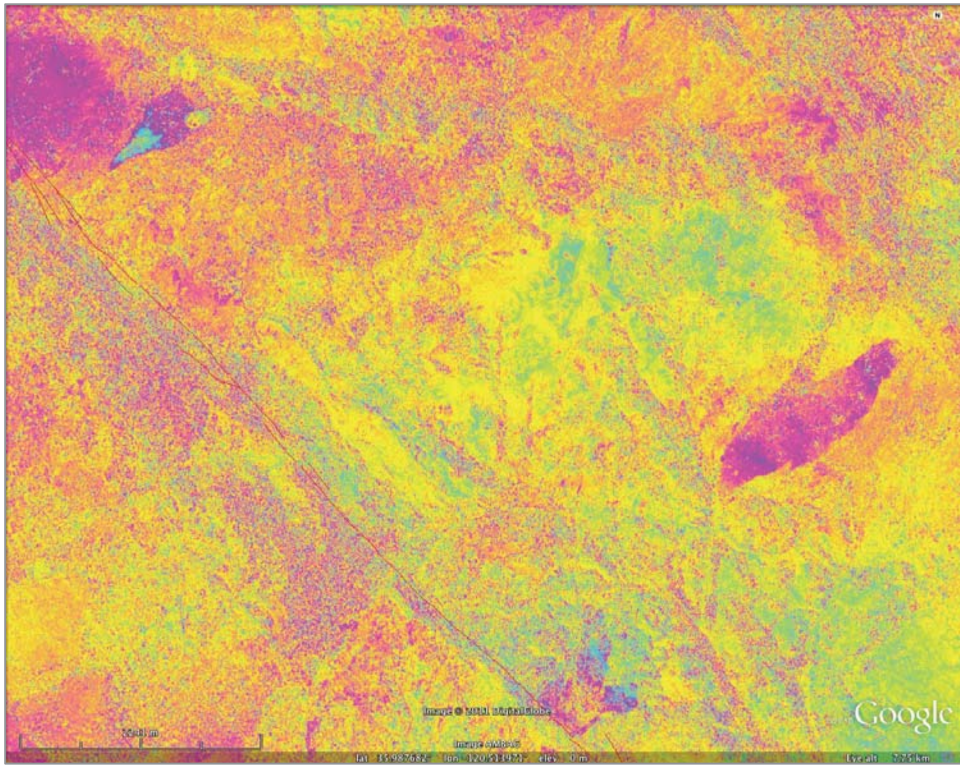
California Coast Mountain Ranges – Diablo Range and the San Andreas Fault



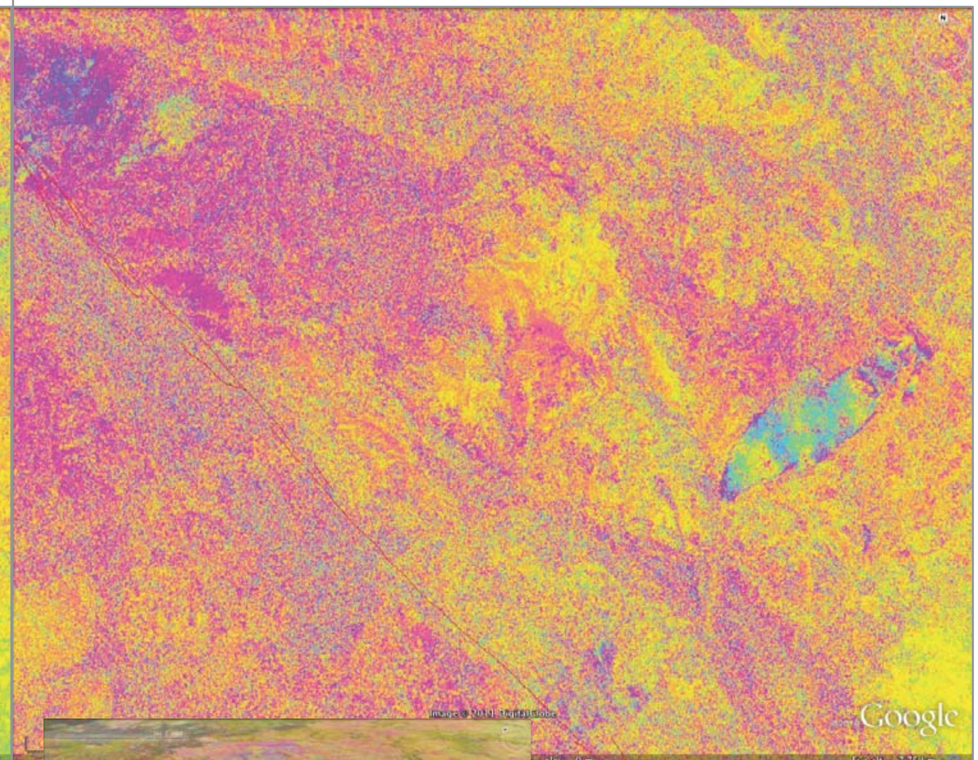
Landslide Detection

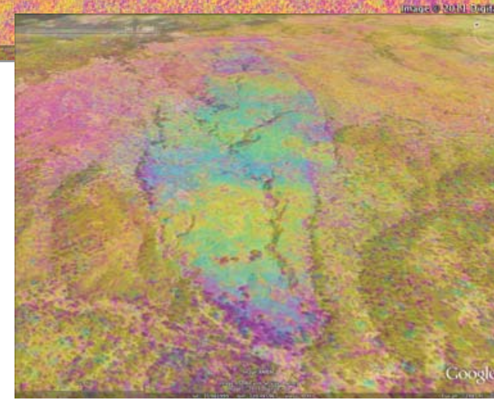
Slow Creep Landslides

189 days
5/11/2010 to 11/16/2010



427 days
5/11/2010 to 7/12/2011

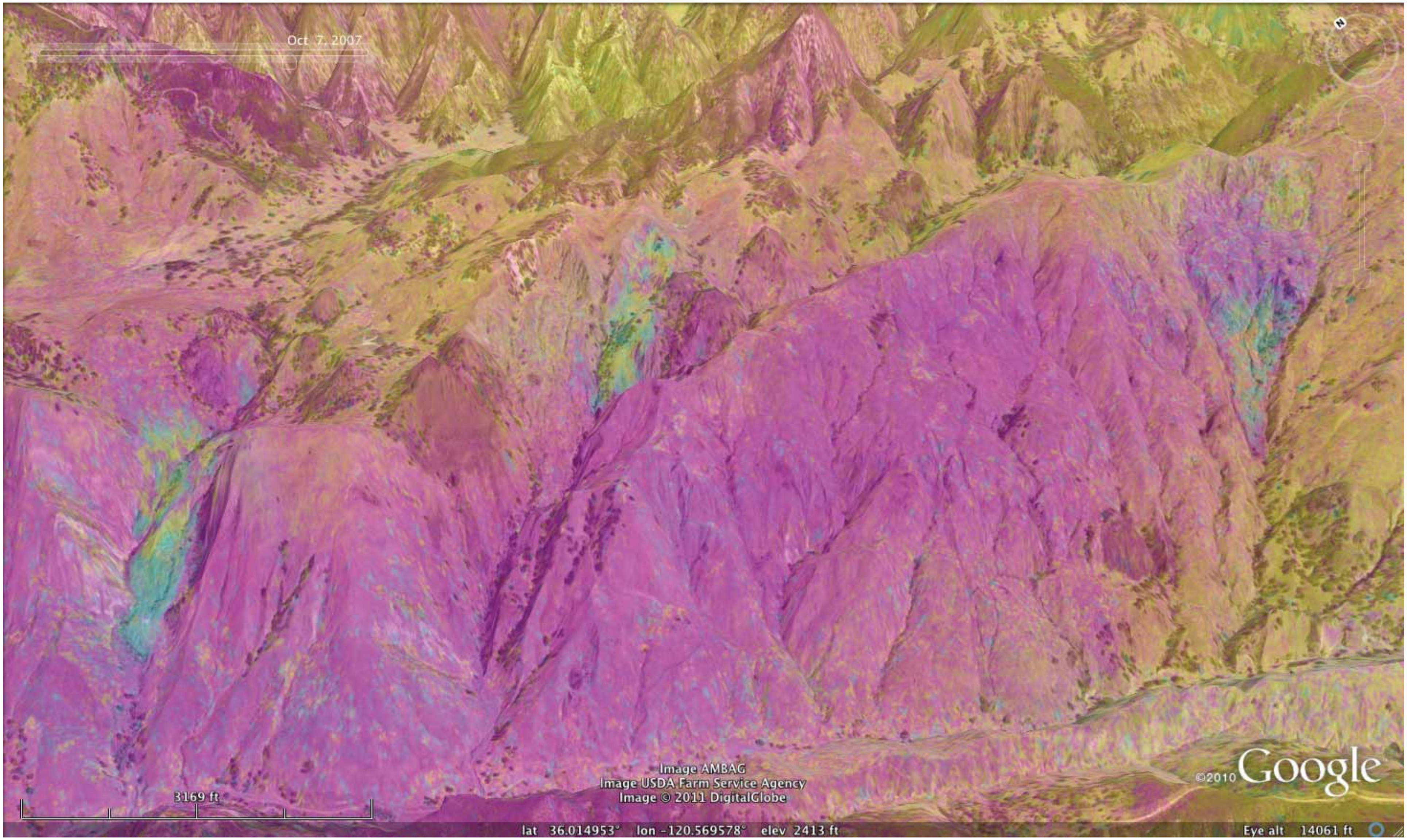




Landslide Detection

Slow Creep Landslides and Rotation Slumps

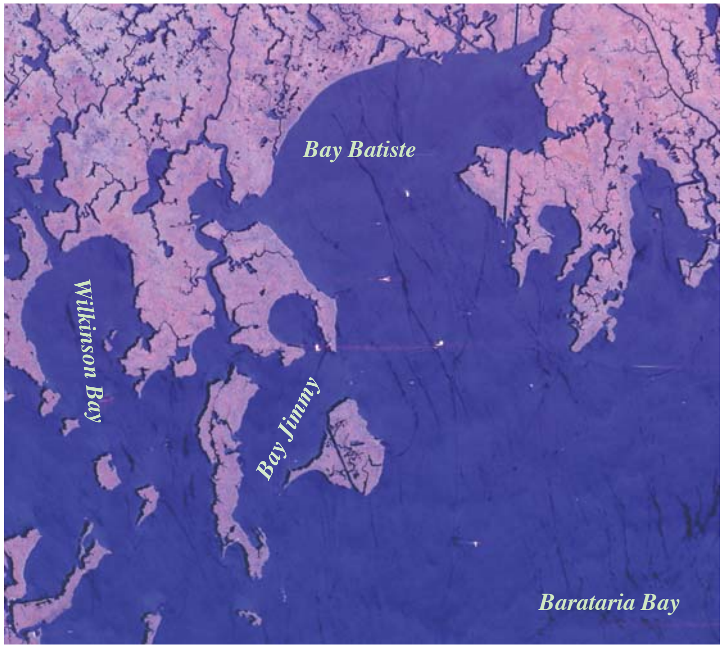
189 days   5/11/2010 to 11/16/2010



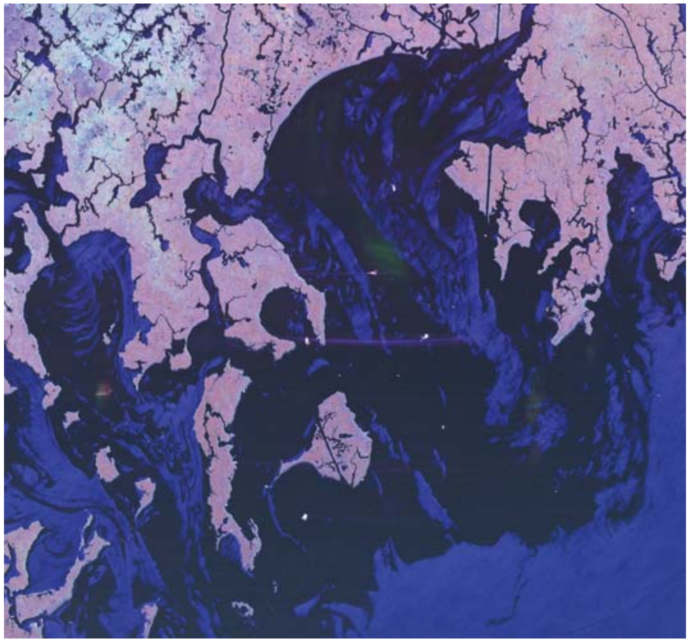
Oil Spill Detection within Coastal Waterways

Deepwater Horizon Spill – Impact within Barataria Bay, Louisiana

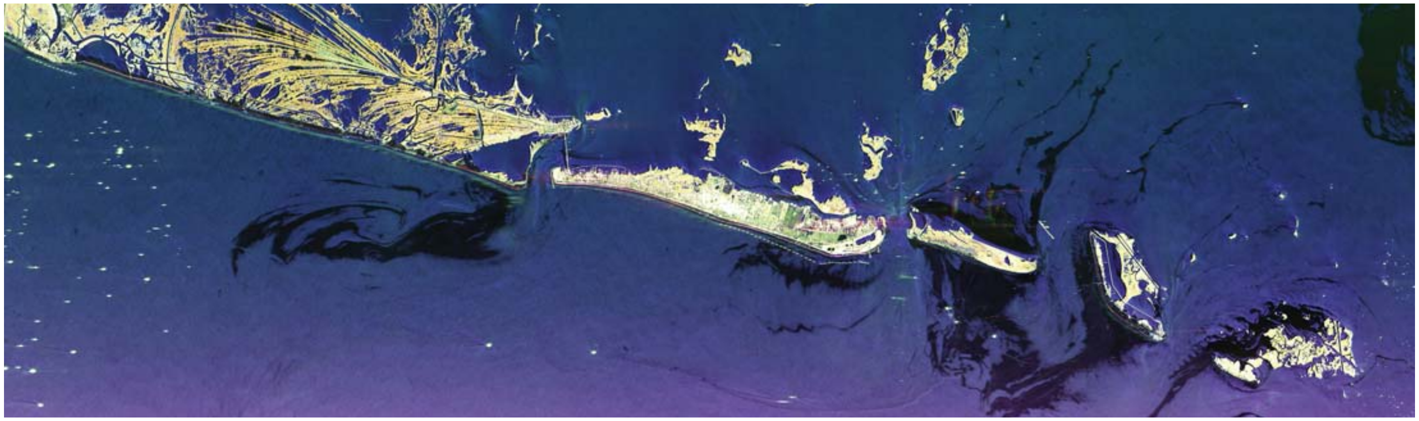
Pre-spill: June 17, 2009



During the spill: June 23, 2010



During the spill: June 23, 2010

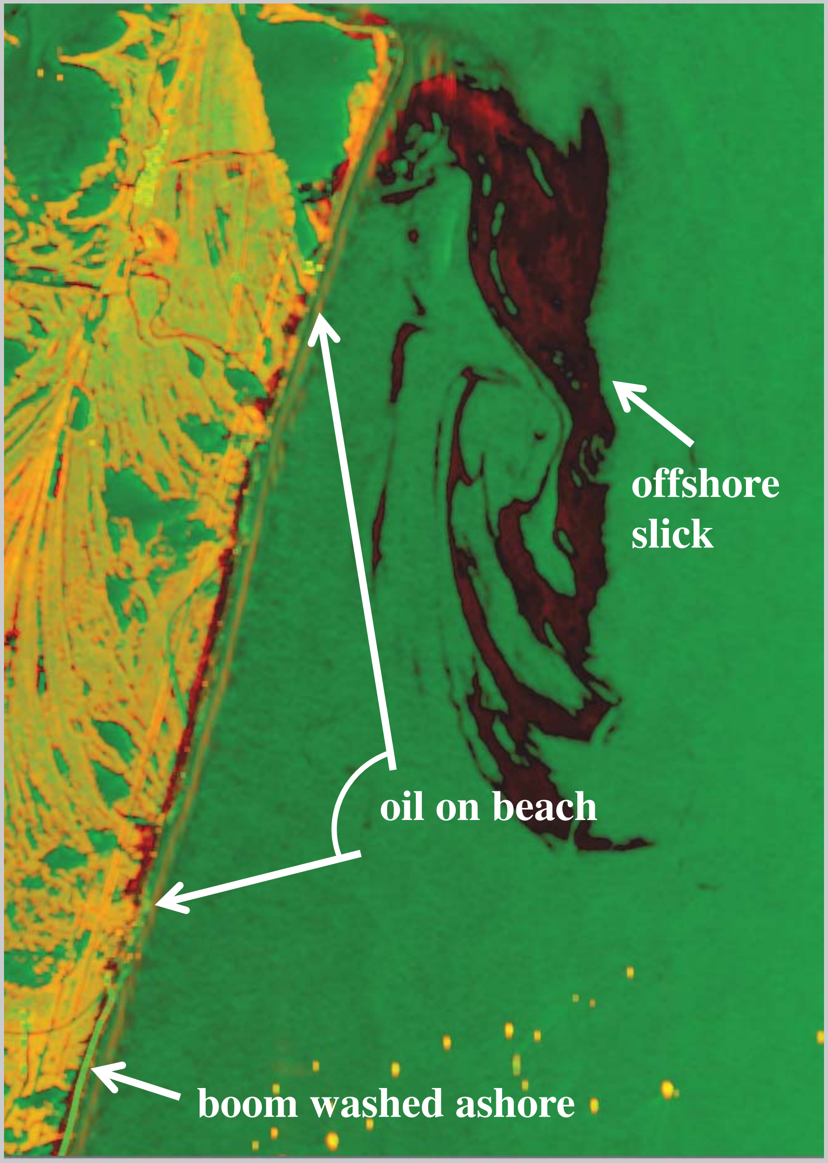


Oil Spill Detection on Beaches

Deepwater Horizon Spill – Coastal Beach Impacted Area Identification

Elmer's Island, Louisiana
June 23, 2010

High resolution L-band radar can be used to identify newly oiled areas overnight to direct response crews the following day.

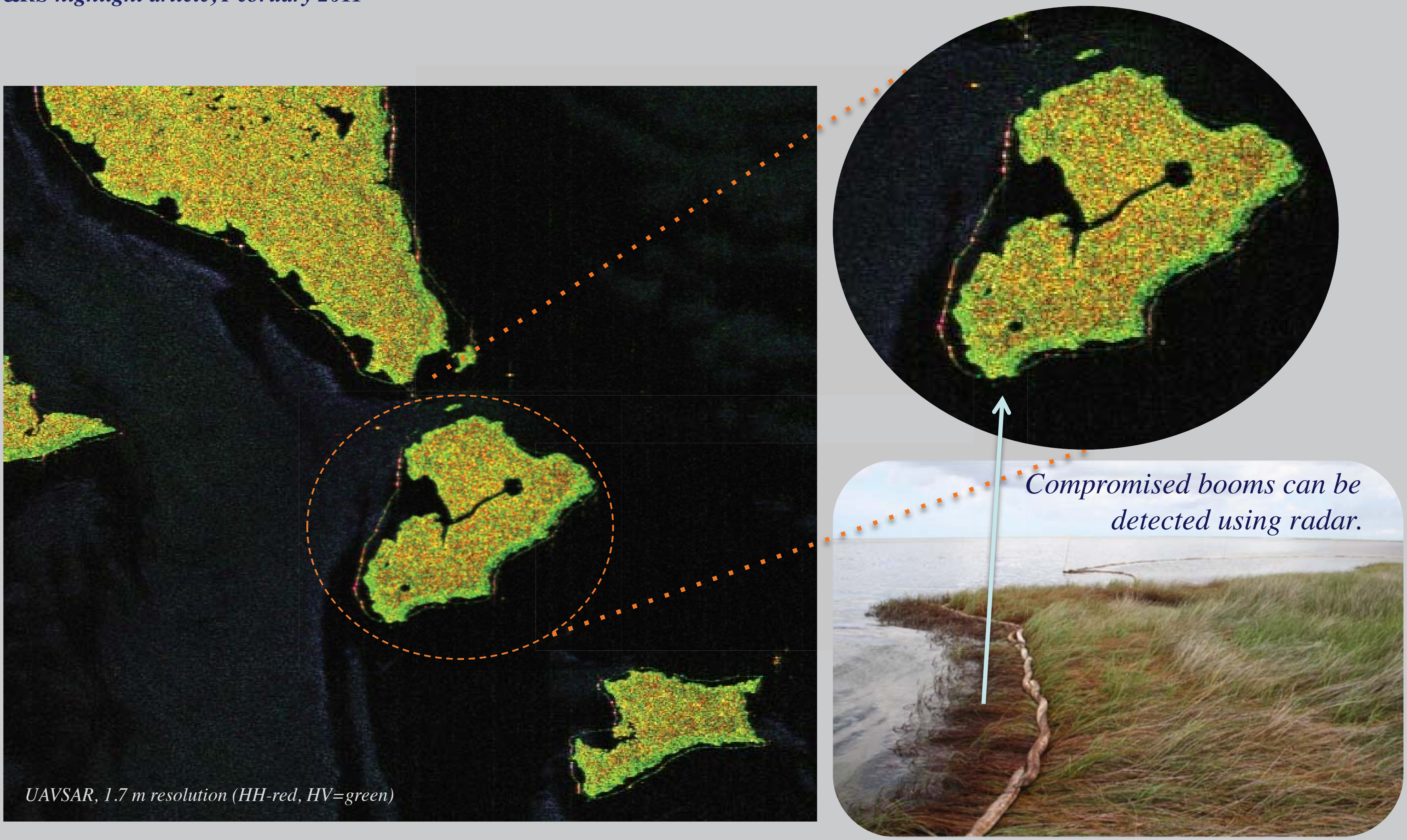


C. E. Jones, B. Holt, S. Hensley (JPL), B. Minchew (Caltech)

High Resolution Radar for Response and Recovery: Monitoring Containment Booms in Barataria Bay

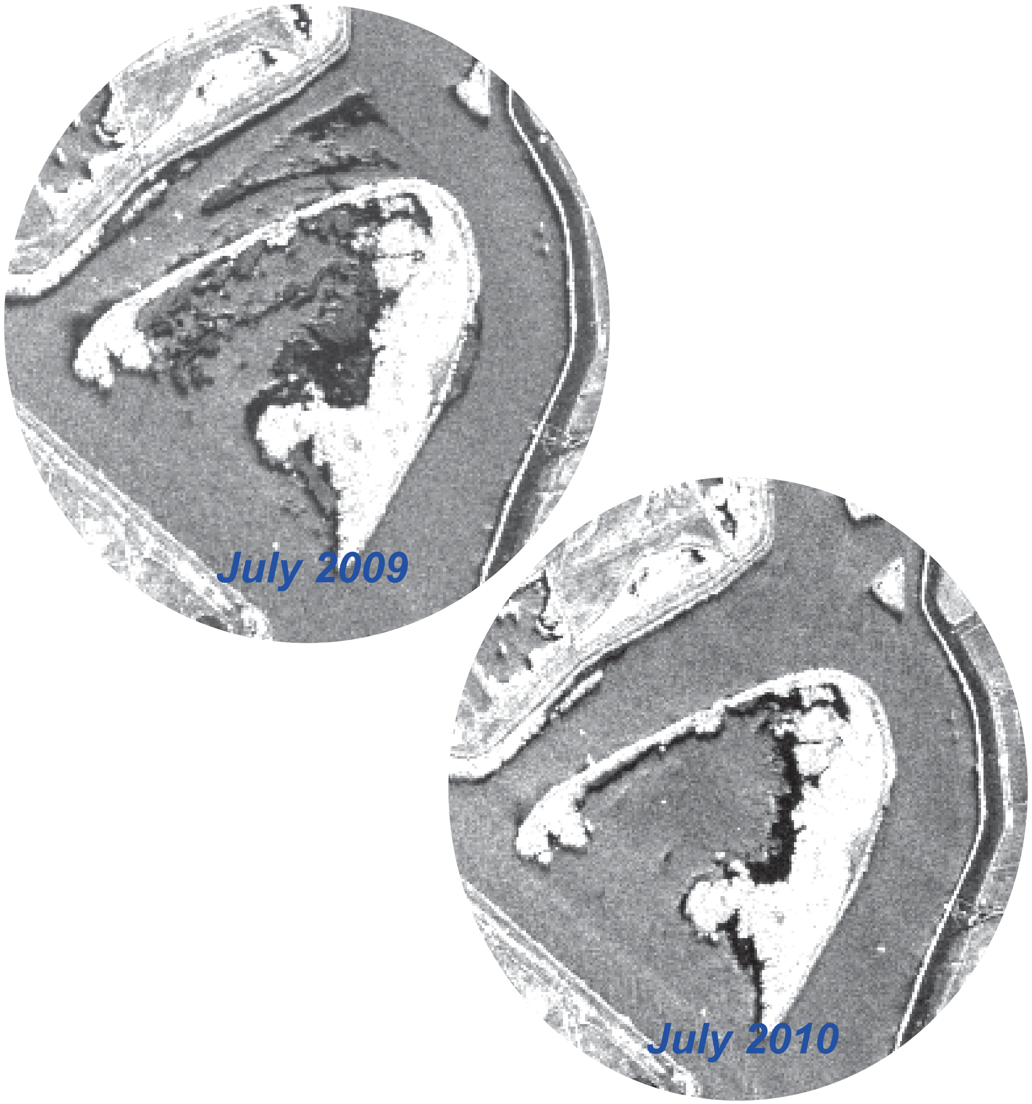
Cathleen Jones *(JPL/Caltech)*, Bruce A. Davis *(DHS)*

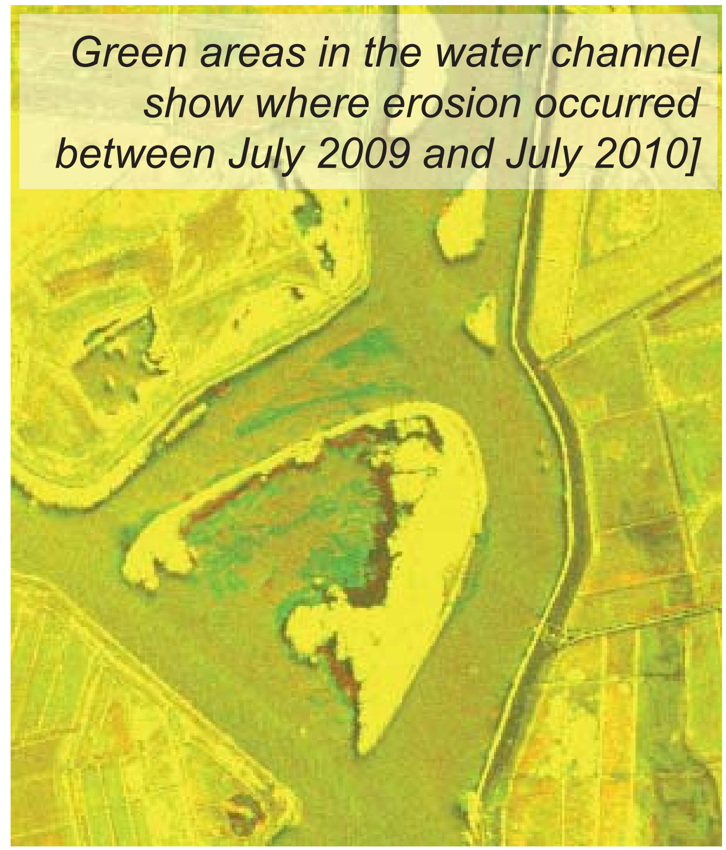
PE&RS highlight article, February 2011



Example: Sediment Transport

Deposition and Erosion (Sacramento Delta)





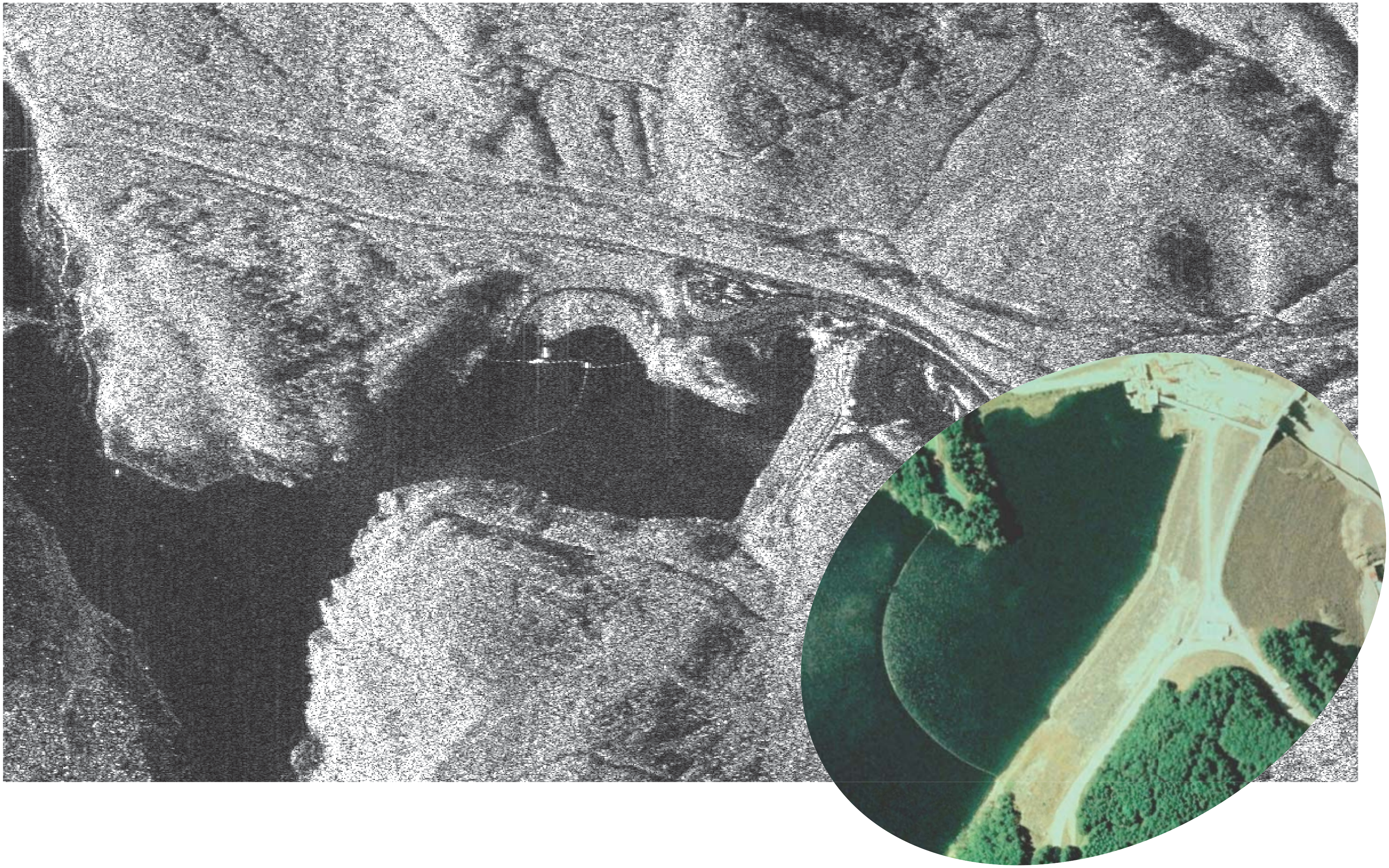
Discussion

Extra Slides

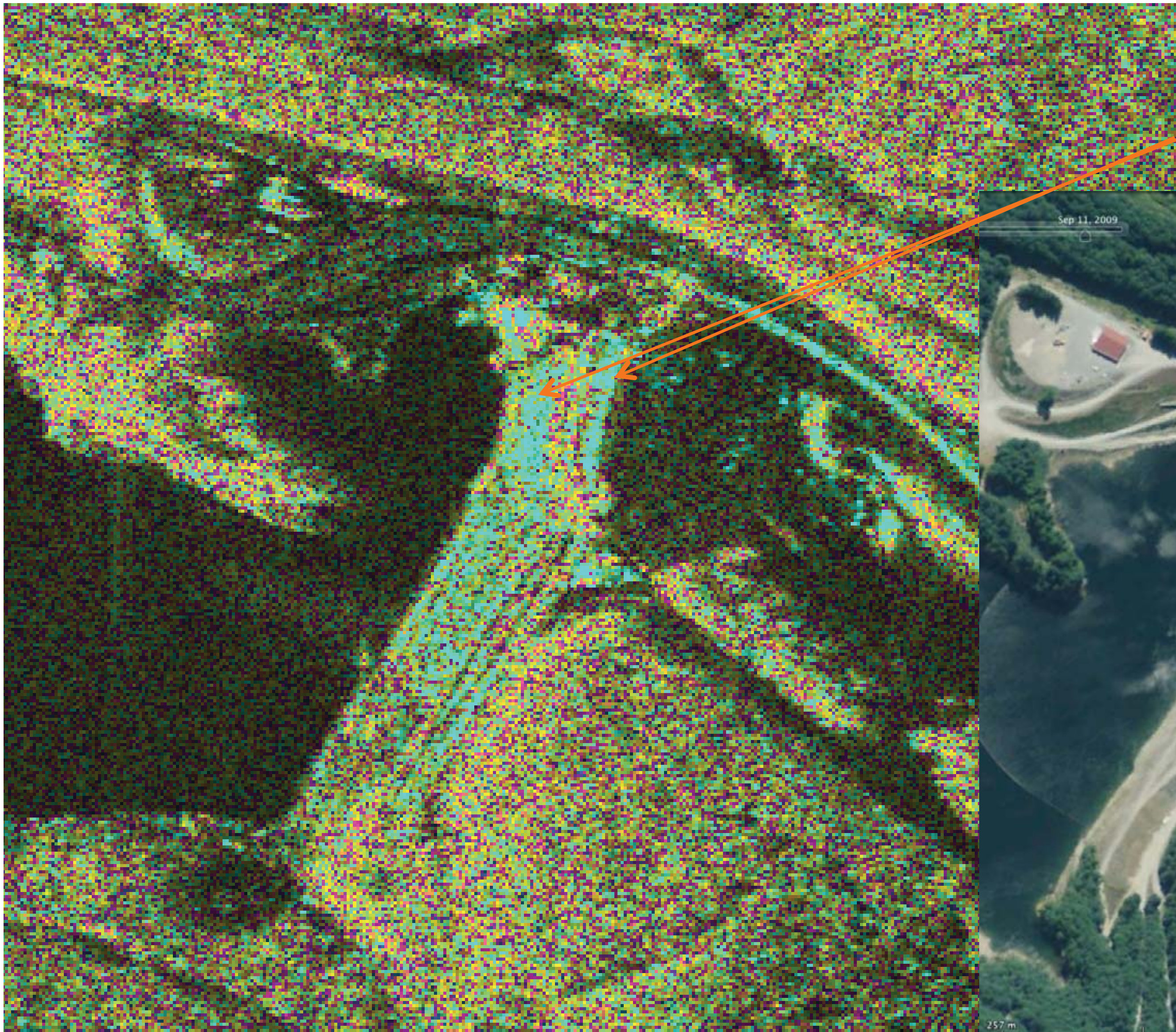
Construction Area, Sept. 2009

UAVSAR image of the Green River watershed near the Howard Hanson Dam, collected from 41,000 feet altitude and processed to 10 m ground resolution:

UAVSAR Overflight #2 - Nov. 9, 2010 – Radar Return Power



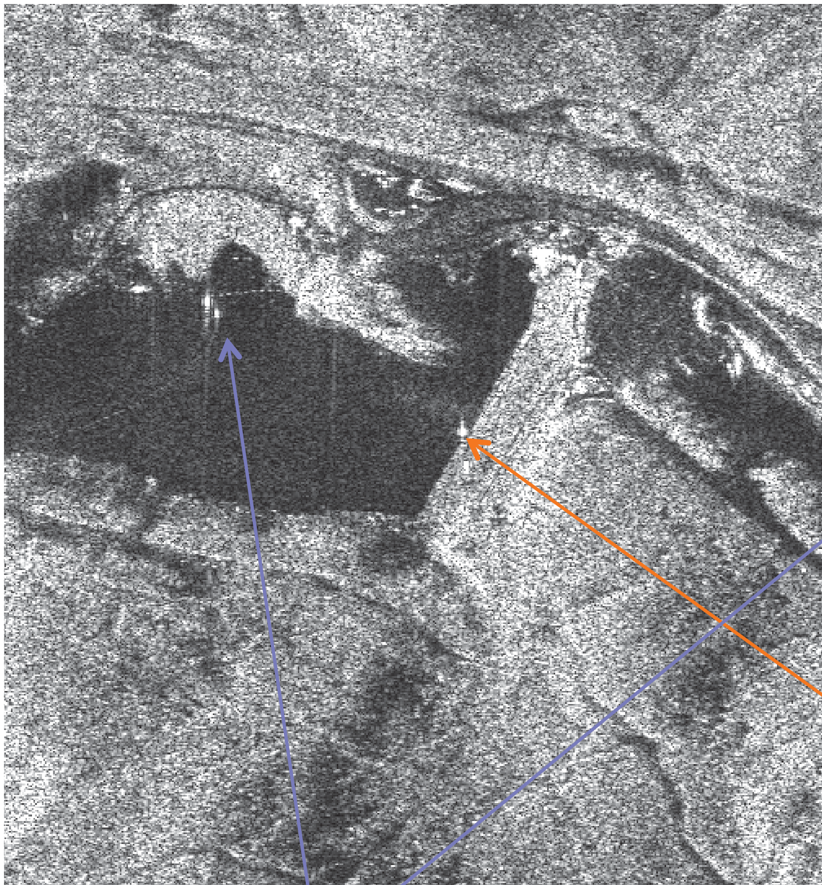
UAVSAR Nov. 2009 to Nov. 2010
Radar Data Processed for Change Detection - Correlation



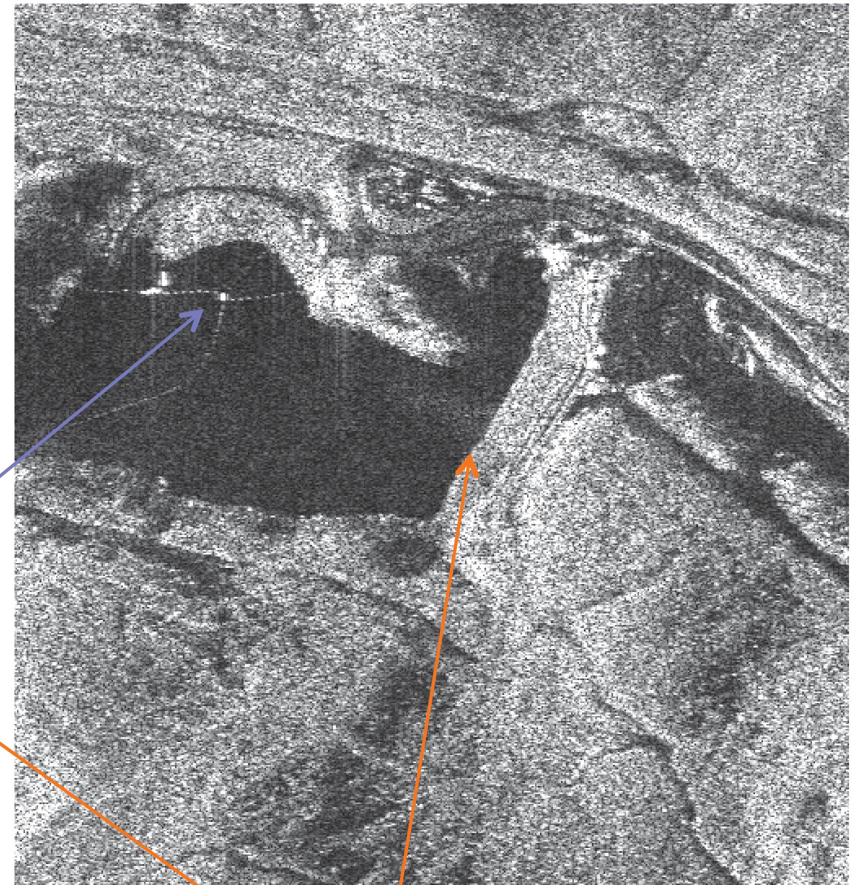
High correlation => most stable in this area along embankment. Decorrelation is seen along roads where traffic changes the surface.

Reservoir Comparison 2009 vs. 2010 – Radar Return Power

November 4, 2009



November 9, 2010



The buoys and restrictive barriers moved.

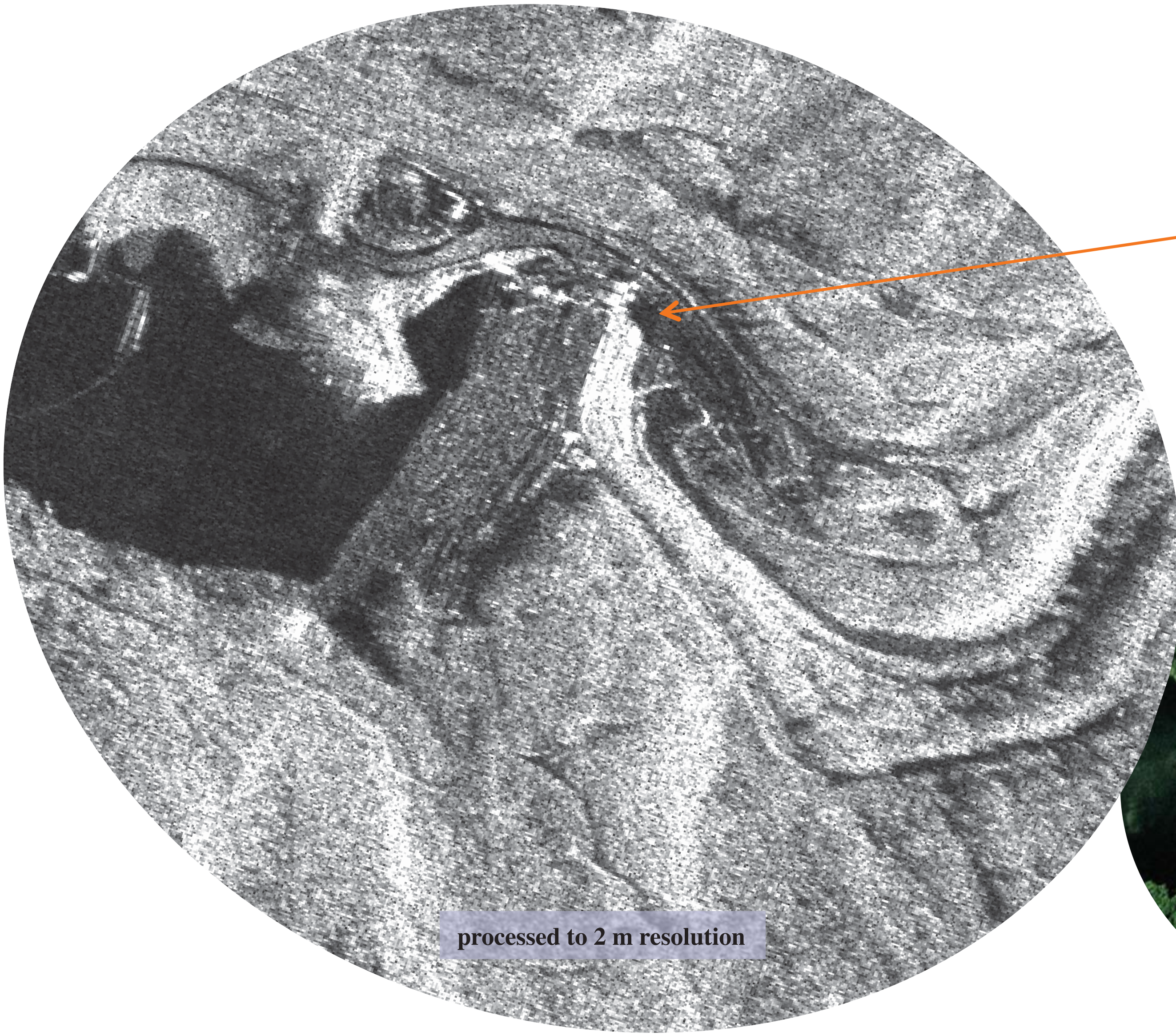
The bright reflector in the water near dam face is gone in 2010.

DOWNSTREAM SIDE OF THE DAM EMBANKMENT AND RIGHT ABUTMENT

UAVSAR FLIGHT LINE HEADING: 230°

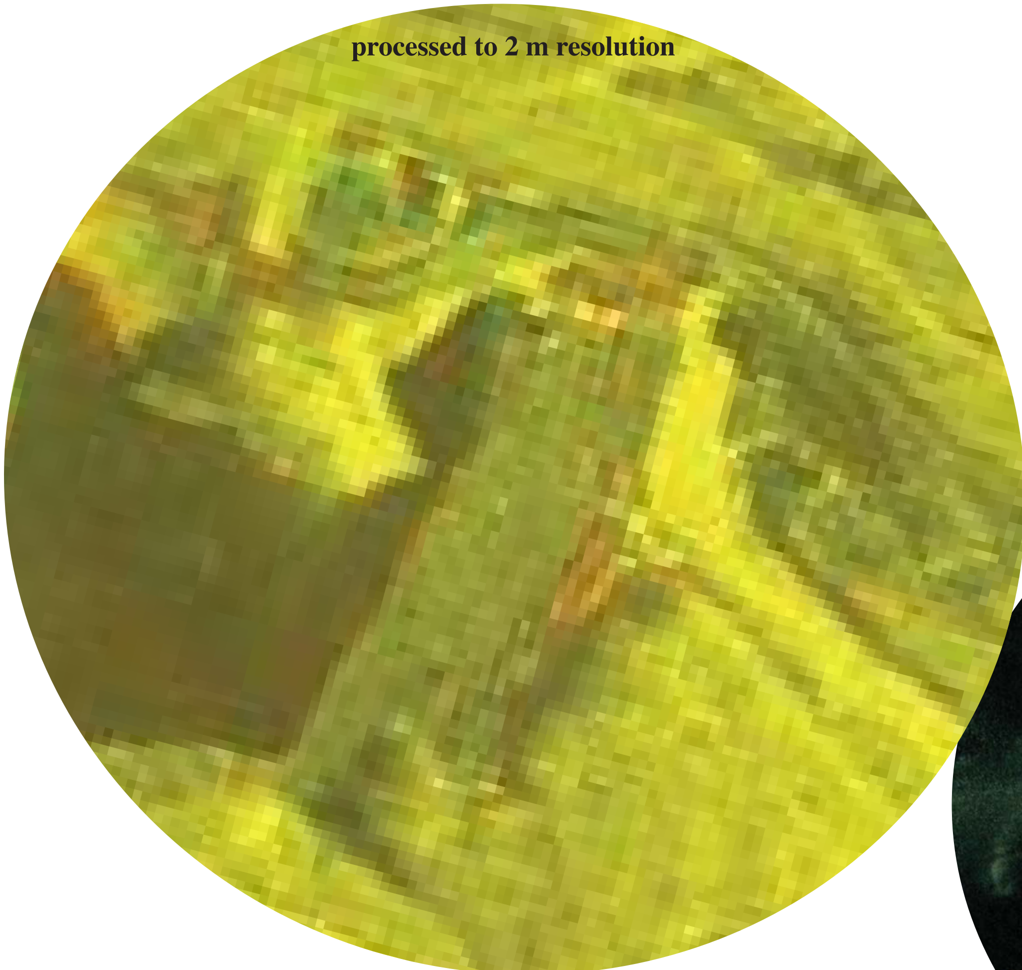
November 2009 to November 2010

UAVSAR 230° Heading – Downstream Face
Average Radar Return Power



From this aircraft heading (230°), the downstream face is illuminated more strongly. Although we still get some return from the upstream face of the dam the correlation and phase from data with this look direction will be noisier on the upstream face than for the data acquired at 40° aircraft heading.

UAVSAR Nov. 2009 to Nov. 2010
Radar Data Processed for Change Detection – Return Power Change

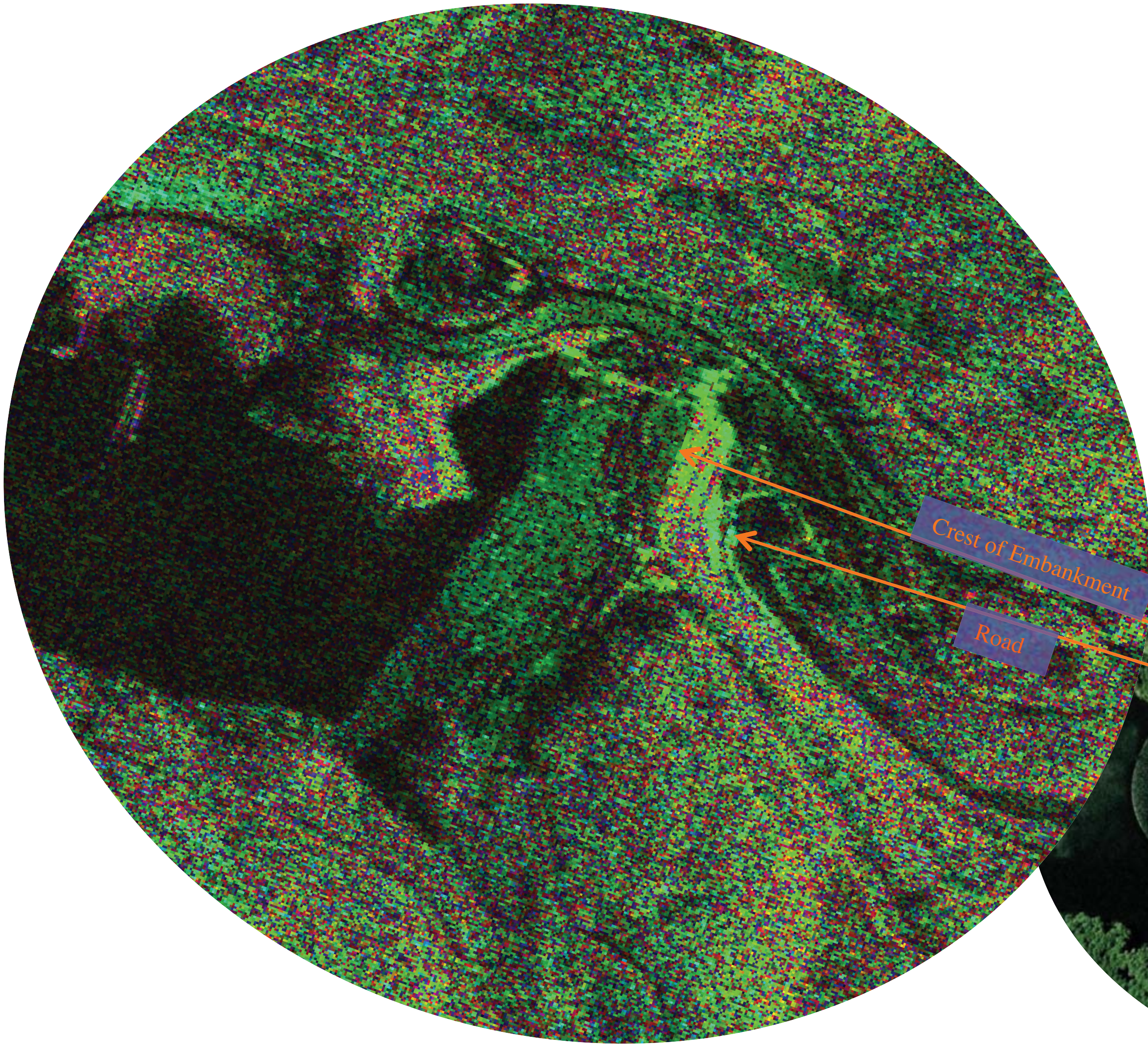


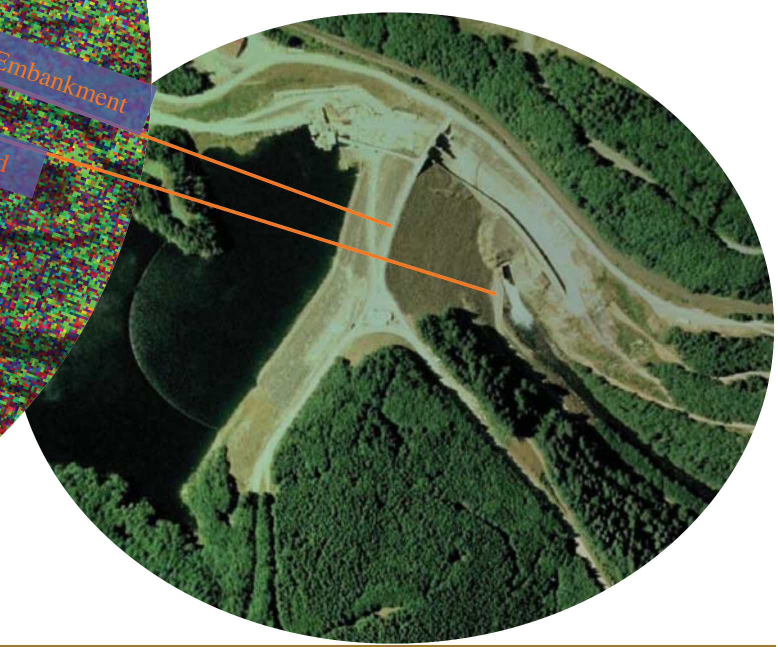
Date of Flight	Pool Level
11/4/2009	1076 ft
11/9/2010	1080 ft
Difference	+ 4 ft

Red = Brighter in 2009
Green = Brighter in 2010
Yellow = same in 2009 and 2010

UAVSAR Nov. 2009 to Nov. 2010 – Downstream Face
Radar Data Processed for Change Detection – Phase and Correlation

The dam face is foreshortened in the radar imagery because it is more perpendicular to the incidence angle of the microwave radiation.

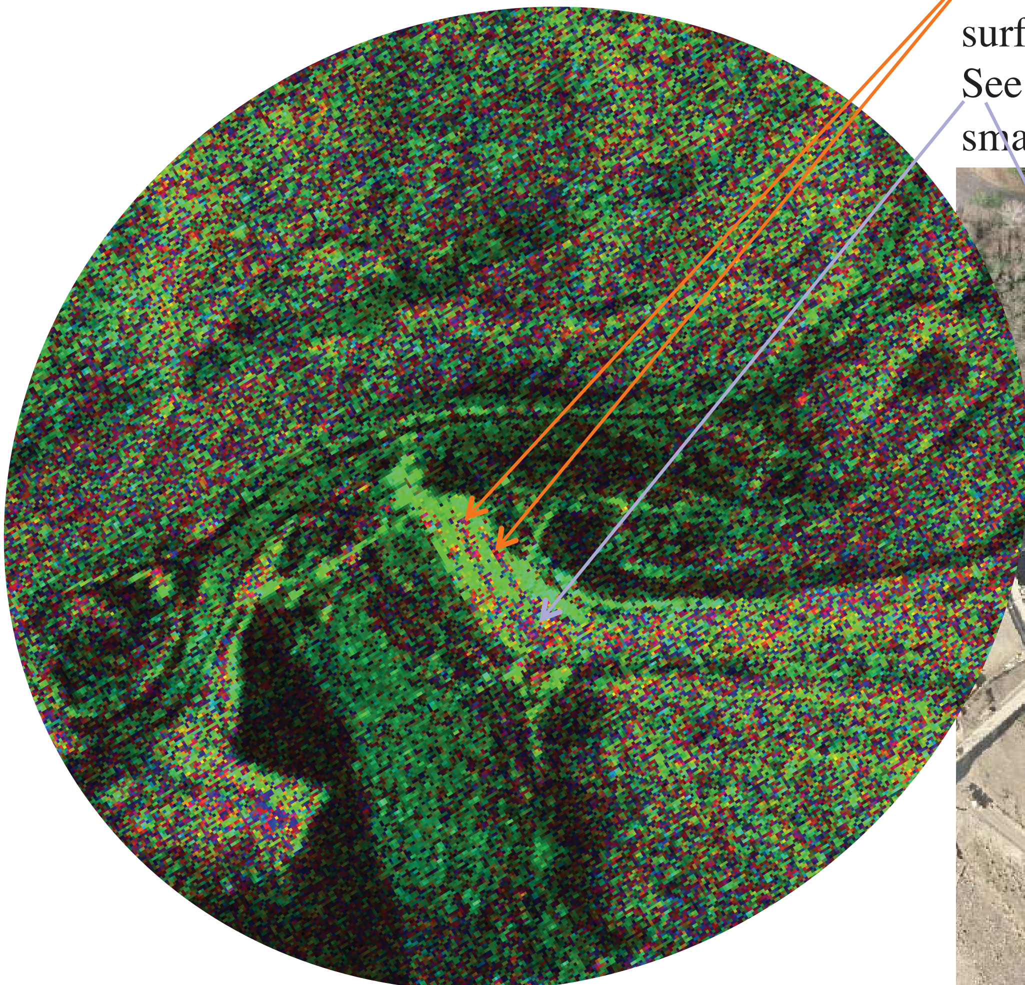




UAVSAR Nov. 2009 to Nov. 2010 – Downstream Face
Radar Data Processed for Change Detection – Phase and Correlation

Change is indicated along two lines on the dam face - surface disruption along paths?

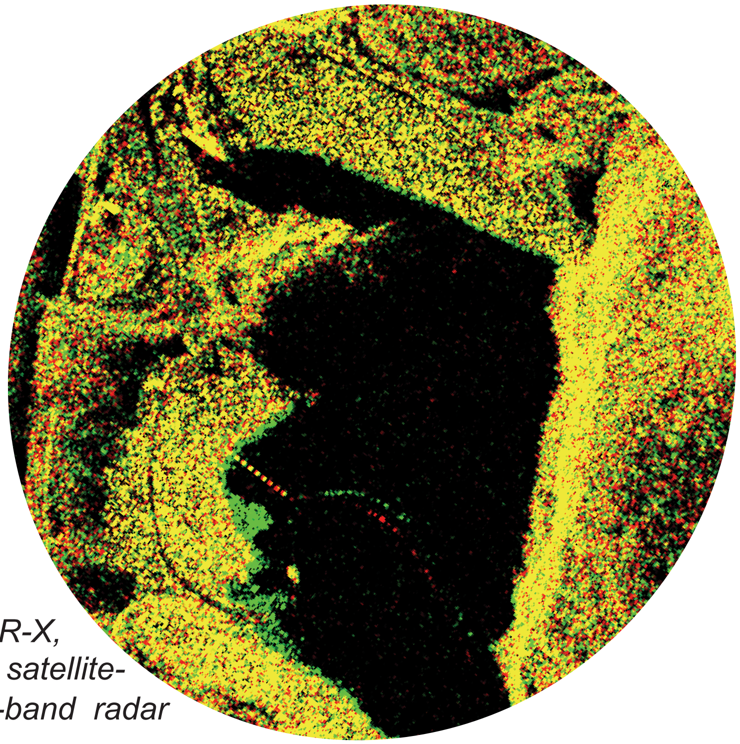
See change in area without any large vegetation – small rubble shifts/slides, moisture change?



Example of Satellite Monitoring

Water Level Change in Reservoirs

Green areas below indicate surface areas exposed during the 22 days in November 2010 when the reservoir pool water level was lowered.



TerraSAR-X, German satellite-borne X-band radar