# Some First Results from the UAVSAR Instrument

Cathleen Jones
Jet Propulsion Laboratory
Earth Science Technology Conference
June 25, 2008

# UAVSAR Project Design and Objectives

- UAVSAR is a portable pod-based synthetic aperture radar (SAR) system instrumented with a phased array, polarimetric, L-band antenna. It is designed to support a wide range of science investigations including geology, vegetation mapping and land use classification, archeological research, soil moisture mapping, and cold land processes.
- The modular design supports portability to other platforms and reconfiguration to use antennas at other radar frequencies, in addition to joint experiments with other radar instruments.
- The primary objectives of the UAVSAR project are:
  1. Develop a miniaturized polarimetric L-band synthetic aperture radar (SAR) for measuring surface deformation using radar repeat-pass interferometry that is suitable for implementation on a UAV.
  2. Develop the associated processing algorithms for repeat-pass differential interferometric measurements from an airborne platform.
  3. Conduct measurements of geophysical interest, particularly changes of rapidly deforming surfaces such as volcanoes or earthquakes.
- UAVSAR is currently in the final months of a four year program. Operational use of the instrument will begin in 10/2008.

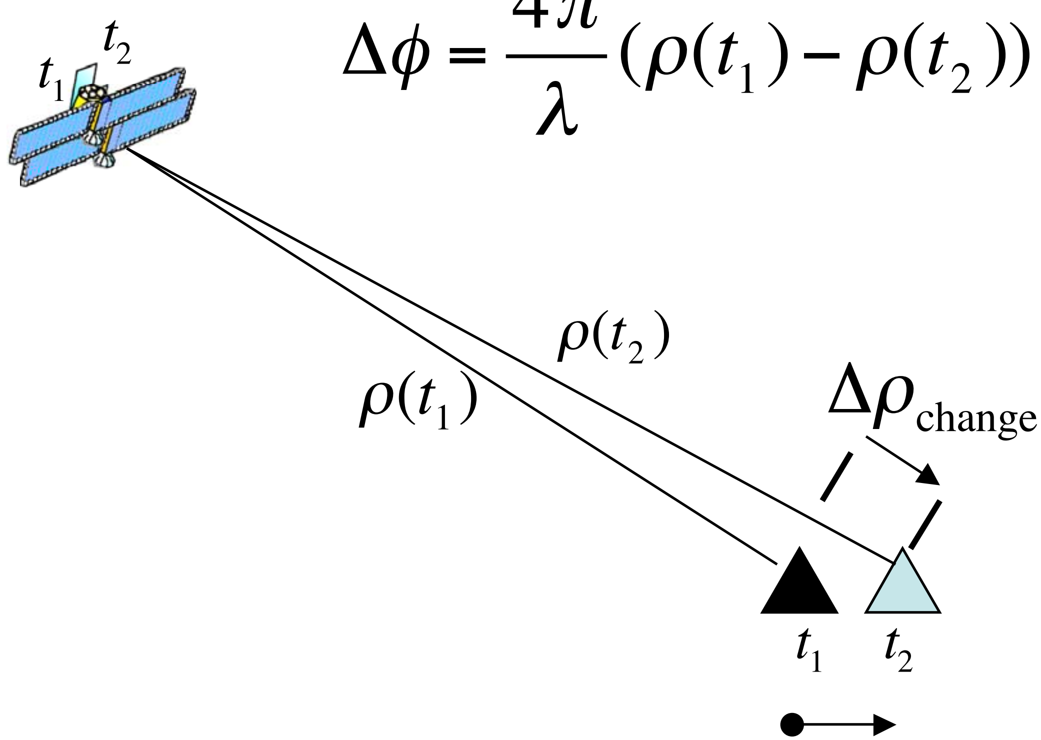
# Key Radar Instrument Parameters

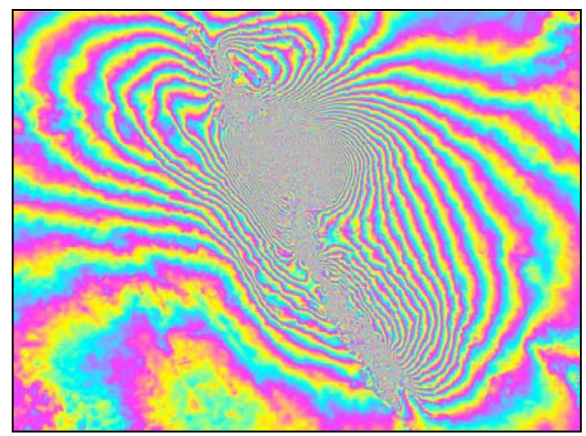
| Parameter | Value |
|---|---|
| Frequency | L-Band 1217.5 to 1297.5 MHz |
| Bandwidth | 80 MHz |
| Resolution | 1.67 m Range, 0.8 m Azimuth |
| Polarization | Full Quad-Polarization |
| ADC | 12 bit ADC with selectable Bit Floating Point Quantization compression to 2, 4, 6, 8, 10 or 12 bits; 180 MHz sampling frequency |
| Waveform | Nominal Chirp/Arbitrary Waveform |
| Antenna Aperture | 0.5 m range/1.5 azimuth (electrical) |
| Azimuth Steering | Greater than ±20° |
| Transmit Power | > 3.1 kW |
| Polarization Isolation | <-25 dB |

# Deformation Interferometry

When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{change}$$



Surface Deformation of the 1999 Hector Mine Earthquake

# Airborne RPI Instrument

- Spaceborne repeat pass radar interferometry derived deformation measurements has become a standard tool for the solid earth science and glaciological science communities.
  - Repeat times controlled by the the repeat orbit cycle of spaceborne SAR systems, e.g. ERS-1,2 (35 days), Radarsat (24 days), JERS (44 days), and Envisat ( 35 days).
- An airborne platform provides coverage unavailable with spaceborne platforms.
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  - The flight track is more difficult to repeat accurately in an aircraft.
    - Motion compensation must be done very accurately.
      - Knowledge of aircraft motion (Inertial Measurement Unit)
      - Correction of residual (unmeasured) motion
    - The images decorrelate unless the repeat pass baseline is small, ~<10 m.
      - Knowledge of aircraft position (Differential GPS)
      - Precision control of the aircraft flight path (Precision Autopilot)
  - The need to compensate for aircraft attitude angle changes between flight tracks, which arise from varying flight conditions, like winds aloft, turbulence, flight speed, fuel load.

# UAVSAR on the Gulfstream III

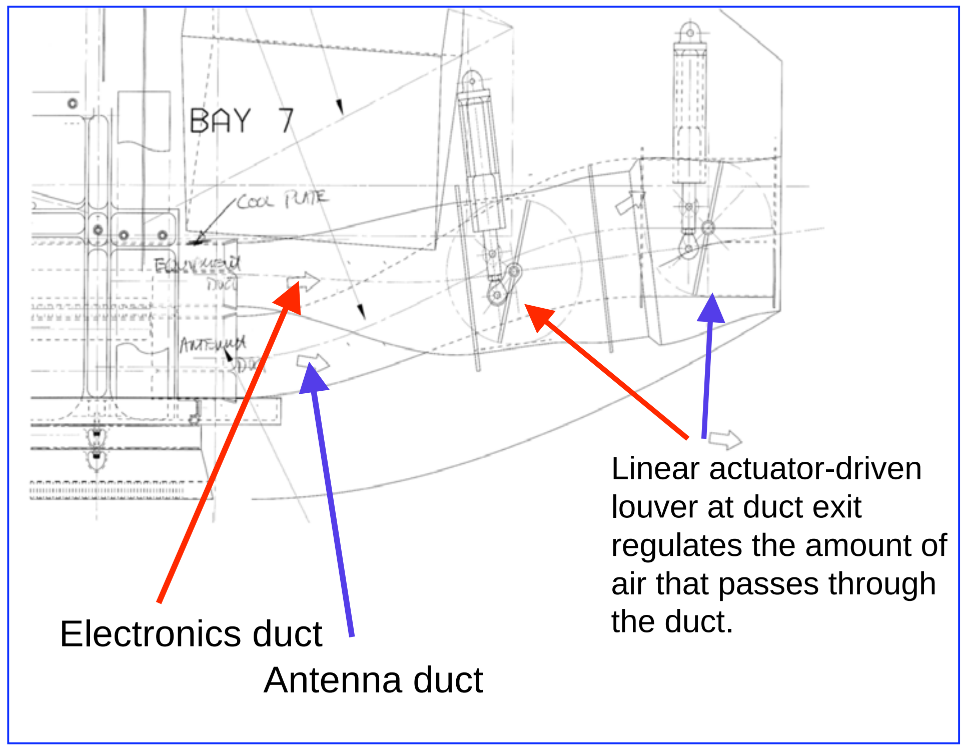

Unique features of UAVSAR:

1. Ambient air cooling: Uses regulated airflow through louvers to cool, heaters to warm the antenna T/R modules and the radar electronics in the pod.
2. Precision autopilot to maintain the flight track within a 10 meter tube around the desired track.
3. Phased array antenna plus adaptive steering to maintain pointing direction of the radar beam.

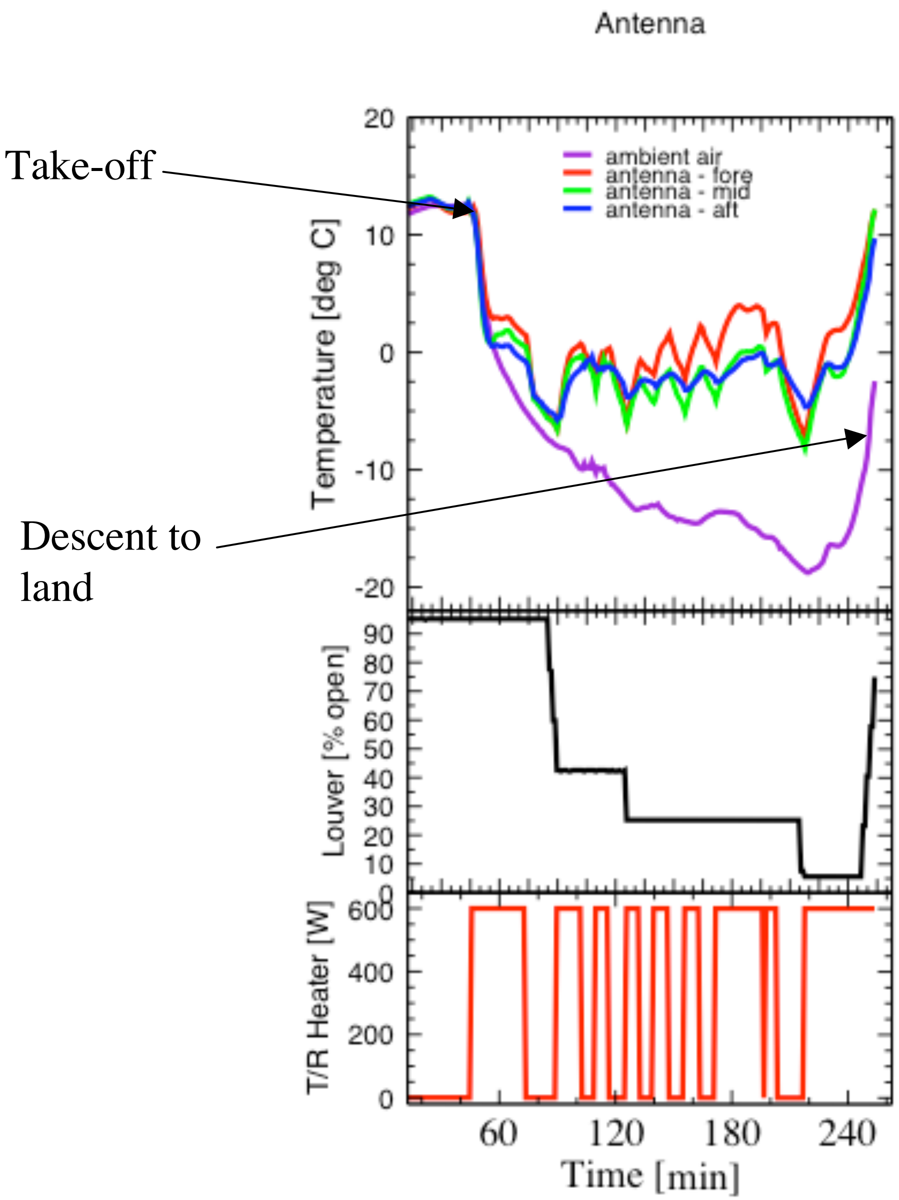
# Ambient Air Cooling


- Flying in an unpressurized pod allowed for maximal portability to other platforms, however this necessitated a fairly involved thermal control system to keep the various units within an acceptable temperature range and avoid condensation during descent.

Louvers:



# Antenna Temperature Control

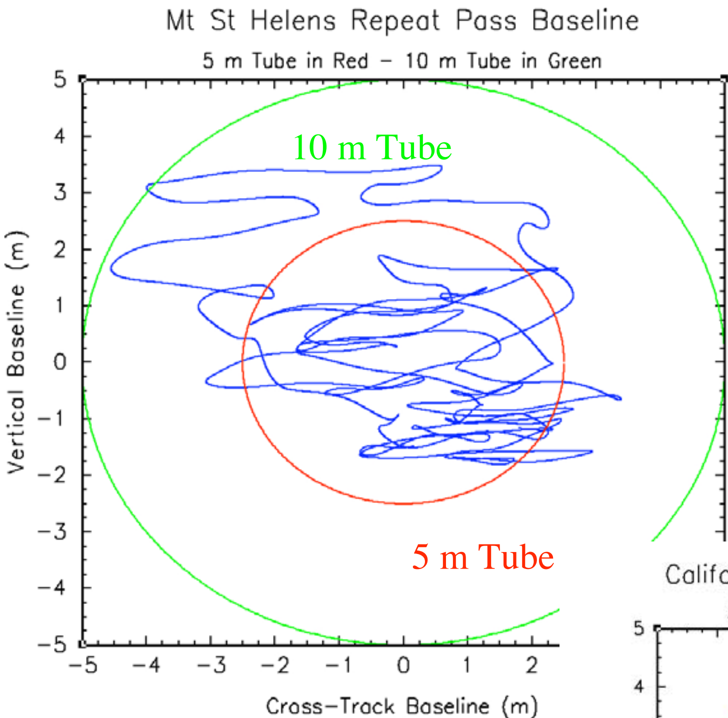


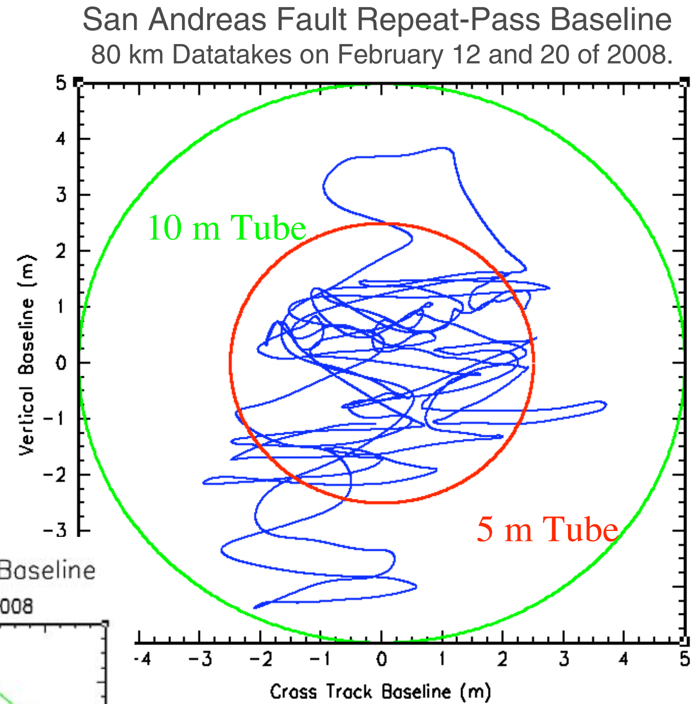

As the outside air temperature drops, the louvers close to maintain the antenna temperature between +5 and -10 °C.

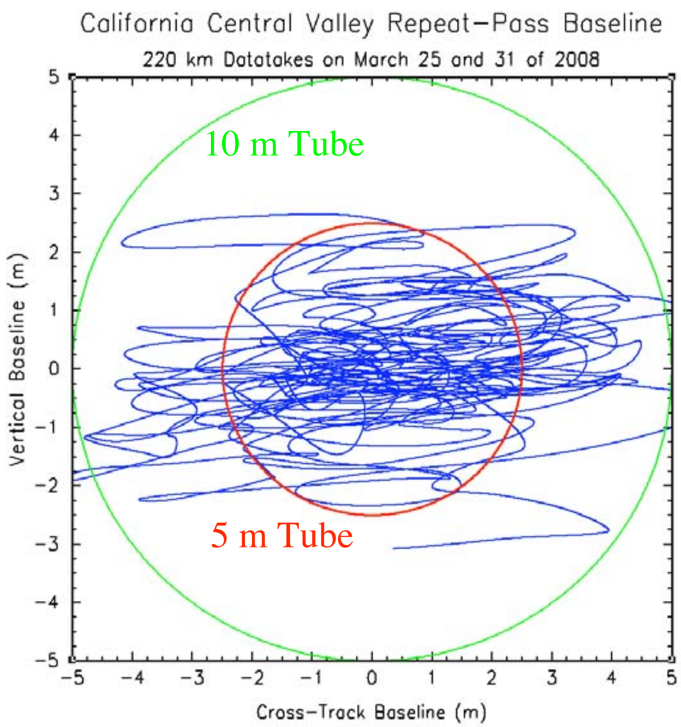
Louver adjustment

Heaters on T/R modules provide replacement heat to maintain near-constant temperature during transmission.

# Precision Autopilot Repeat Pass Baseline




The Precision Autopilot System was designed and developed at Dryden Flight Research Center.

Overall, the PPA maintains the planned flight path within a 5 m tube nearly 90-95% of the time. The requirement on tracking is to maintain a 10 m tube for >90% of the flight track under light turbulence conditions.

# L-Band Phased Array Antenna

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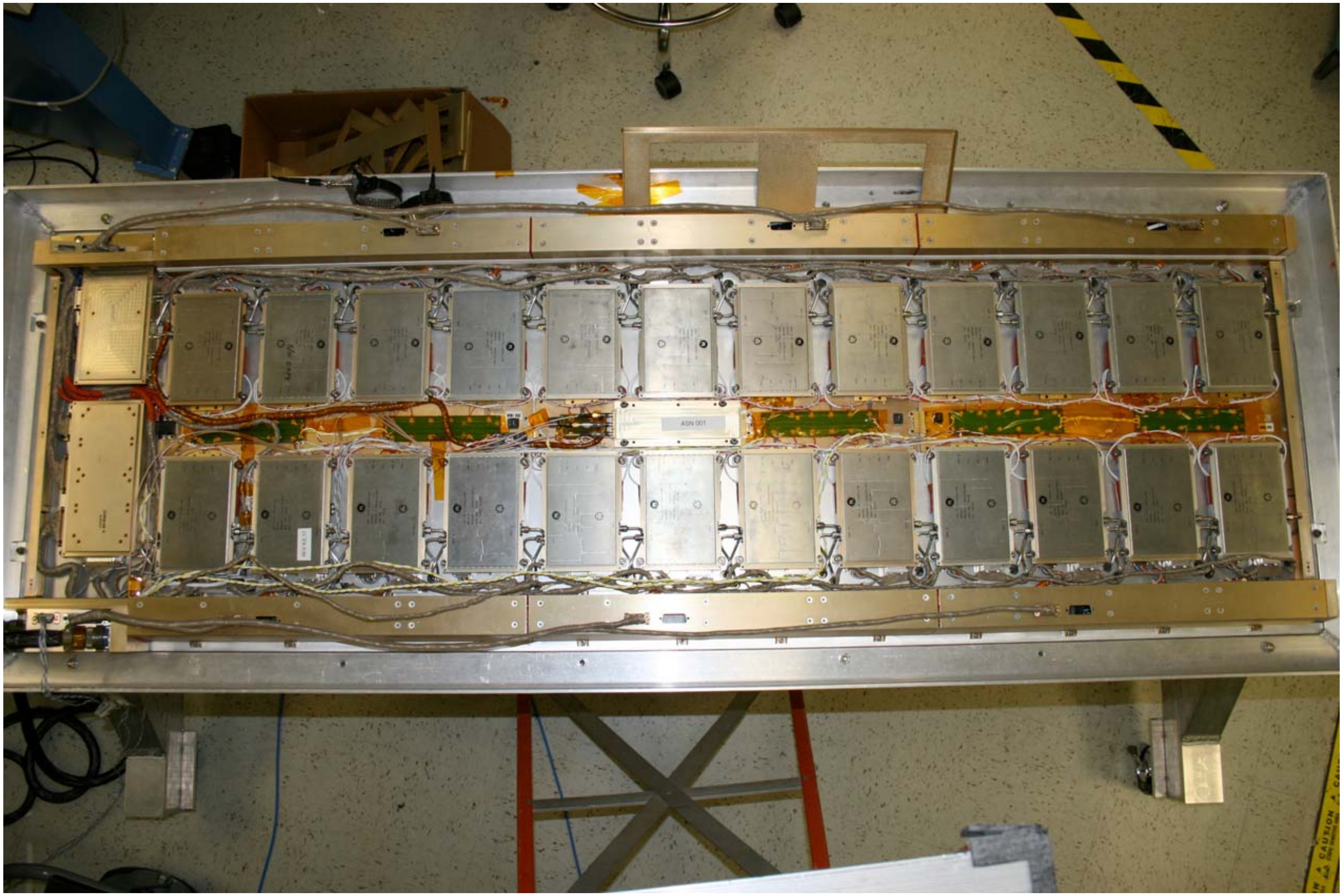
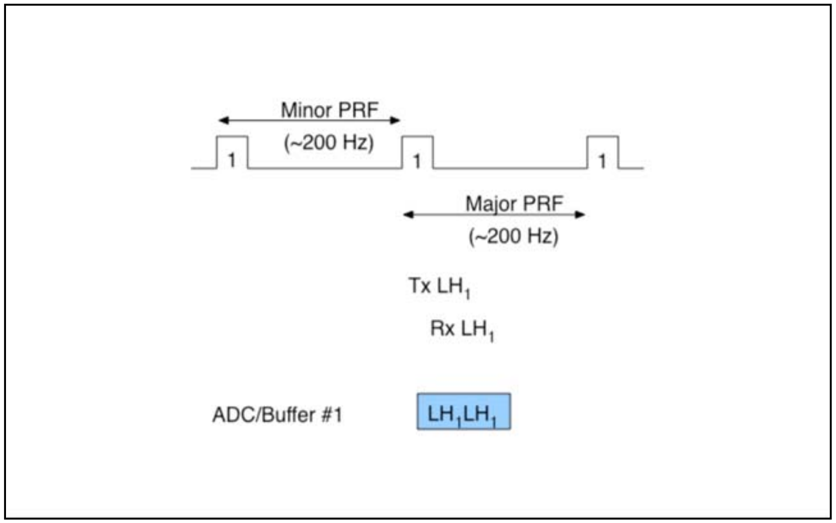
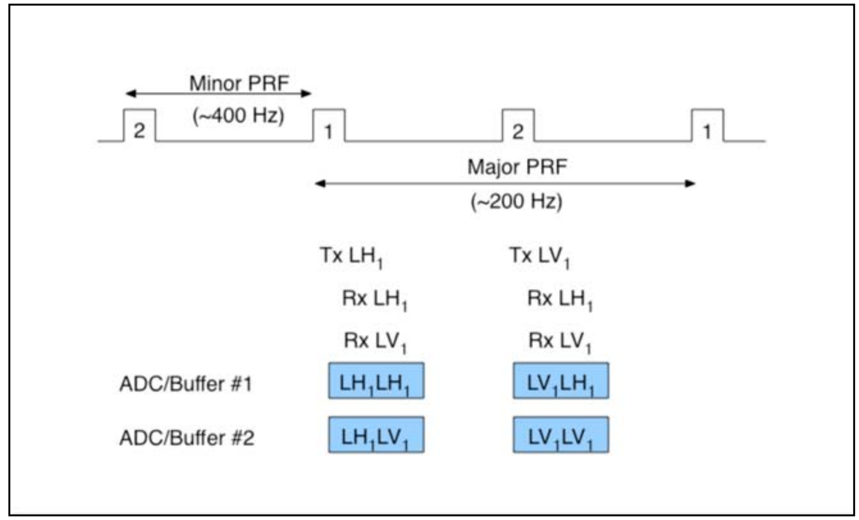


# UAVSAR Modes

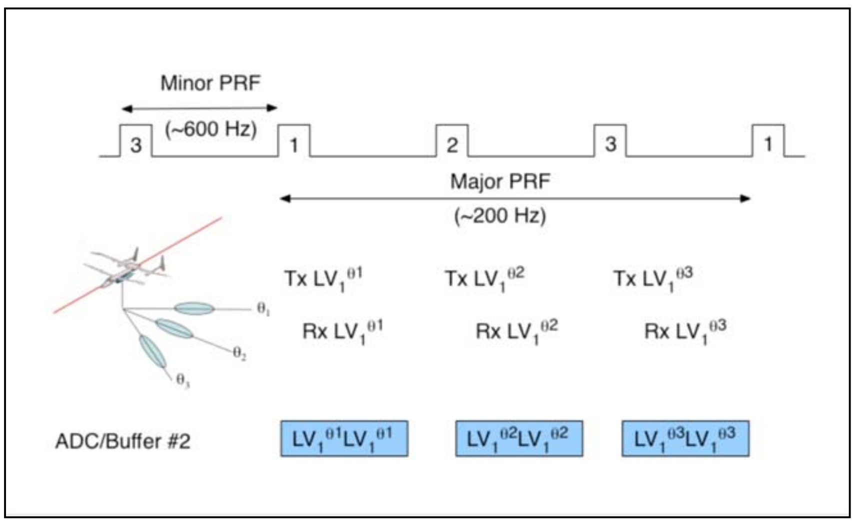
## Strip Mode SAR



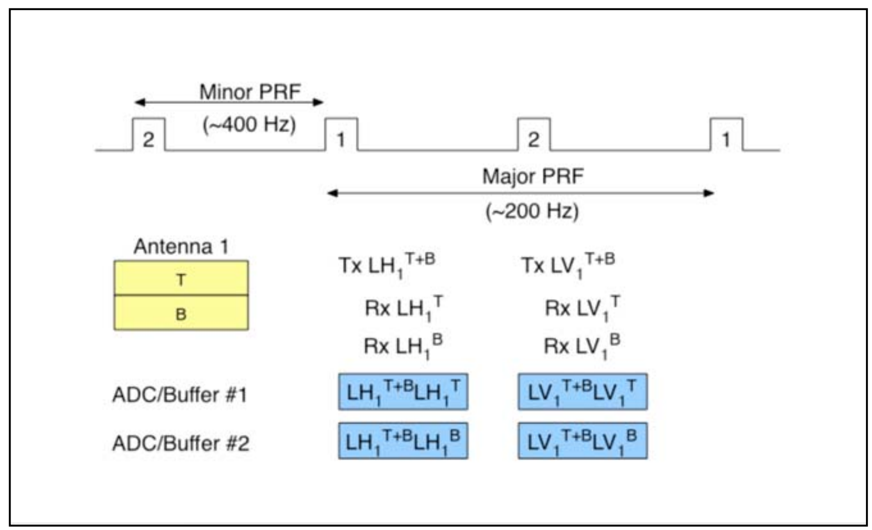

## Polarimetric SAR




## Multi-Squint Vector Deformation




## CoPol Monopulse



# UAVSAR Flight Tests

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| Kings Canyon, CA | 1 | 7 |
| Long Valley, CA | 2 | 4 |
| Lost Hills, CA | 3 | 10 |
| Mt. Adams, WA | 3 | 3 |
| Mt. St. Helens, WA | 3 | 23 |
| Ocean, Channel Islands, CA | 2 | 5 |
| Parkfield, CA | 3 | 3 |
| Rosamond, CA | 10 | 75 |
| Salton Sea, CA | 3 | 5 |
| San Francisco, Hayward Fault | 6 | 29 |
| San Francisco, San Andreas Fault | 5 | 6 |
| San Joaquin Valley, CA | 2 | 2 |
| Sierra Madre, CA | 1 | 1 |

Current as of 6/16/2008

# Rosamond Lakebed Calibration Array

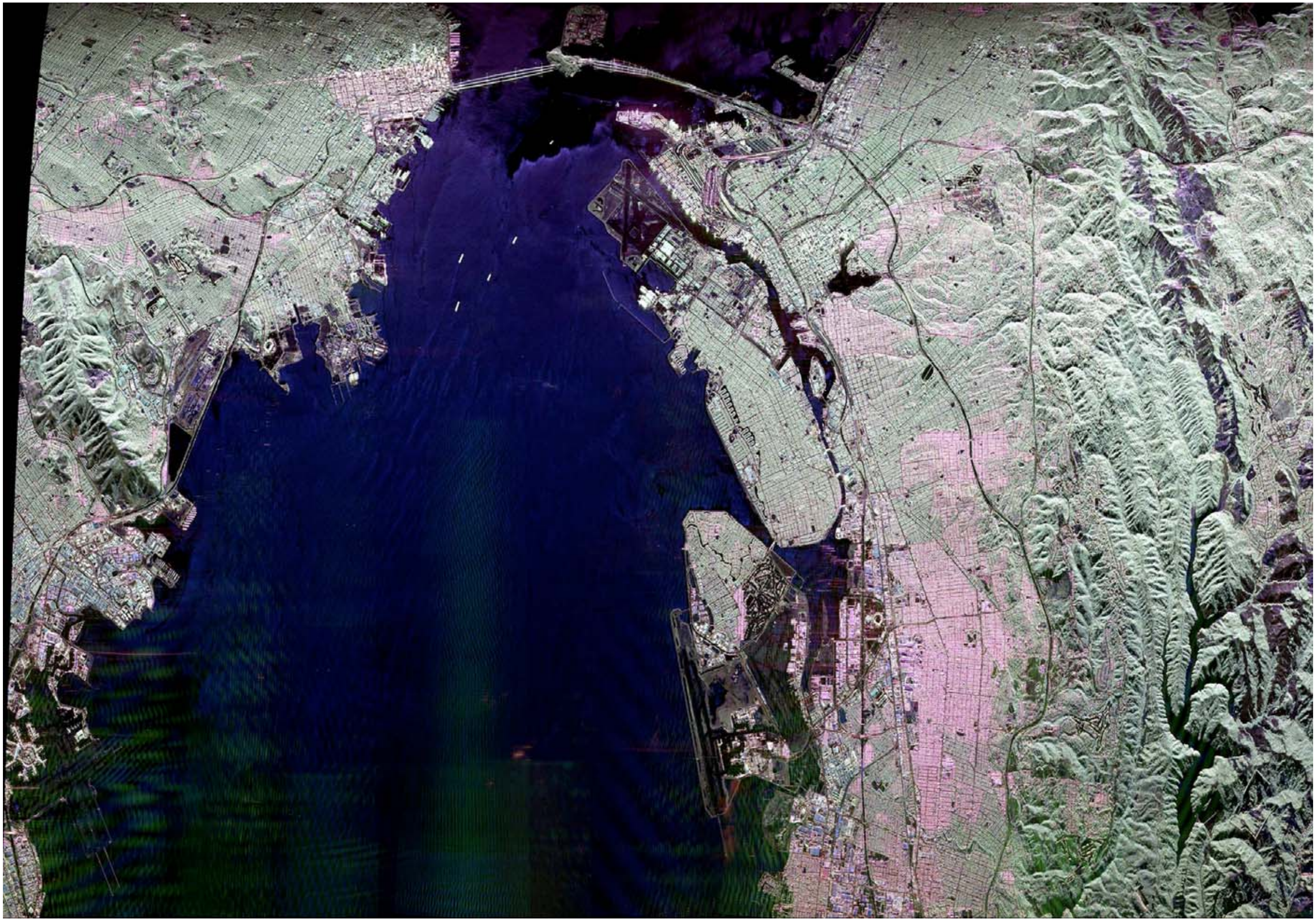
An array of 23 trihedral corner reflectors is set up on the Rosamond dry lakebed near Edwards AFB. The location of each CR's vertex is determined with high precision differential GPS. Standard engineering test flights image this array.

Full Array PolSAR Image

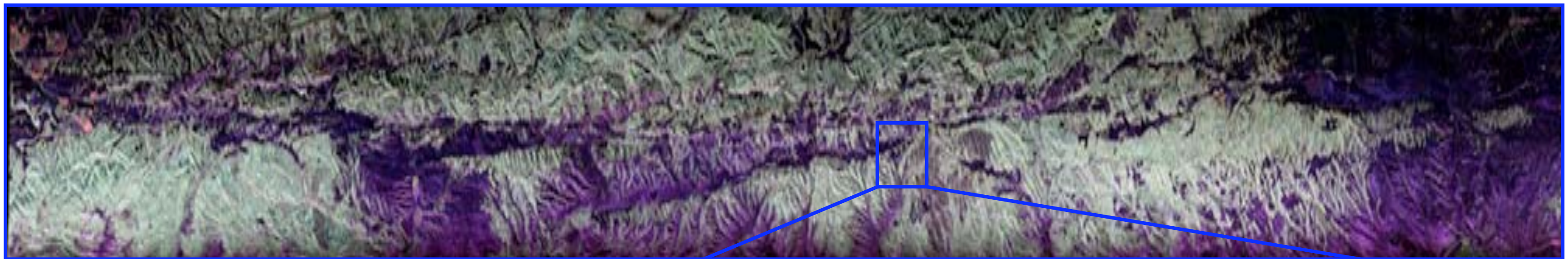
LHH=red
LHV=green
LVV=blue

- Data collected Dec 6 over Rosamond Lake Bed, from an altitude of 39000 ft.
- Ground swath is over 20 km

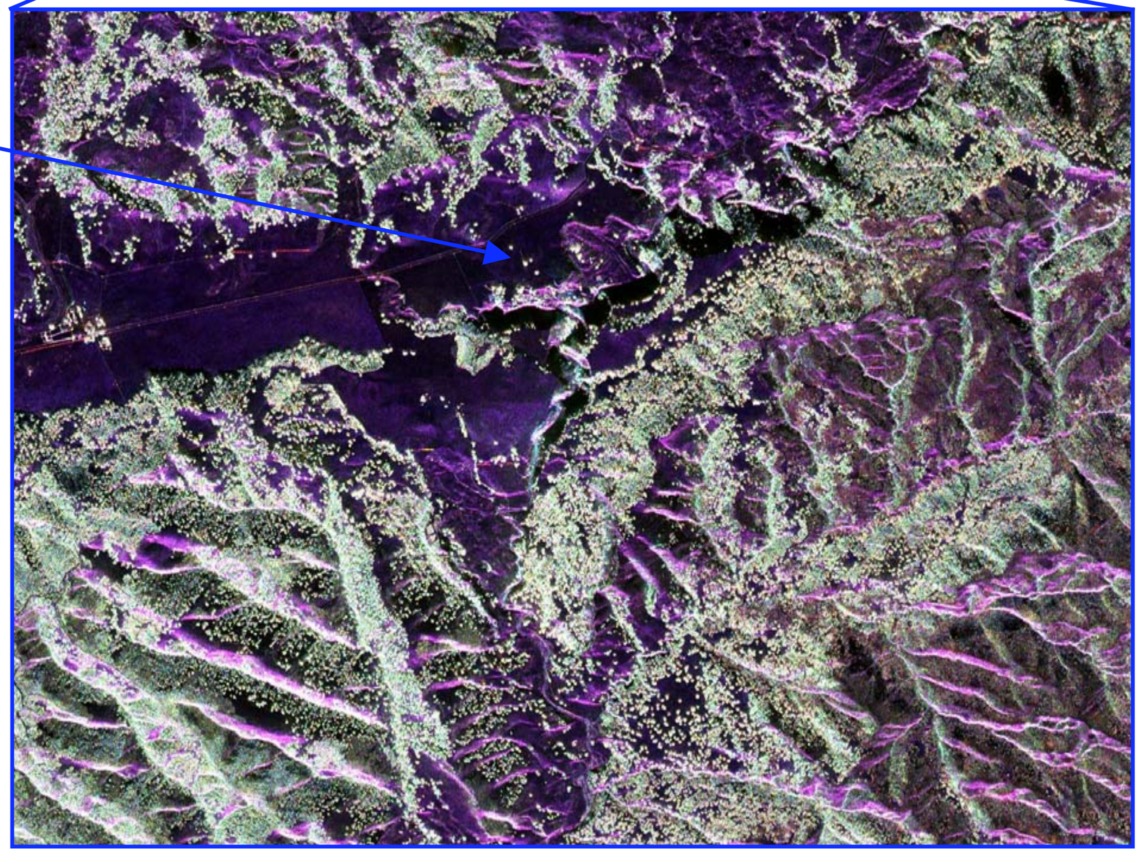
# San Francisco Bay - February 20, 2008



# San Andreas Fault Imagery



The same trees in Google Earth image can be seen in UAVSAR L-band image

The different colors in the UAVSAR image generally correspond to different vegetation characteristics on the surface. Compensation for and projection to surface topography has not yet been applied.

1 km

LHH=red

LHV=green

LVV=blue

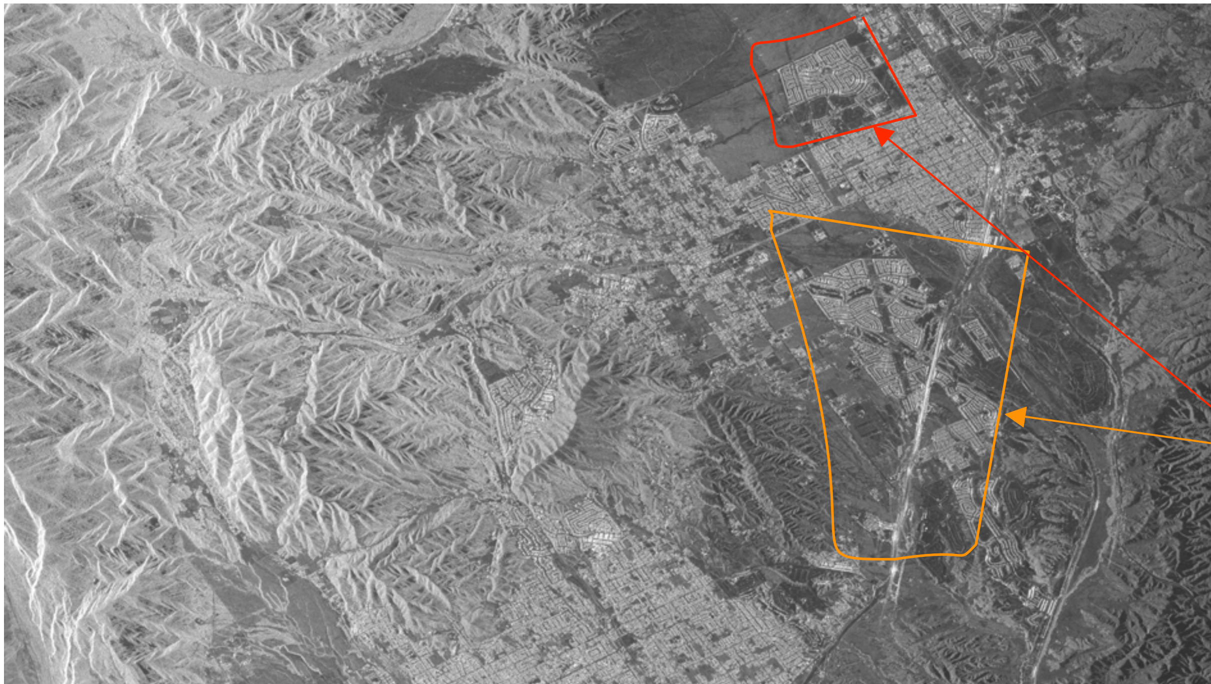
Data collected Feb 12, 2008

2x6 looks (3m resolution)

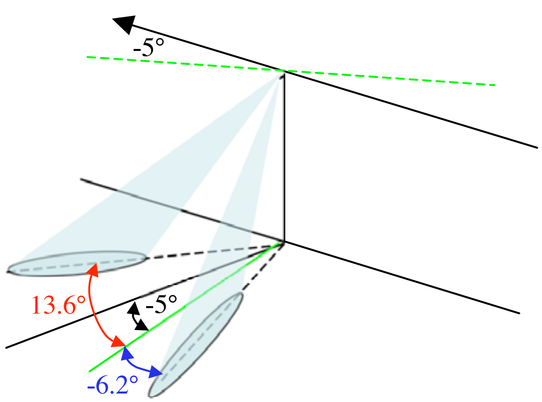
# Multi-Squint Mode

Data collected in the UAVSAR multi-squint mode, at two antenna steering angles:

- Platform had a yaw angle of -5.0°, so the beam was steered in azimuth by 13.6° and -6.2°.
- Anthropogenic features exhibit strong viewing angle scattering signatures.



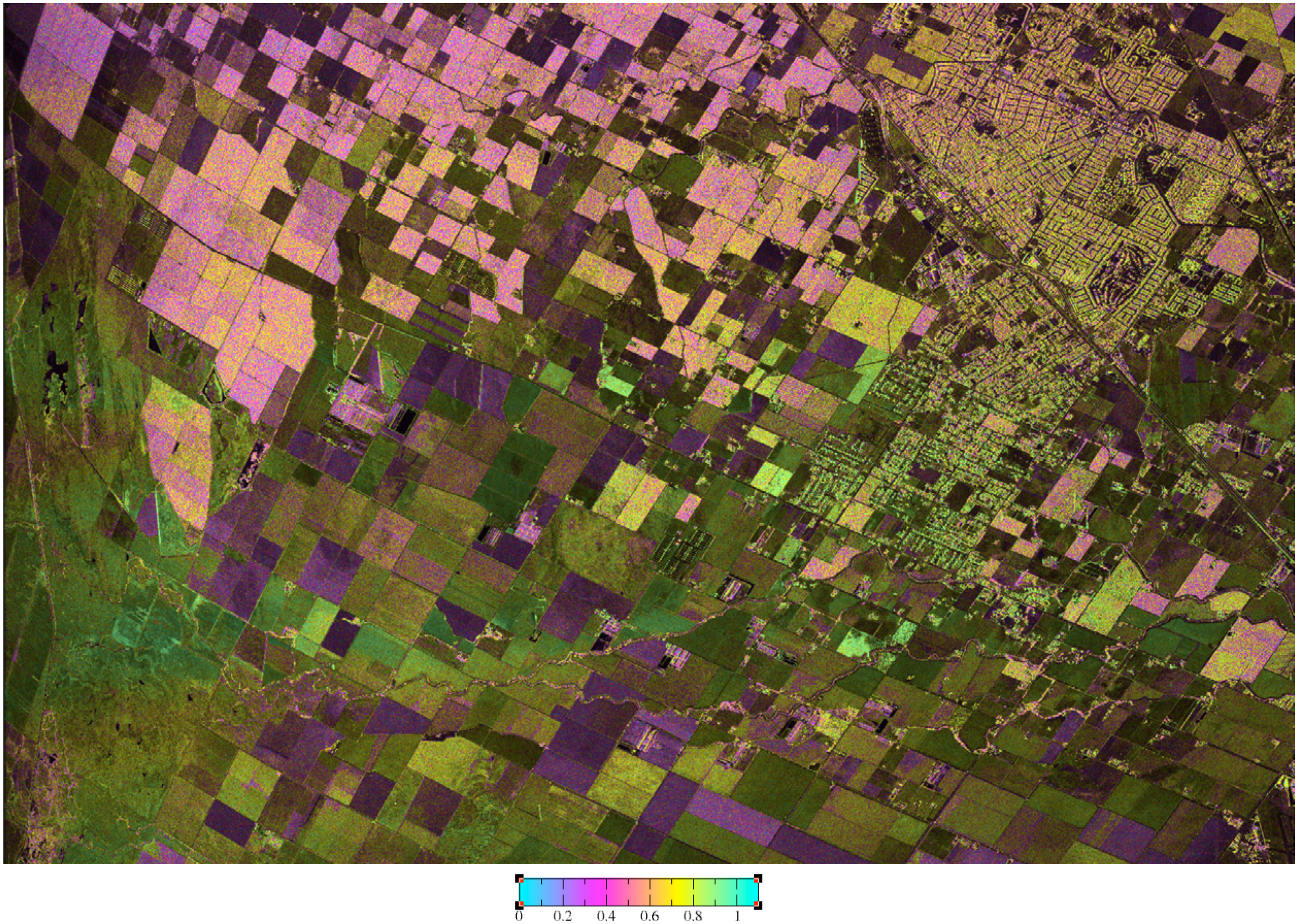
Azimuth Steering Angle: 13.6°




Azimuth Steering Angle: -6.2°

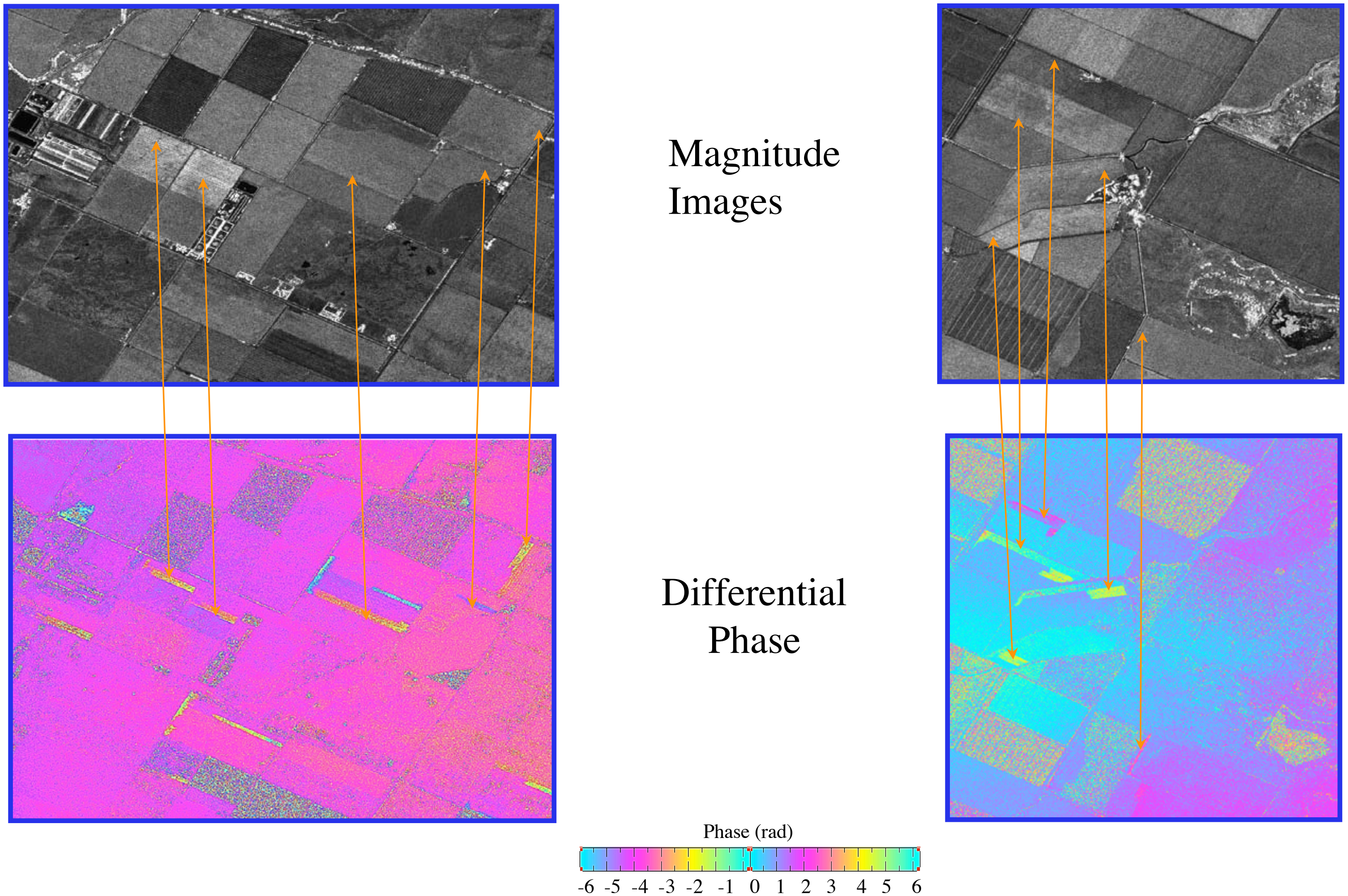
# California Central Valley Repeat Pass

- Correlation map from a portion of two passes collected over the California Central Valley on March 24 and 31 of 2008. Note changes are highly correlated with field boundaries.

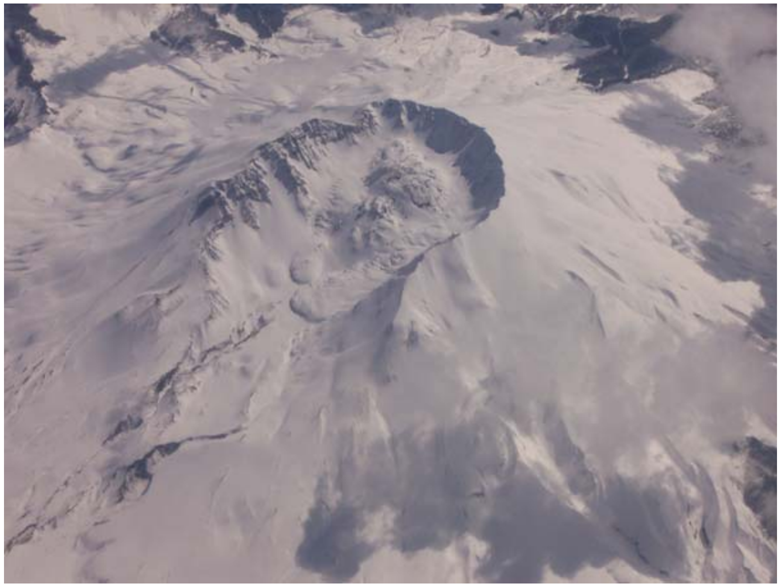


# Deformation in California Central Valley

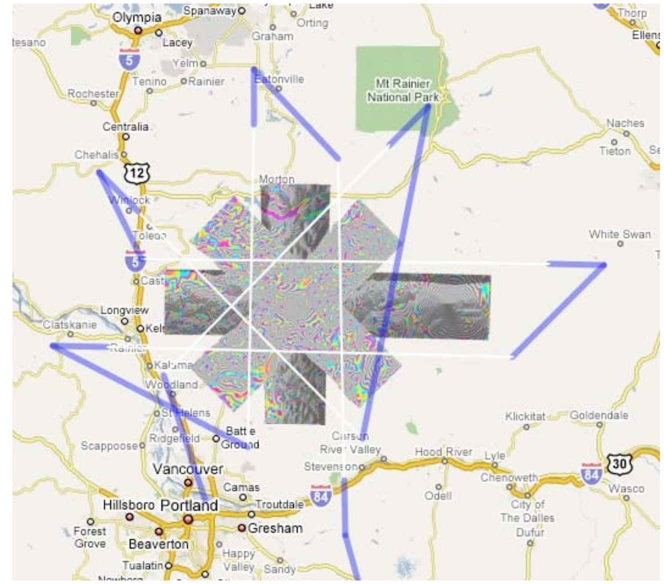
- Contraction or expansion of soil due to changing water content can be observed in the phase differences. One cycle of phase change corresponds to 6 cm of deformation. Observed deformation is on the order of 1-2 cm.



# Mt. St. Helens

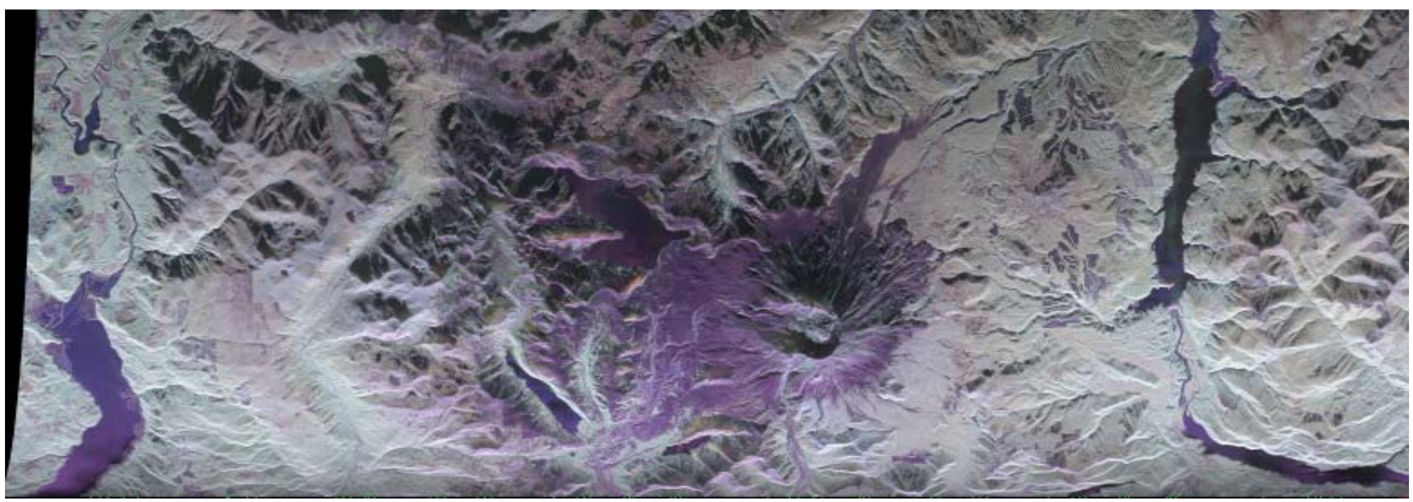


Data was collected along 6 different look directions over Mt. St. Helens.



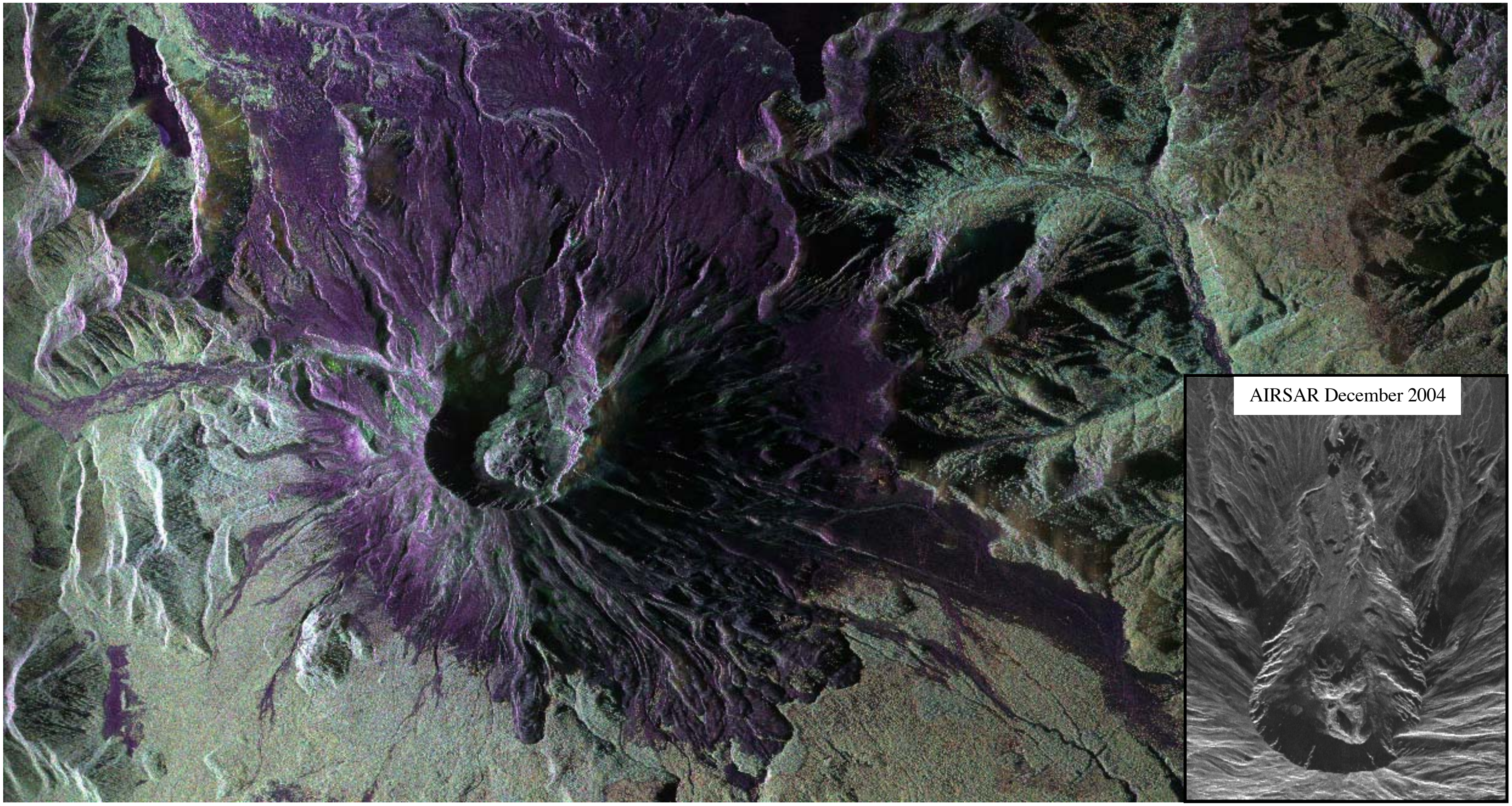

Flight Direction

Fully polarimetric image of Mt. St. Helens collected on March 24, 2008 by the UAVSAR radar. A second acquisition was collected on March 31, 2008.



> 20 km

# L-Band UAVSAR Image of Caldera and Dome

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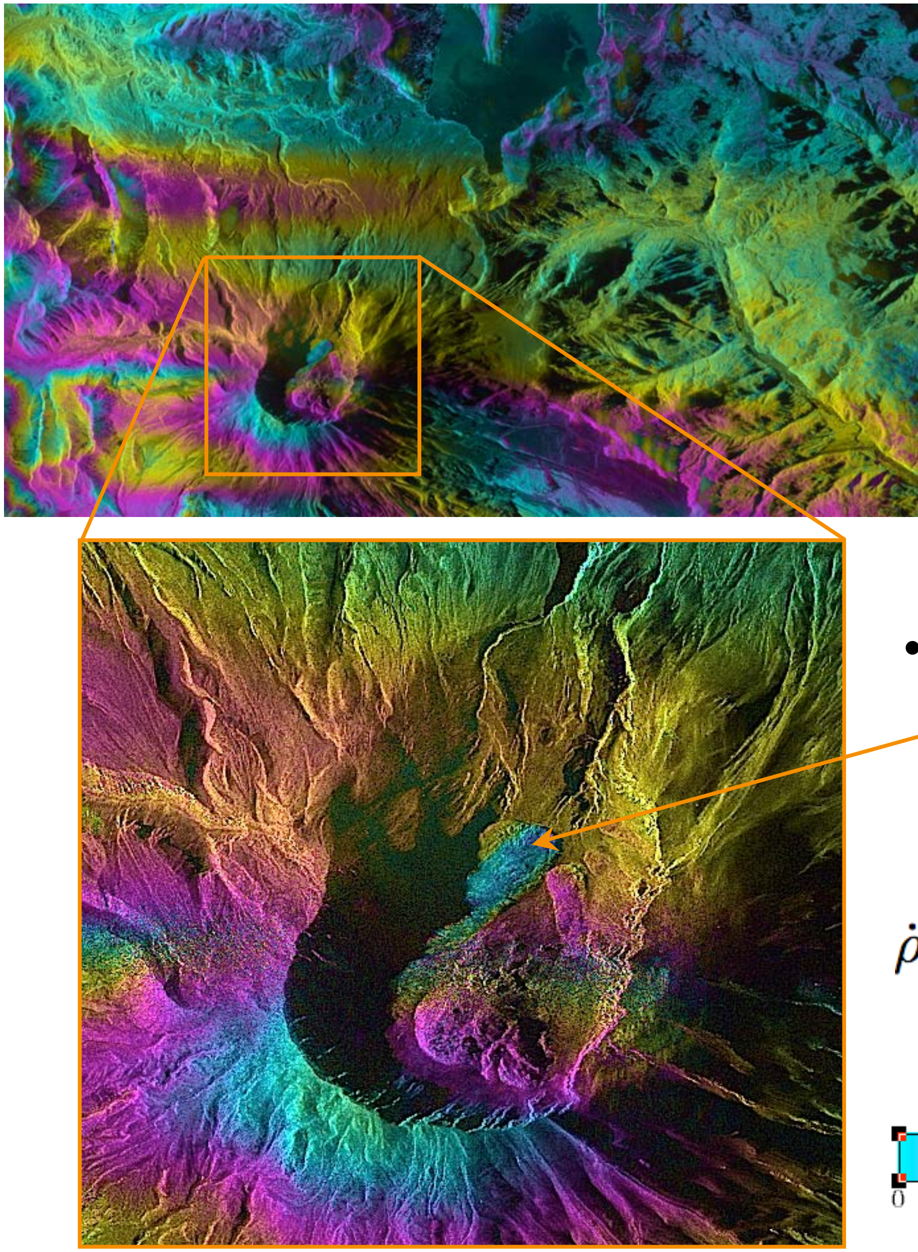
# Mt. St. Helens Interferogram - 4 hour Repeat

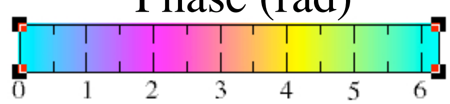


- This is a first cut interferogram
  - no offset measurements
  - no motion correction
  - no topography correction

- Since time between observations is 4.2 hours or .174 days, the estimated rate of motion for an approximate π radians of phase change is

$$\dot{\rho} = \frac{\lambda\phi}{4\pi\Delta t} = \frac{0.24}{4 \cdot 0.174} = 0.344\frac{m}{day}$$

Phase (rad)



# Conclusions

- UAVSAR is an actively scanned fully polarimetric L-band SAR designed to meet a range of remote sensing applications of interest to the science community including specific features to support repeat pass interferometry for deformation studies.
- Results thus far from flight testing indicate:
  - Sensor is meeting all its performance objectives
  - Platform is routinely able to maintain trajectory within the 10 m tube requirement and often stays within a 5 m tube.
  - Available swath width is greater than 20 km with a flight altitude of 12.5 km.
- Ongoing and future work is devoted to:
  - Continued verification of the various radar modes
  - Residual motion estimation and compensation using radar data
  - Quantification of the accuracy of the deformation measurements
  - Tomographic studies for vegetation parameter estimation

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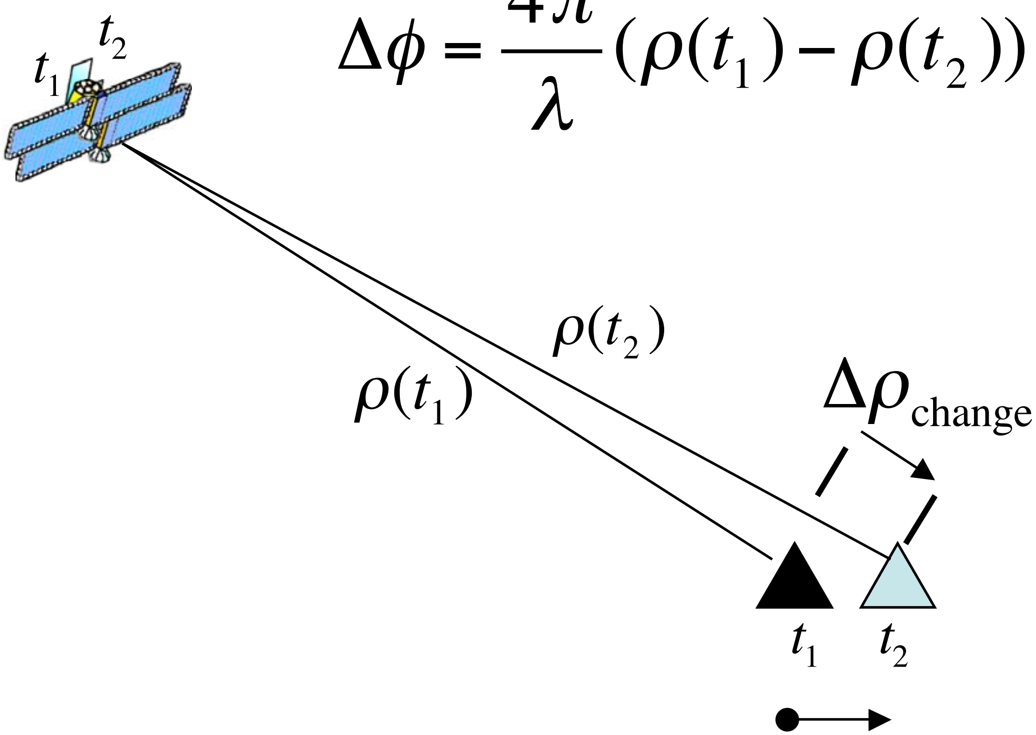


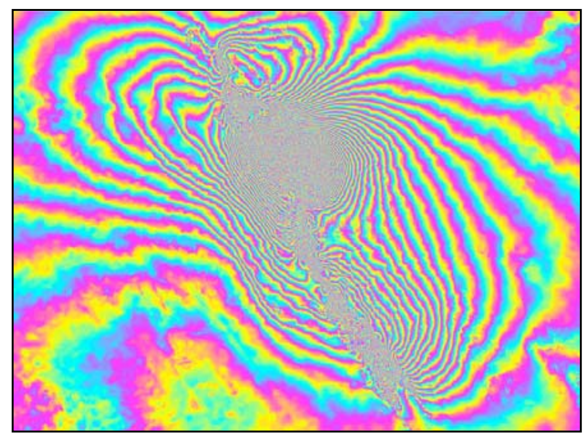

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Air Inlets:

Electronics Duct Inlet

Data Storage Unit Duct Inlet

Antenna Duct Inlet

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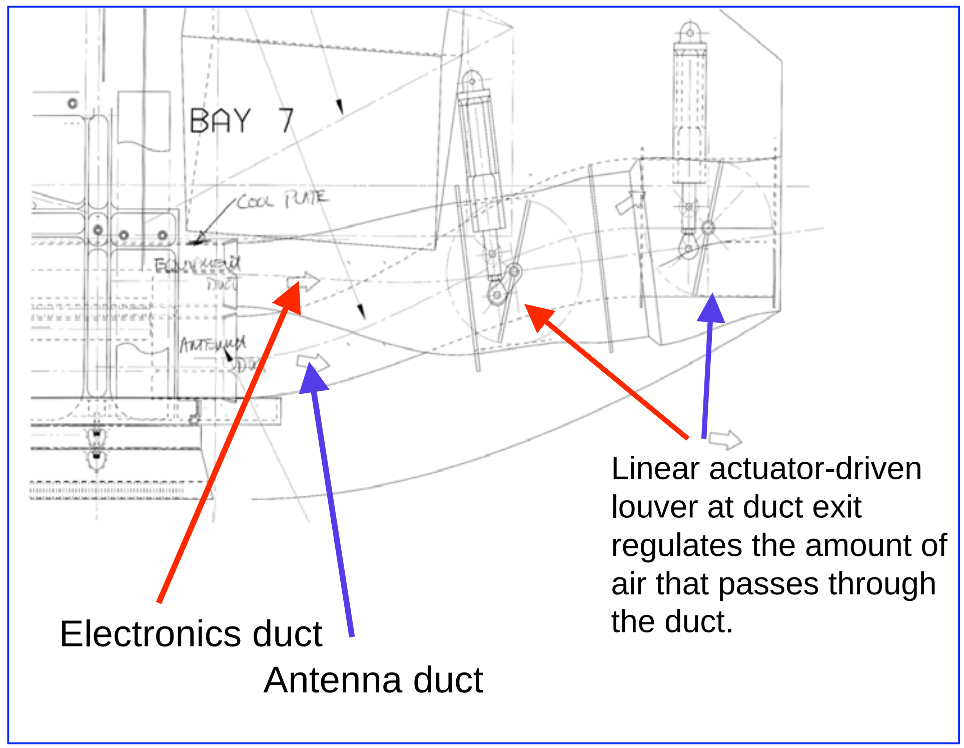
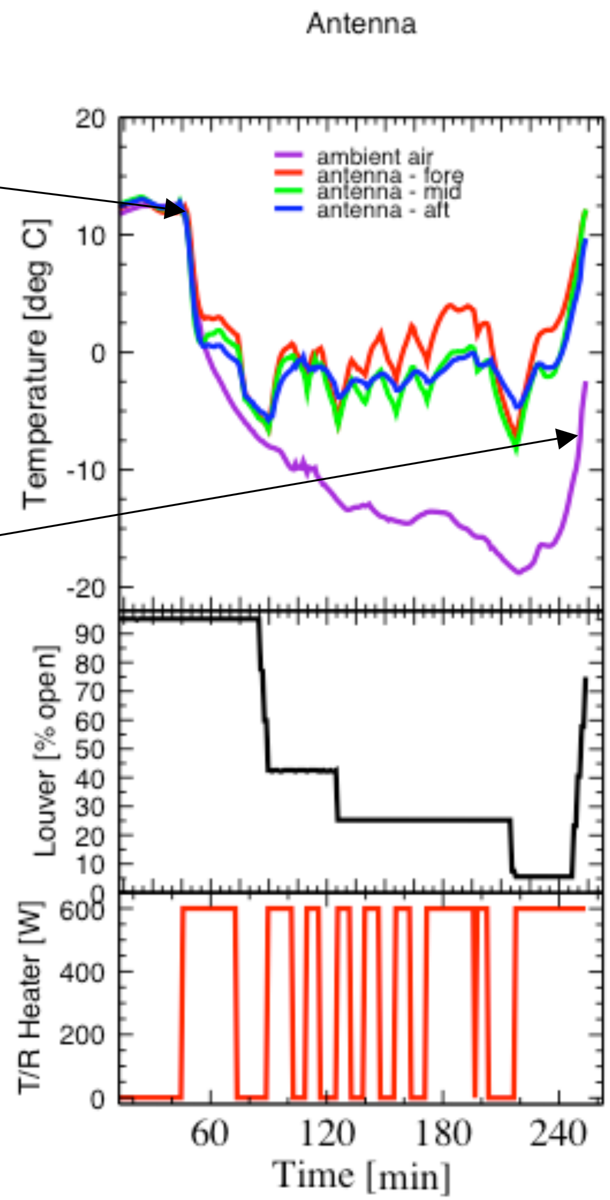


# Antenna Temperature Control

Take-off

Descent to land

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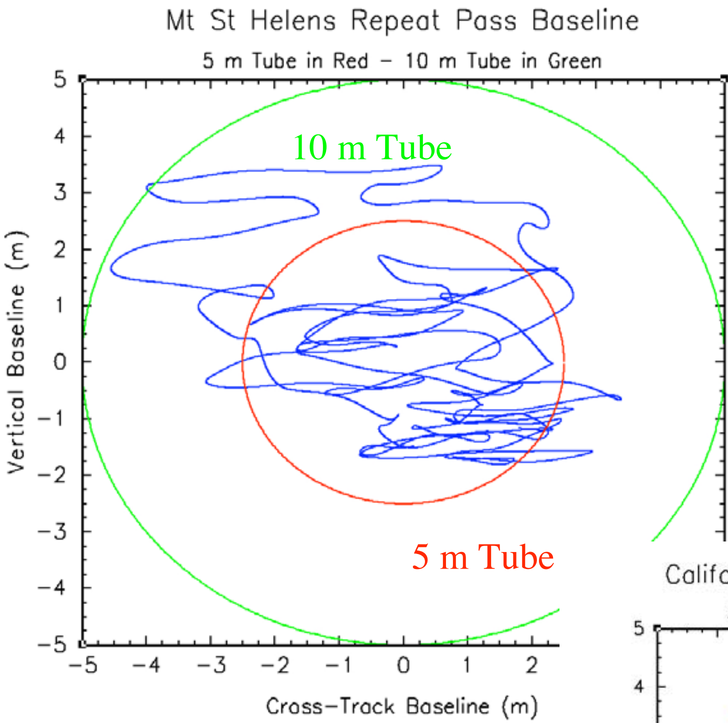


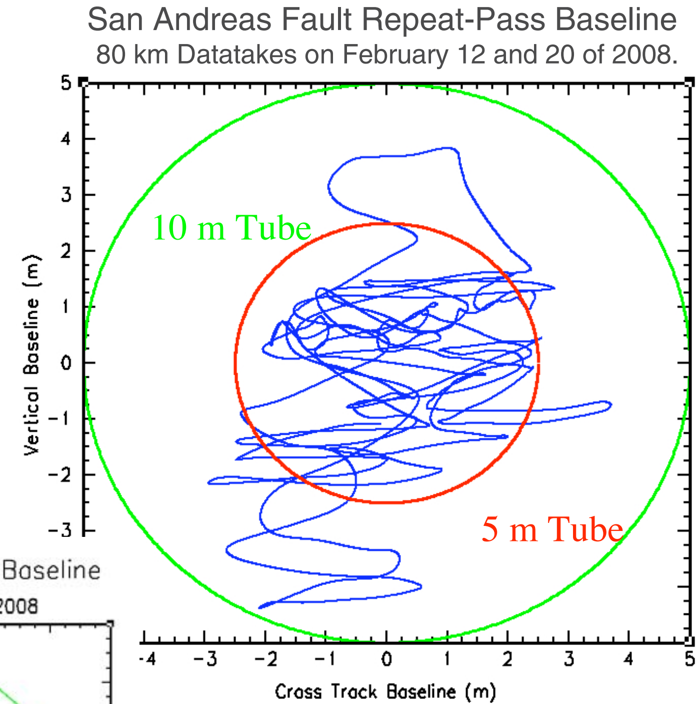


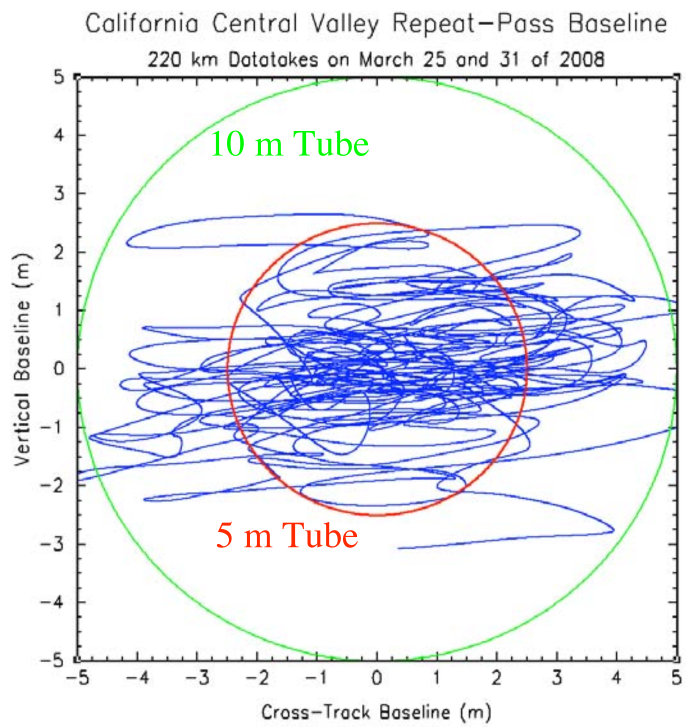


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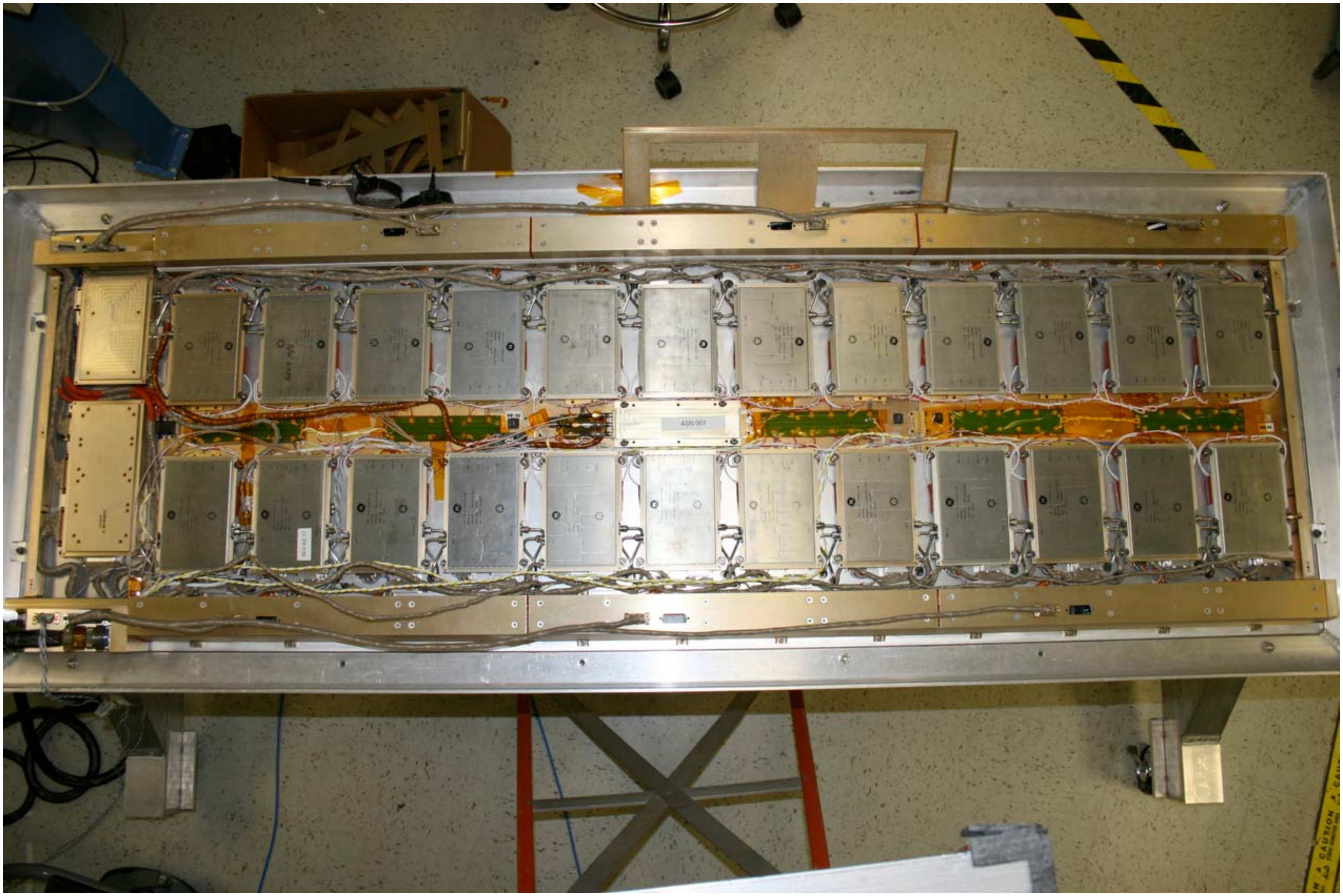

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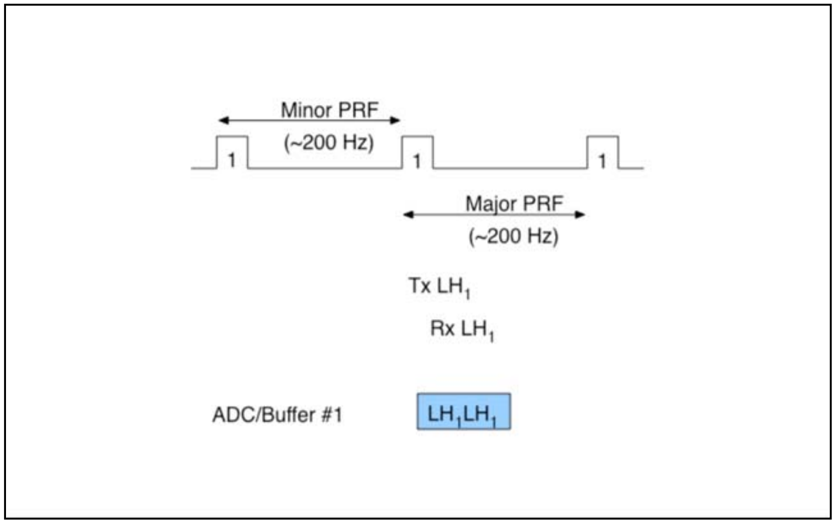


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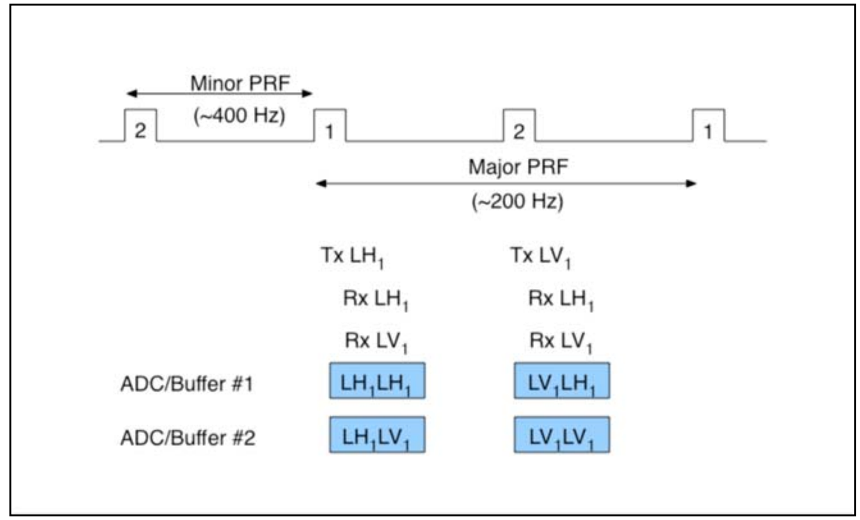


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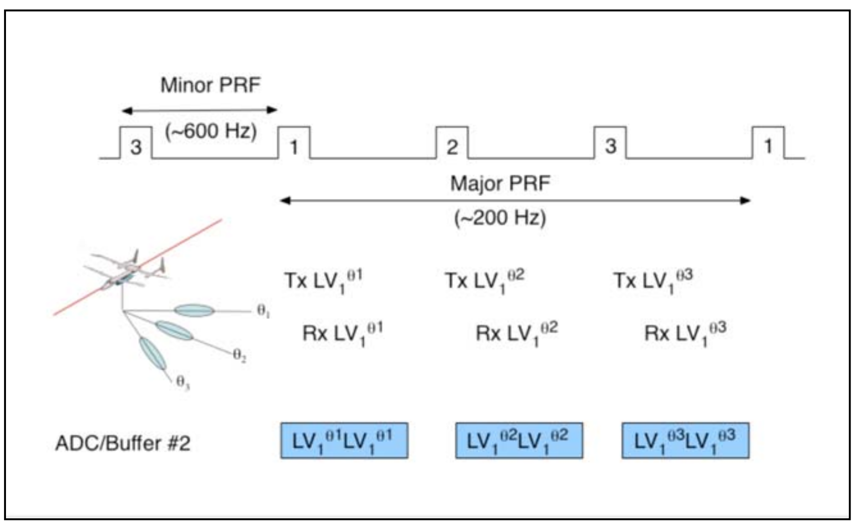


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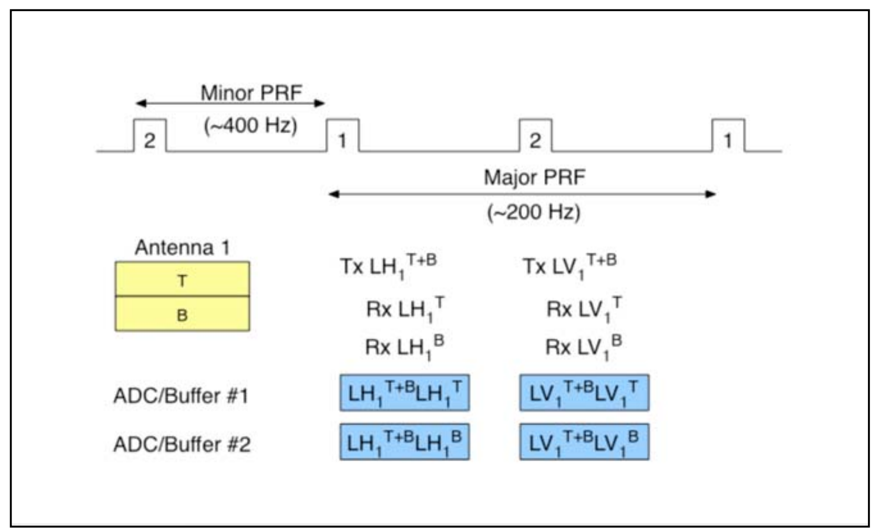

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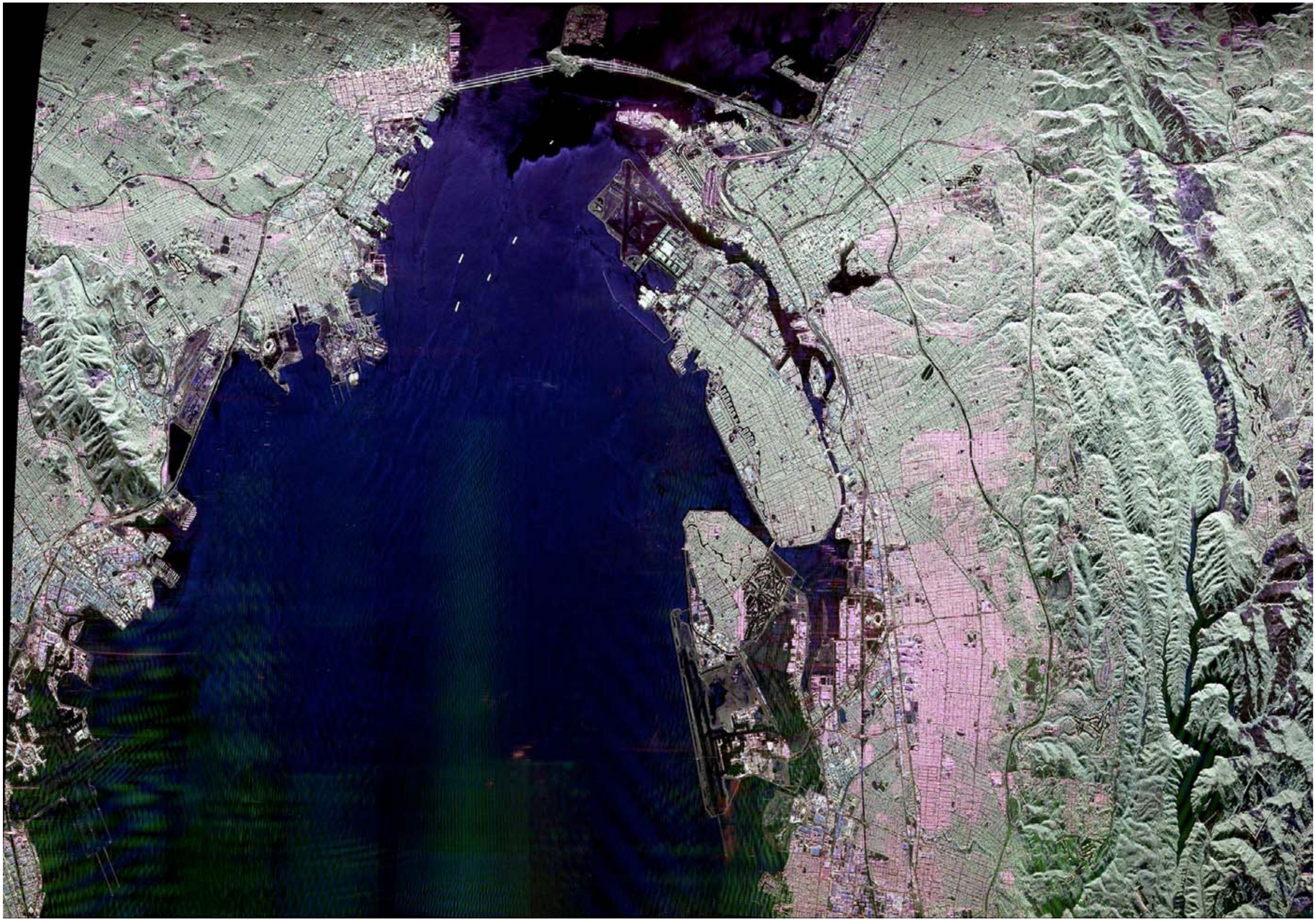
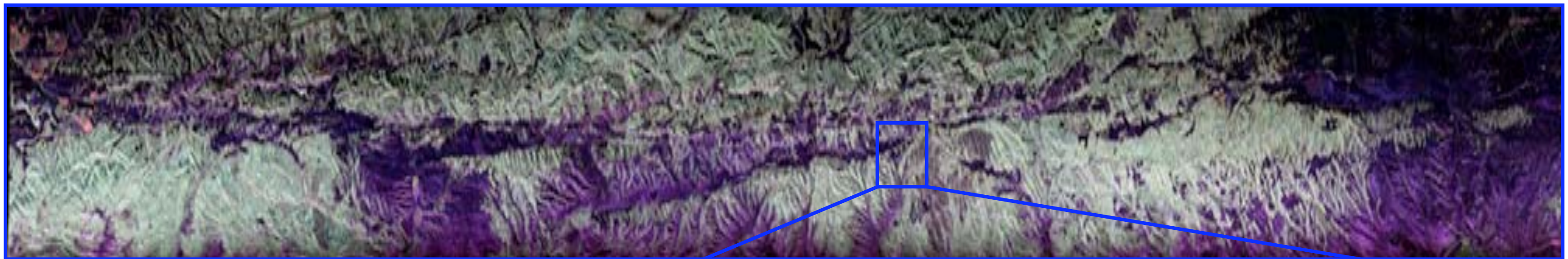
- Ground swath is over 20 km

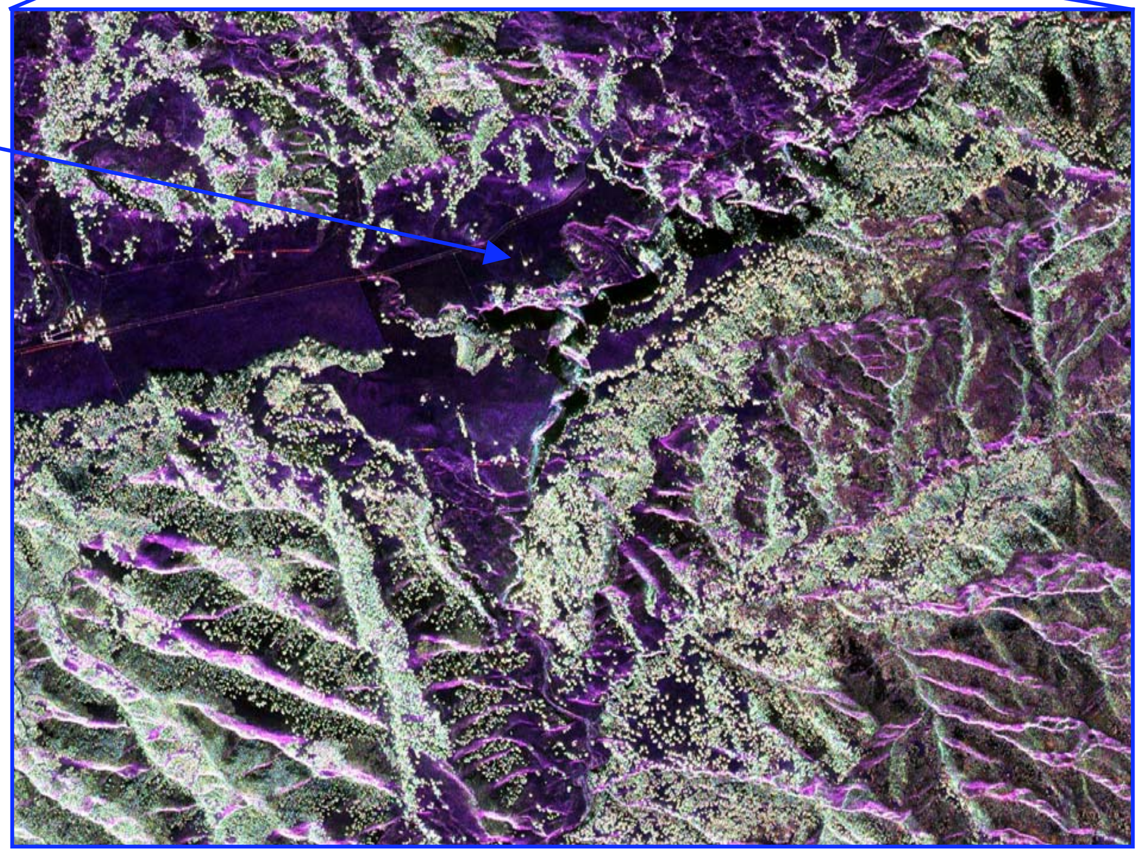
# San Francisco Bay - February 20, 2008



# San Andreas Fault Imagery



The same trees in Google Earth image can be seen in UAVSAR L-band image

1 km

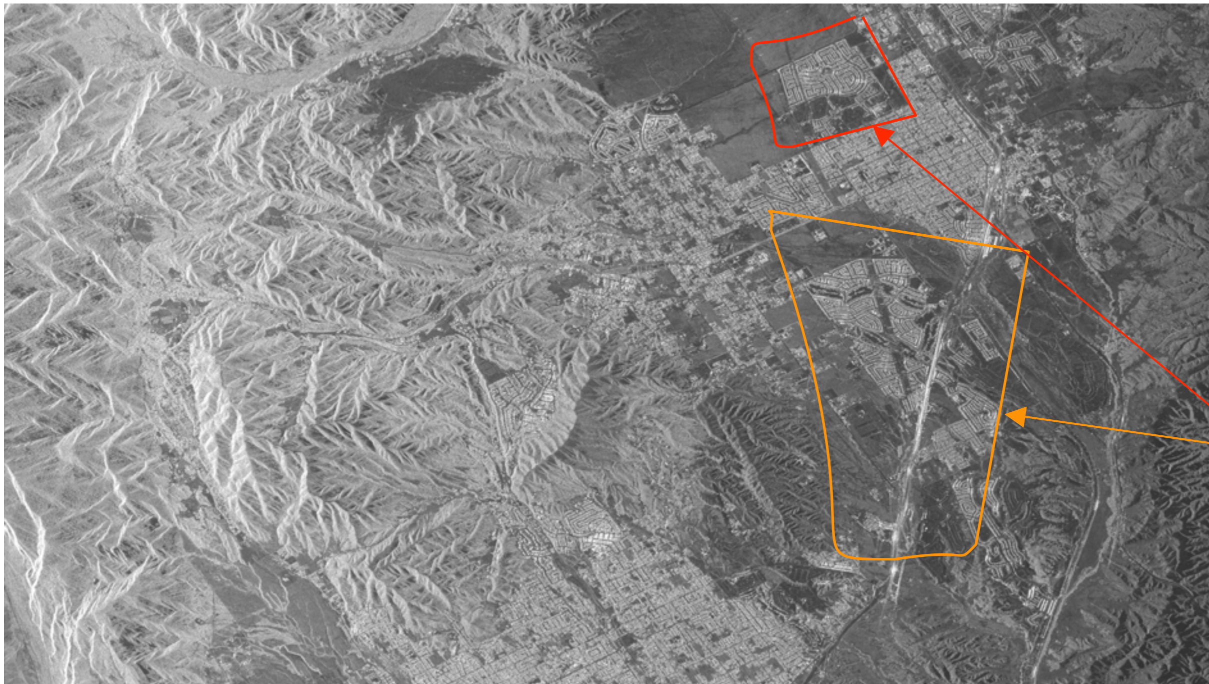
The different colors in the UAVSAR image generally correspond to different vegetation characteristics on the surface. Compensation for and projection to surface topography has not yet been applied.

LHH=red
LHV=green
LVV=blue

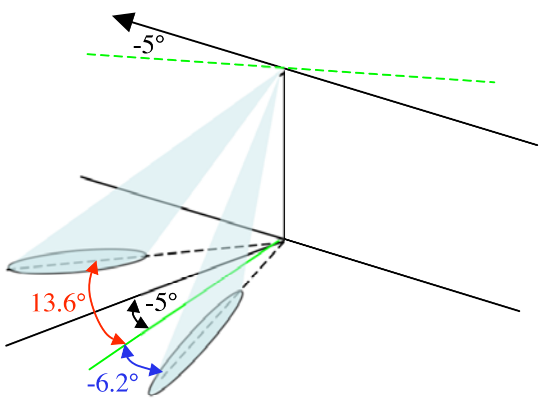
Data collected Feb 12, 2008

2x6 looks (3m resolution)

# Multi-Squint Mode



Azimuth Steering Angle: 13.6°



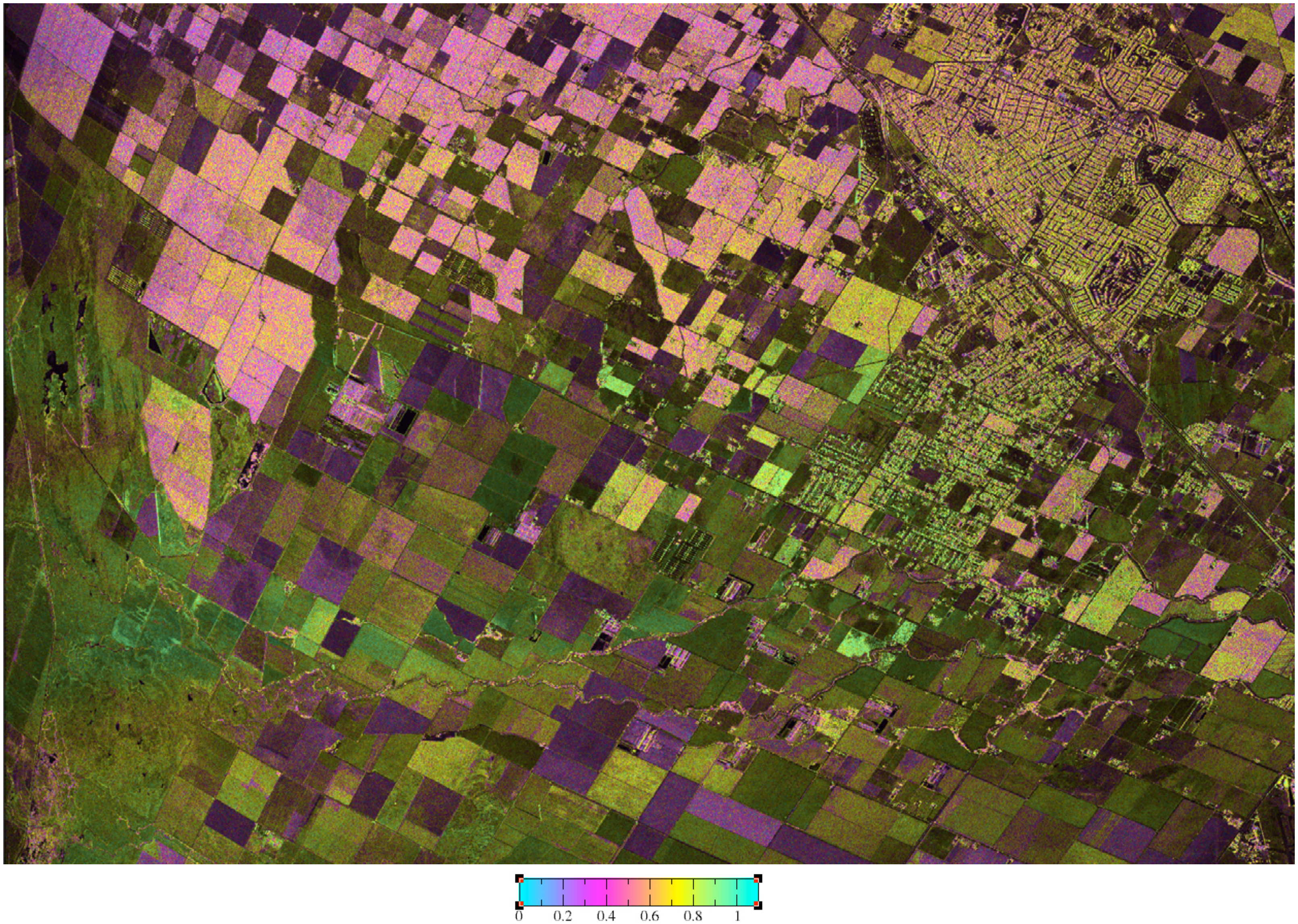

Azimuth Steering Angle: -6.2°

Data collected in the UAVSAR multi-squint mode, at two antenna steering angles:

- Platform had a yaw angle of -5.0°, so the beam was steered in azimuth by 13.6° and -6.2°.
- Anthropogenic features exhibit strong viewing angle scattering signatures.

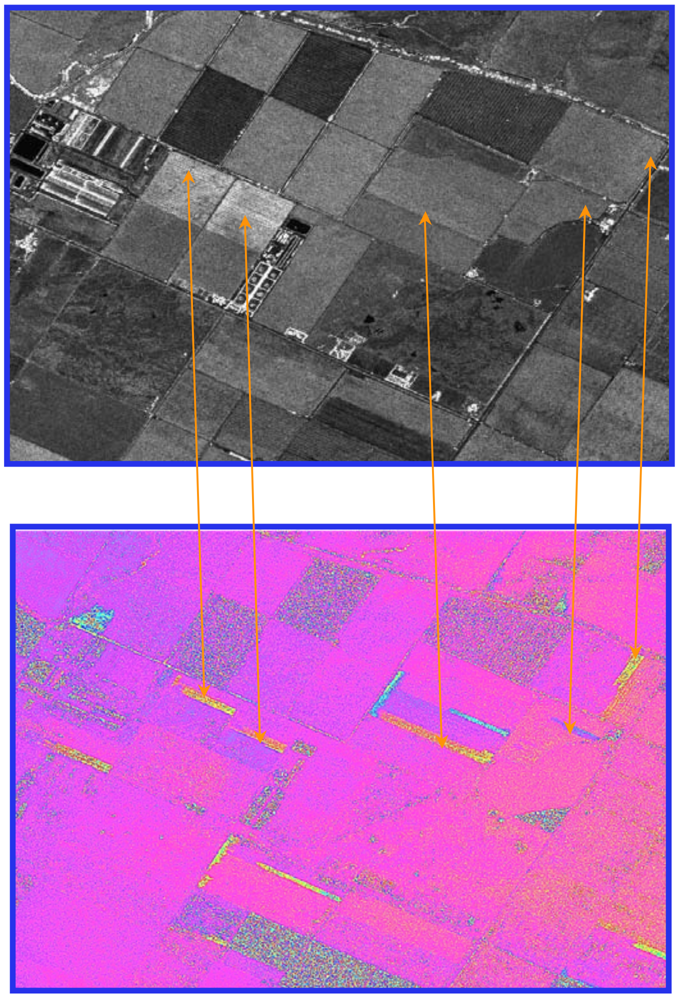
# California Central Valley Repeat Pass

- Correlation map from a portion of two passes collected over the California Central Valley on March 24 and 31 of 2008. Note changes are highly correlated with field boundaries.



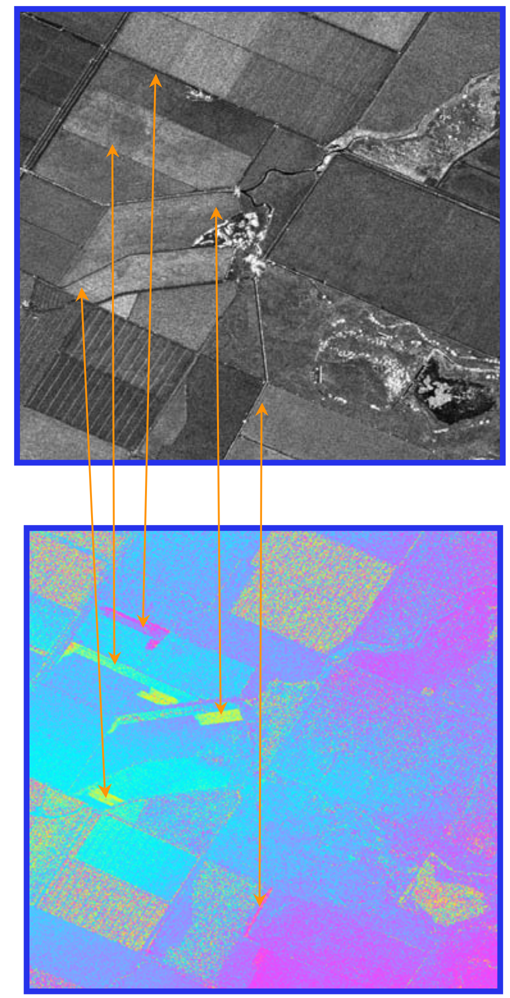
# Deformation in California Central Valley

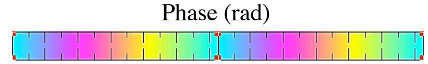
- Contraction or expansion of soil due to changing water content can be observed in the phase differences. One cycle of phase change corresponds to 6 cm of deformation. Observed deformation is on the order of 1-2 cm.



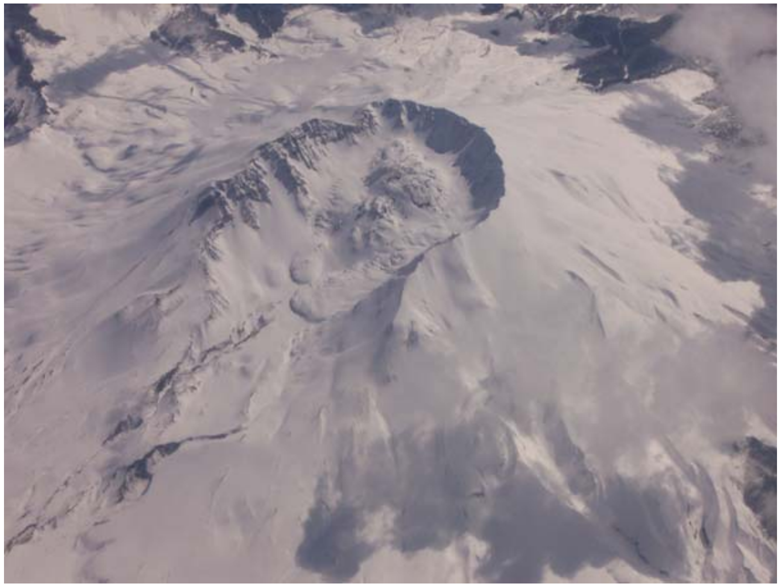
Magnitude Images

Differential Phase

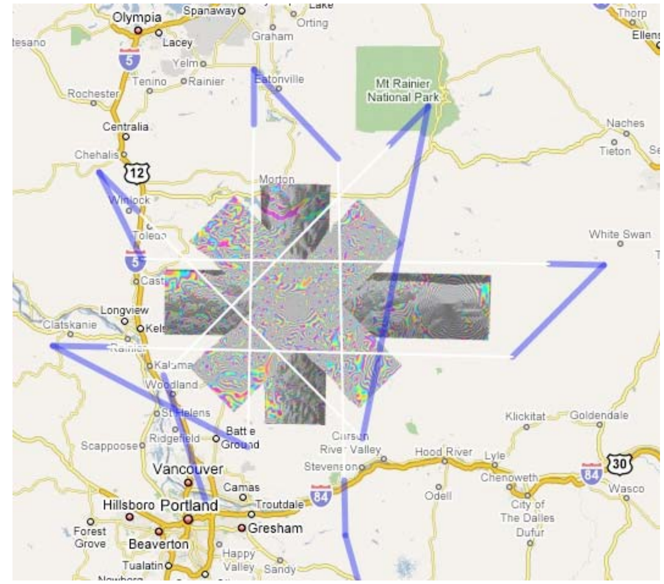




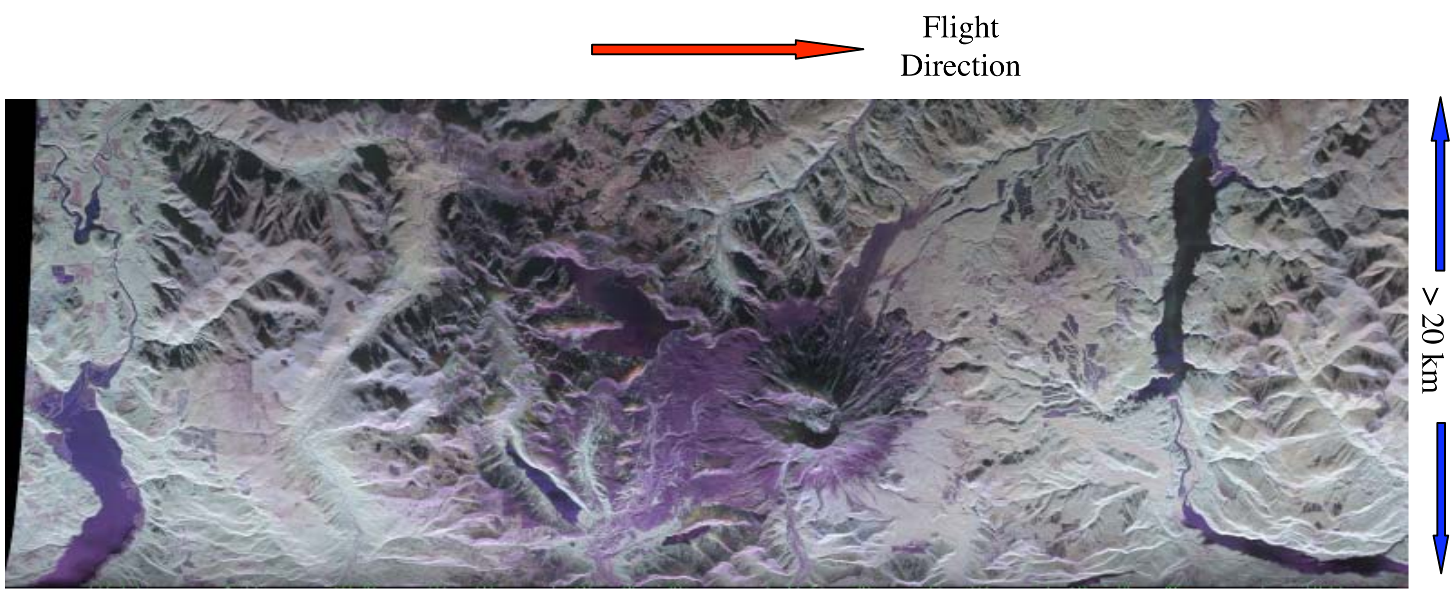
# Mt. St. Helens



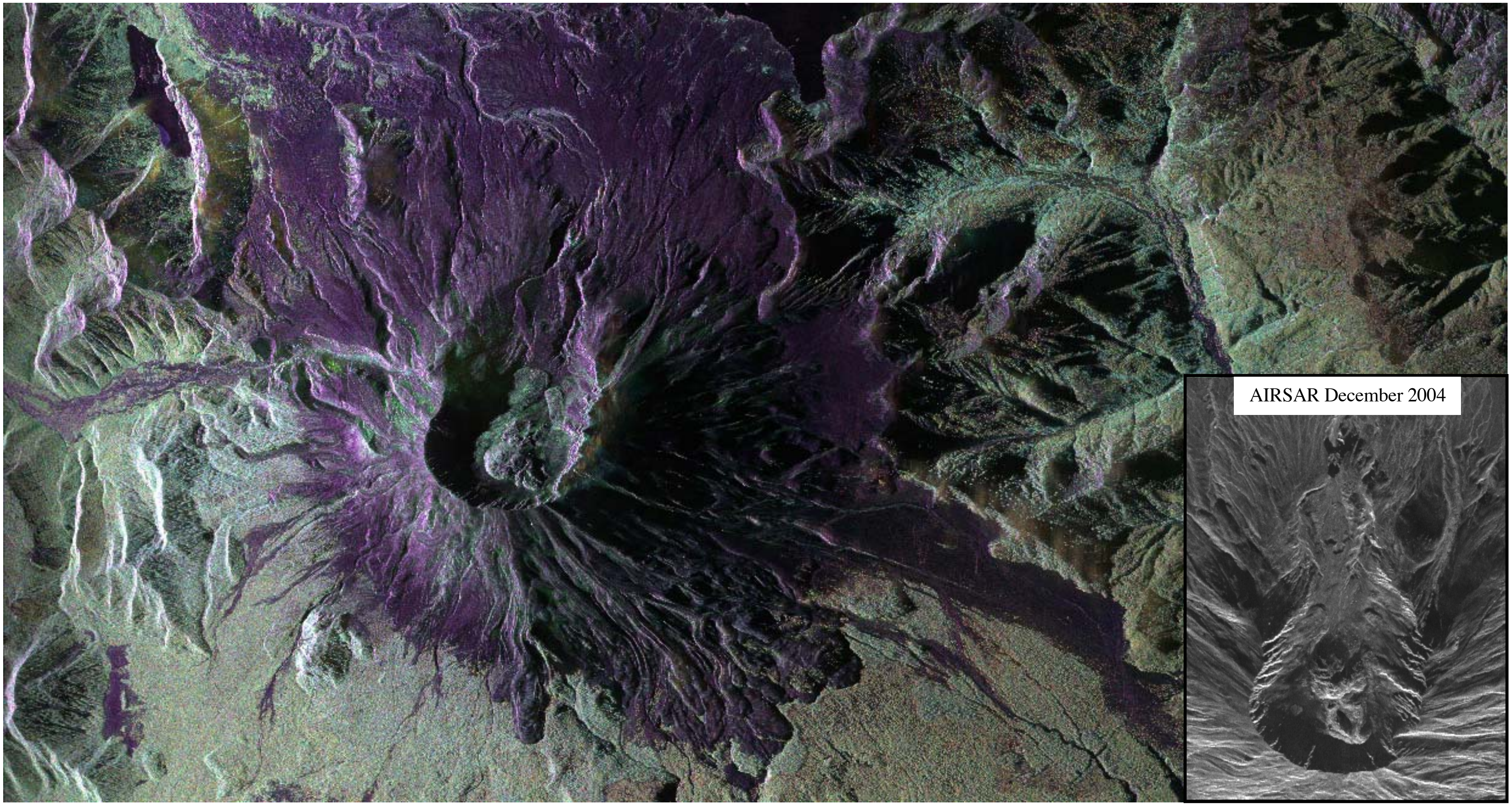
Data was collected along 6 different look directions over Mt. St. Helens.




Fully polarimetric image of Mt. St. Helens collected on March 24, 2008 by the UAVSAR radar. A second acquisition was collected on March 31, 2008.

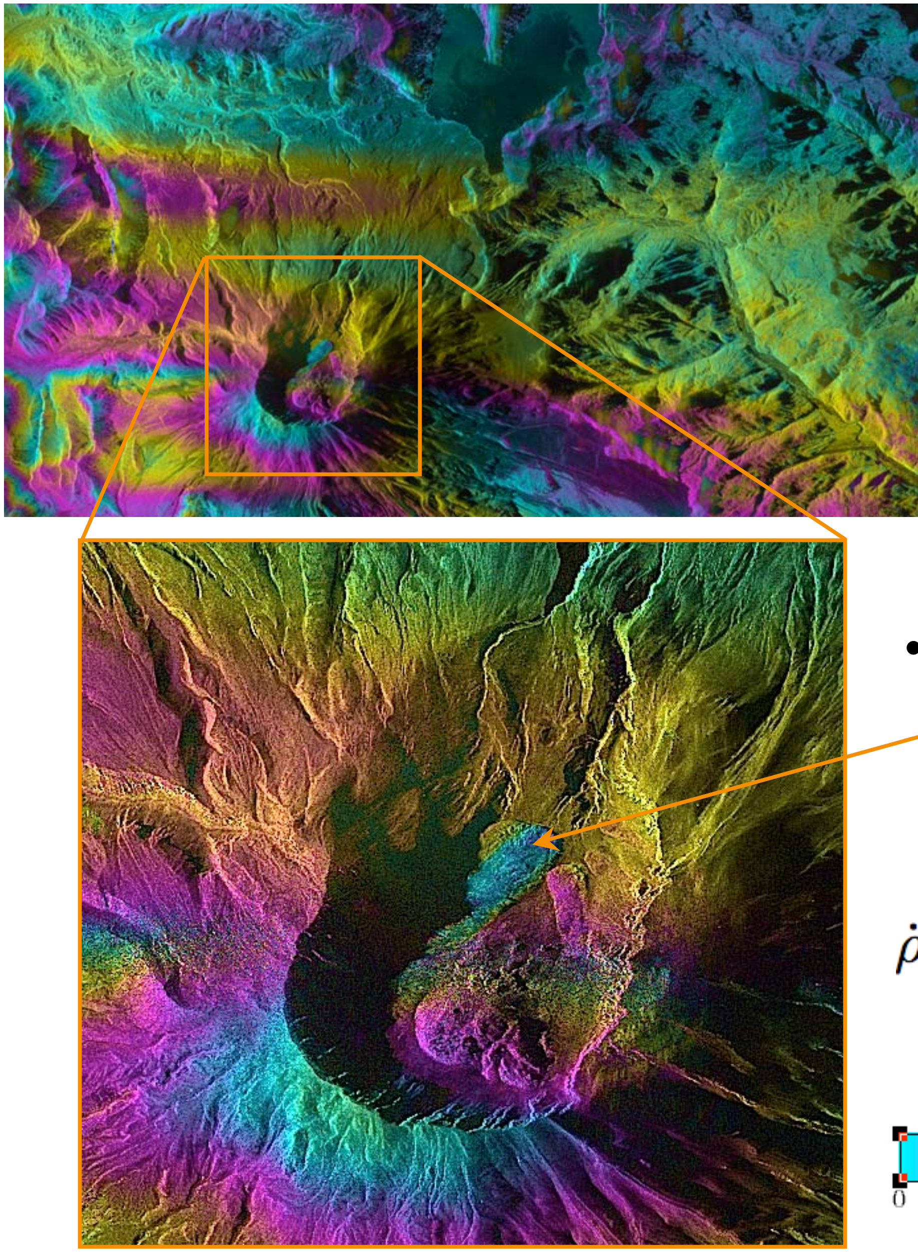


# L-Band UAVSAR Image of Caldera and Dome




LHH=red
LHV=green
LVV=blue

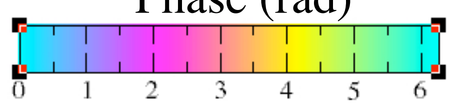
# Mt. St. Helens Interferogram - 4 hour Repeat



- This is a first cut interferogram
  - no offset measurements
  - no motion correction
  - no topography correction

- Since time between observations is 4.2 hours or .174 days, the estimated rate of motion for an approximate π radians of phase change is

$$\dot{\rho} = \frac{\lambda\phi}{4\pi\Delta t} = \frac{0.24}{4 \cdot 0.174} = 0.344\frac{m}{day}$$



# Conclusions

- UAVSAR is an actively scanned fully polarimetric L-band SAR designed to meet a range of remote sensing applications of interest to the science community including specific features to support repeat pass interferometry for deformation studies.
- Results thus far from flight testing indicate:
  - Sensor is meeting all its performance objectives
  - Platform is routinely able to maintain trajectory within the 10 m tube requirement and often stays within a 5 m tube.
  - Available swath width is greater than 20 km with a flight altitude of 12.5 km.
- Ongoing and future work is devoted to:
  - Continued verification of the various radar modes
  - Residual motion estimation and compensation using radar data
  - Quantification of the accuracy of the deformation measurements
  - Tomographic studies for vegetation parameter estimation

# Some First Results from the UAVSAR Instrument


Cathleen Jones
Jet Propulsion Laboratory

Earth Science Technology Conference
June 25, 2008

# UAVSAR Project Design and Objectives

- UAVSAR is a portable pod-based synthetic aperture radar (SAR) system instrumented with a phased array, polarimetric, L-band antenna. It is designed to support a wide range of science investigations including geology, vegetation mapping and land use classification, archeological research, soil moisture mapping, and cold land processes.
- The modular design supports portability to other platforms and reconfiguration to use antennas at other radar frequencies, in addition to joint experiments with other radar instruments.
- The primary objectives of the UAVSAR project are:
  1. Develop a miniaturized polarimetric L-band synthetic aperture radar (SAR) for measuring surface deformation using radar repeat-pass interferometry that is suitable for implementation on a UAV.
  2. Develop the associated processing algorithms for repeat-pass differential interferometric measurements from an airborne platform.
  3. Conduct measurements of geophysical interest, particularly changes of rapidly deforming surfaces such as volcanoes or earthquakes.
- UAVSAR is currently in the final months of a four year program. Operational use of the instrument will begin in 10/2008.

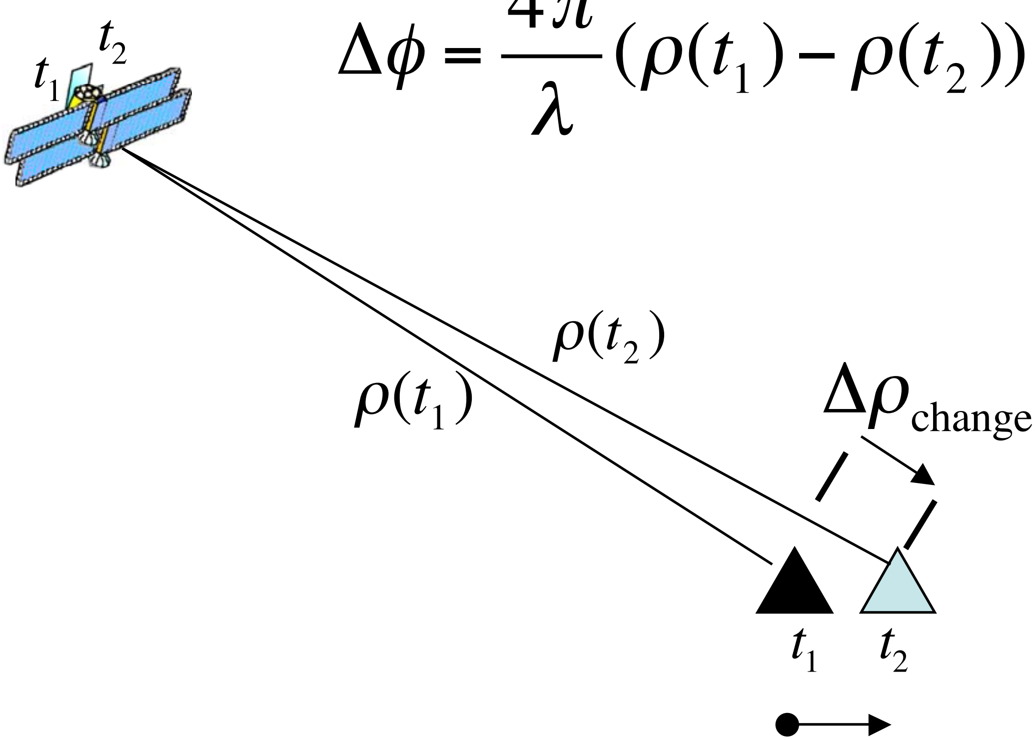
# Key Radar Instrument Parameters

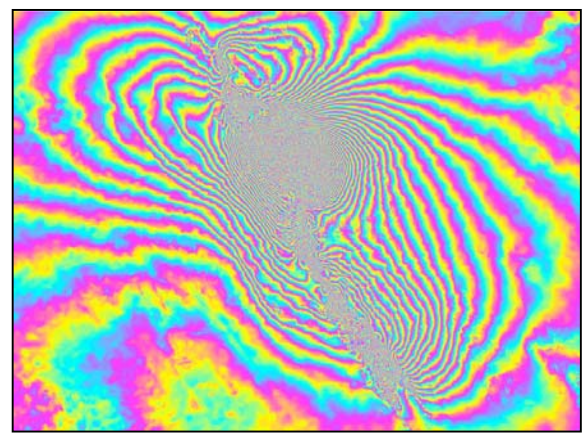
| Parameter | Value |
|---|---|
| Frequency | L-Band 1217.5 to 1297.5 MHz |
| Bandwidth | 80 MHz |
| Resolution | 1.67 m Range, 0.8 m Azimuth |
| Polarization | Full Quad-Polarization |
| ADC | 12 bit ADC with selectable Bit Floating Point Quantization compression to 2, 4, 6, 8, 10 or 12 bits; 180 MHz sampling frequency |
| Waveform | Nominal Chirp/Arbitrary Waveform |
| Antenna Aperture | 0.5 m range/1.5 azimuth (electrical) |
| Azimuth Steering | Greater than ±20° |
| Transmit Power | > 3.1 kW |
| Polarization Isolation | <-25 dB |

# Deformation Interferometry

When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

$$\Delta\phi = \frac{4\pi}{\lambda}(\rho(t_1) - \rho(t_2)) = \frac{4\pi}{\lambda}\Delta\rho_{change}$$



Surface Deformation of the 1999 Hector Mine Earthquake

# Airborne RPI Instrument

- Spaceborne repeat pass radar interferometry derived deformation measurements has become a standard tool for the solid earth science and glaciological science communities.
  - Repeat times controlled by the the repeat orbit cycle of spaceborne SAR systems, e.g. ERS-1,2 (35 days), Radarsat (24 days), JERS (44 days), and Envisat ( 35 days).
- An airborne platform provides coverage unavailable with spaceborne platforms.
  - Rapidly deforming features such as some volcanoes and glaciers or deformation from post seismic rebound require repeat times of a day or less to fully study the time varying nature of the deformation signal.
- There are additional challenges associated with repeat pass interferometric measurements from an airborne platform:
  - The flight track is more difficult to repeat accurately in an aircraft.
    - Motion compensation must be done very accurately.
      - Knowledge of aircraft motion (Inertial Measurement Unit)
      - Correction of residual (unmeasured) motion
    - The images decorrelate unless the repeat pass baseline is small, ~<10 m.
      - Knowledge of aircraft position (Differential GPS)
      - Precision control of the aircraft flight path (Precision Autopilot)
  - The need to compensate for aircraft attitude angle changes between flight tracks, which arise from varying flight conditions, like winds aloft, turbulence, flight speed, fuel load.

# UAVSAR on the Gulfstream III

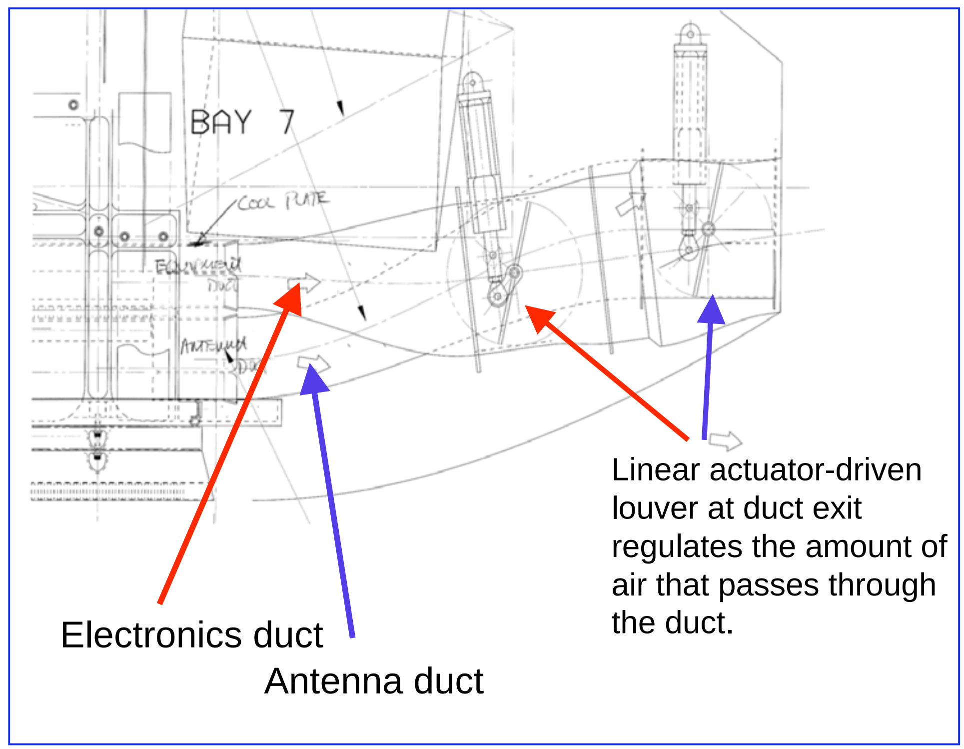
Unique features of UAVSAR:

1. Ambient air cooling: Uses regulated airflow through louvers to cool, heaters to warm the antenna T/R modules and the radar electronics in the pod.
2. Precision autopilot to maintain the flight track within a 10 meter tube around the desired track.
3. Phased array antenna plus adaptive steering to maintain pointing direction of the radar beam.

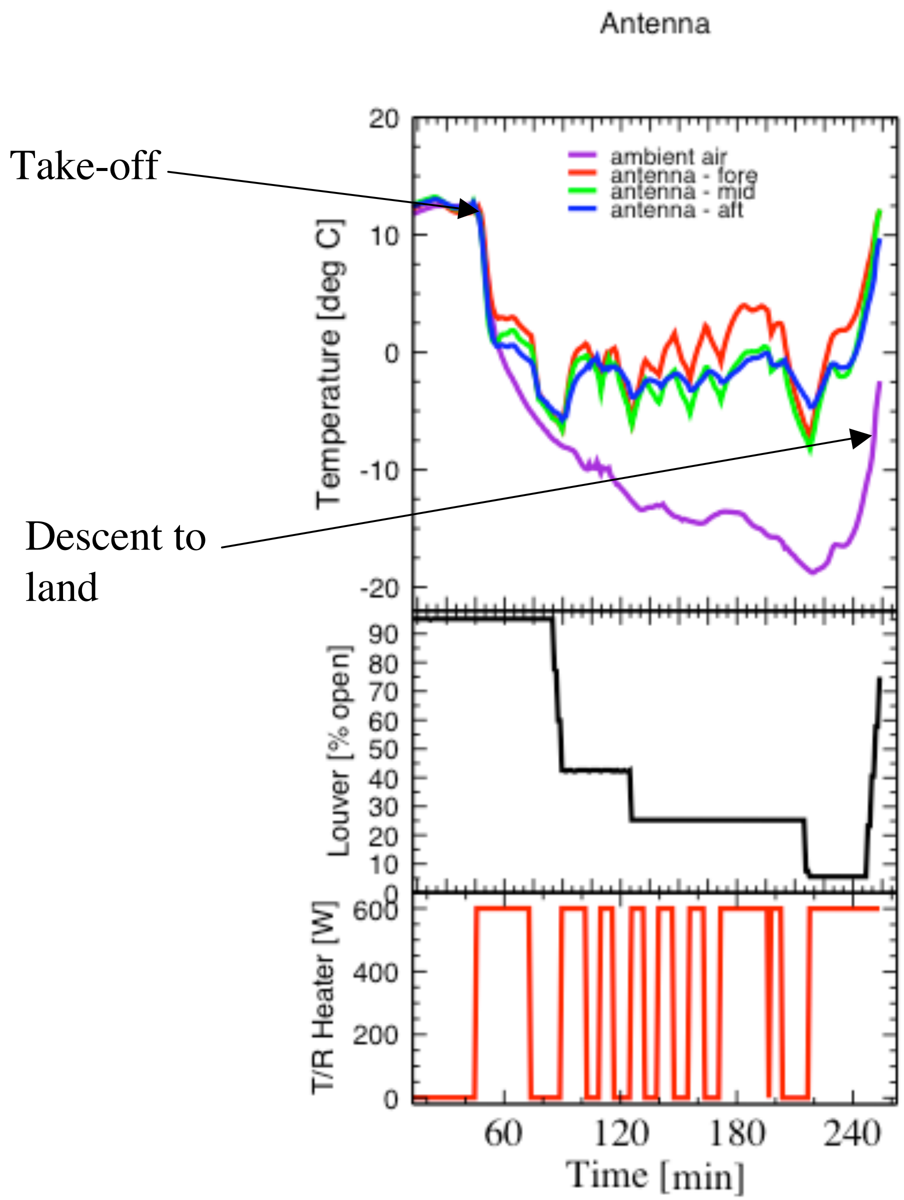
# Ambient Air Cooling


- Flying in an unpressurized pod allowed for maximal portability to other platforms, however this necessitated a fairly involved thermal control system to keep the various units within an acceptable temperature range and avoid condensation during descent.

Louvers:



# Antenna Temperature Control

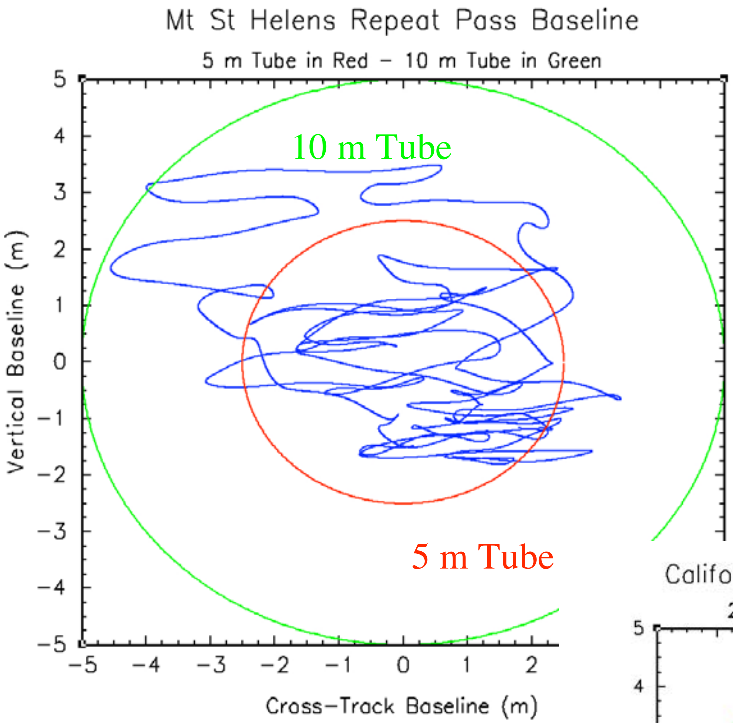


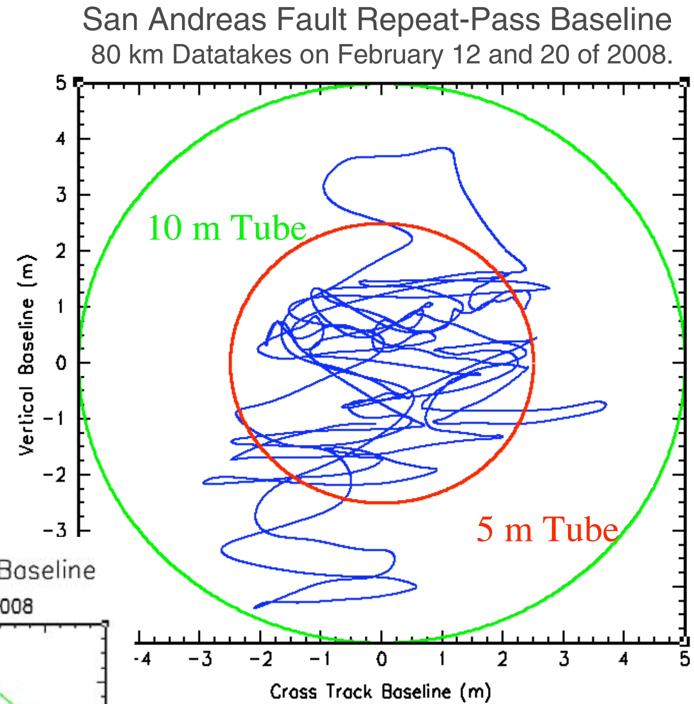

As the outside air temperature drops, the louvers close to maintain the antenna temperature between +5 and -10 °C.

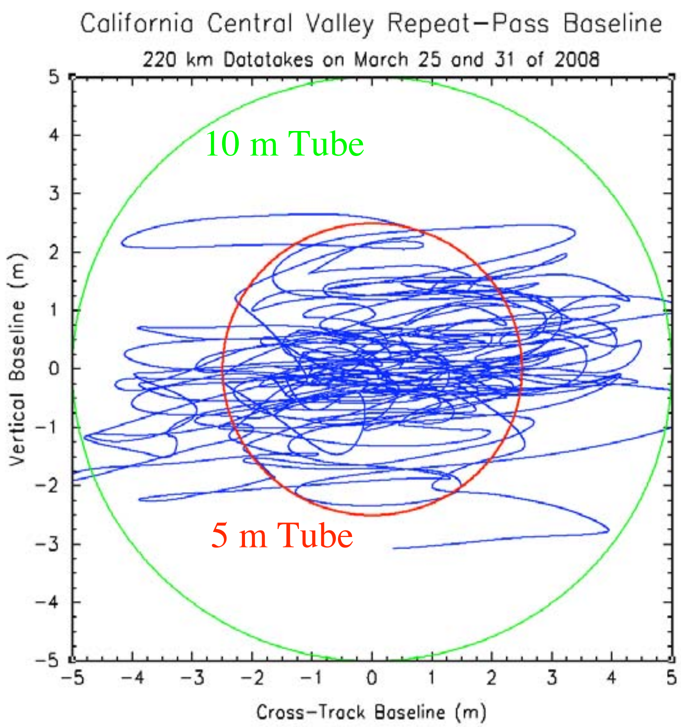
Louver adjustment

Heaters on T/R modules provide replacement heat to maintain near-constant temperature during transmission.

# Precision Autopilot Repeat Pass Baseline



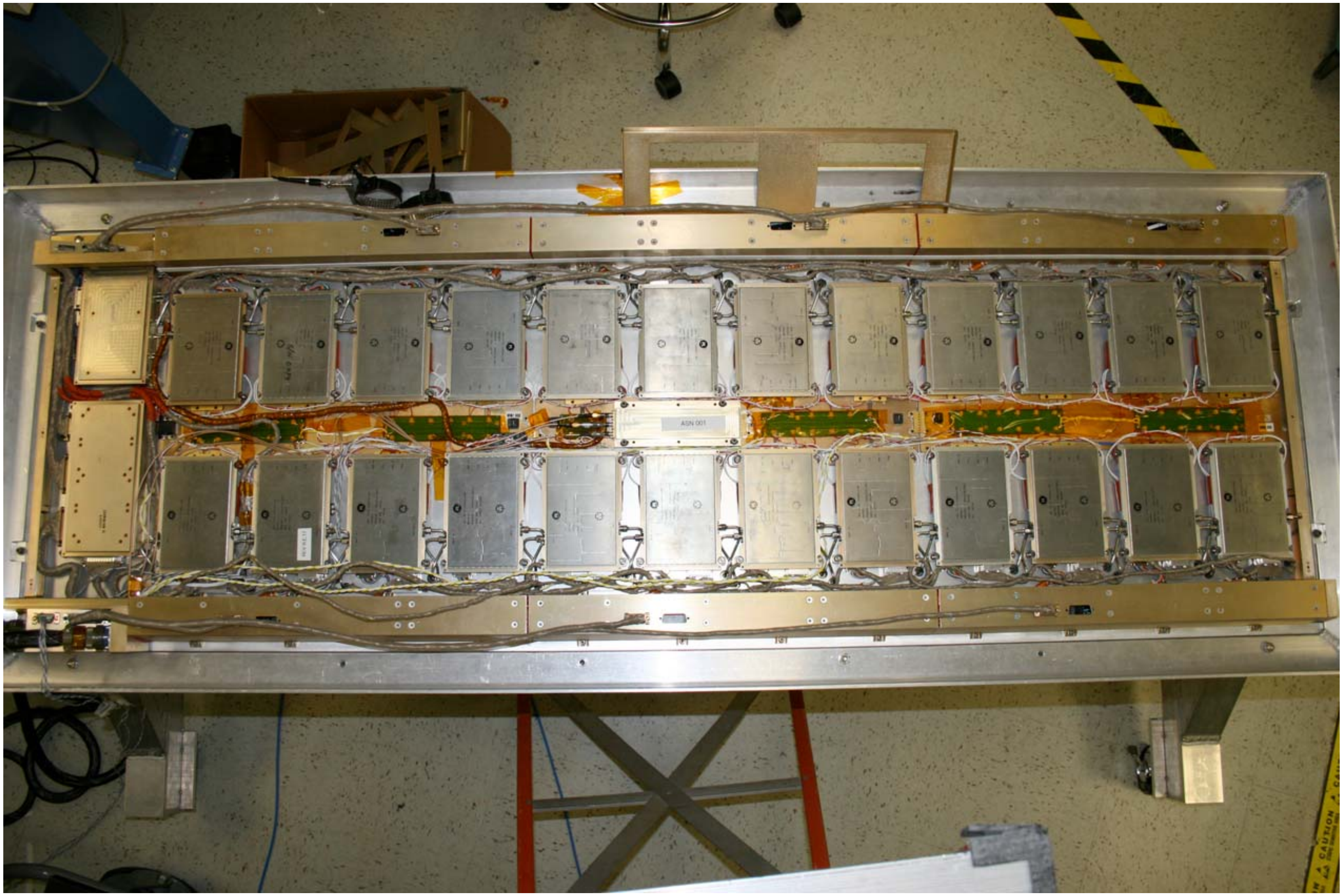




The Precision Autopilot System was designed and developed at Dryden Flight Research Center.

Overall, the PPA maintains the planned flight path within a 5 m tube nearly 90-95% of the time. The requirement on tracking is to maintain a 10 m tube for >90% of the flight track under light turbulence conditions.

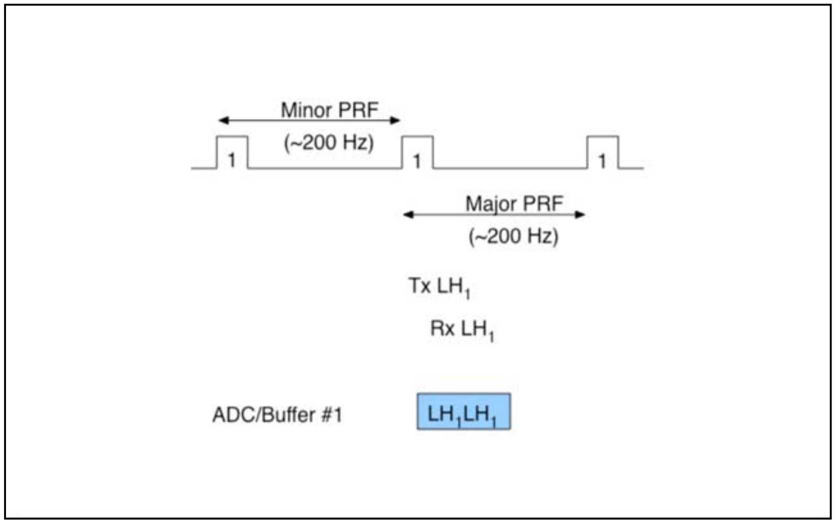
# L-Band Phased Array Antenna

Active steering of the antenna beam allows us to maintain the look direction independent of the platform yaw. This is accomplished by adjusting the phase of the individual T/R modules to steer the antenna beam.

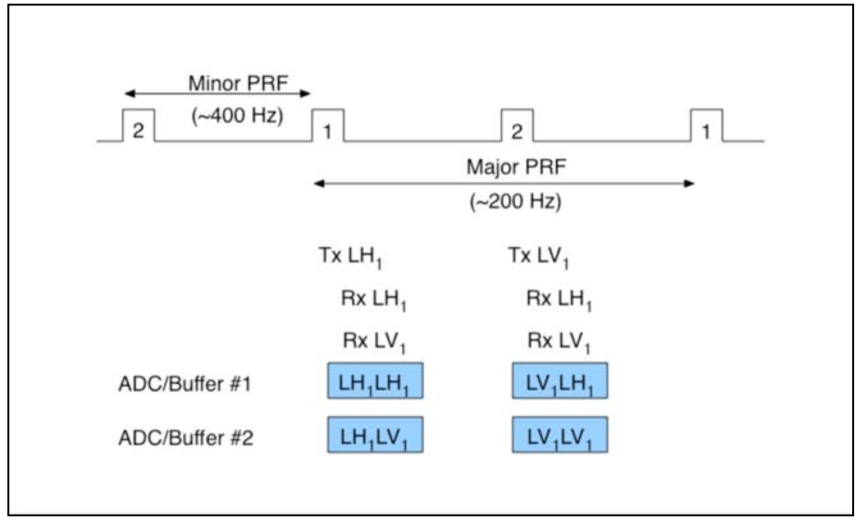


# UAVSAR Modes

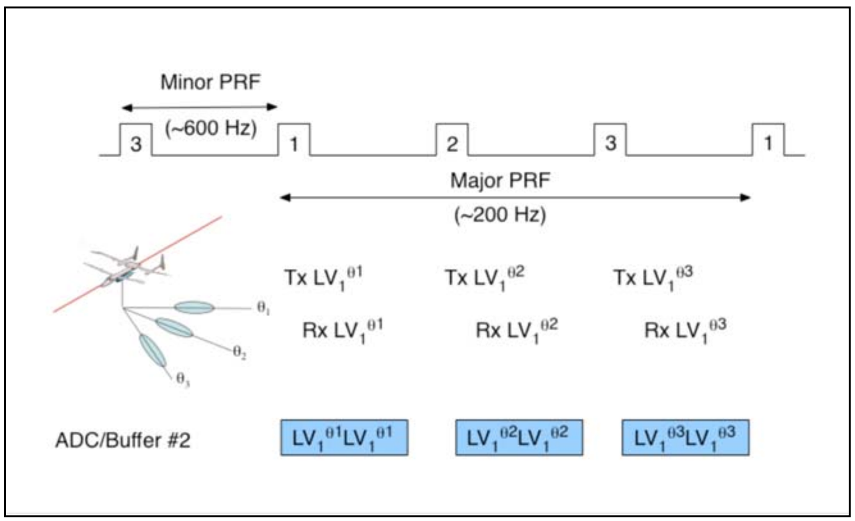
## Strip Mode SAR



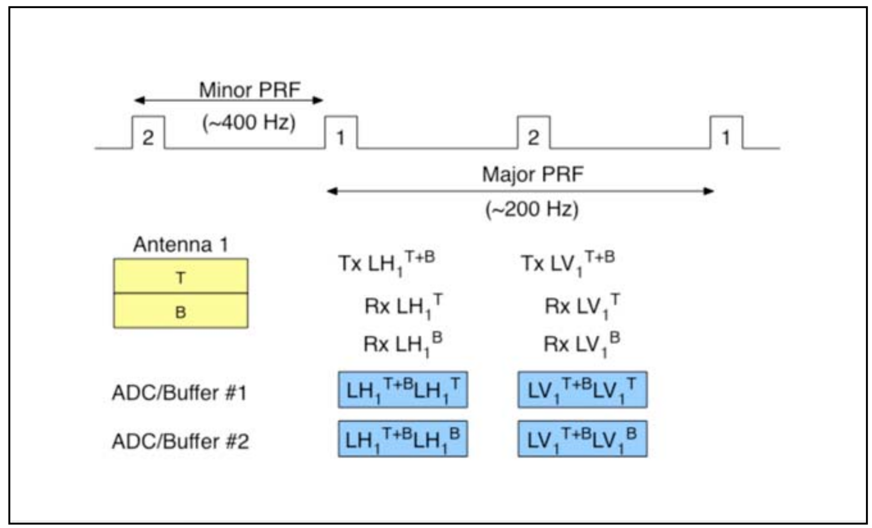

## Polarimetric SAR




## Multi-Squint Vector Deformation




## CoPol Monopulse



# UAVSAR Flight Tests

- Prior to tests of the radar, numerous flight tests of the Precision Autopilot system and two flights tests of the temperature regulation system were made with the pod populated with dummy units.
- The first flight test of the UAVSAR radar was made on July 19, 2007. The flight tests will continue through July 2008.
- Since then, approximately 3.3 TB of radar data has been collected. The first pass data processing is usually completed within 24 hours of data return to JPL.

| SITE | # flights | # lines |
|---|---|---|
| Kings Canyon, CA | 1 | 7 |
| Long Valley, CA | 2 | 4 |
| Lost Hills, CA | 3 | 10 |
| Mt. Adams, WA | 3 | 3 |
| Mt. St. Helens, WA | 3 | 23 |
| Ocean, Channel Islands, CA | 2 | 5 |
| Parkfield, CA | 3 | 3 |
| Rosamond, CA | 10 | 75 |
| Salton Sea, CA | 3 | 5 |
| San Francisco, Hayward Fault | 6 | 29 |
| San Francisco, San Andreas Fault | 5 | 6 |
| San Joaquin Valley, CA | 2 | 2 |
| Sierra Madre, CA | 1 | 1 |

Current as of 6/16/2008

# Rosamond Lakebed Calibration Array

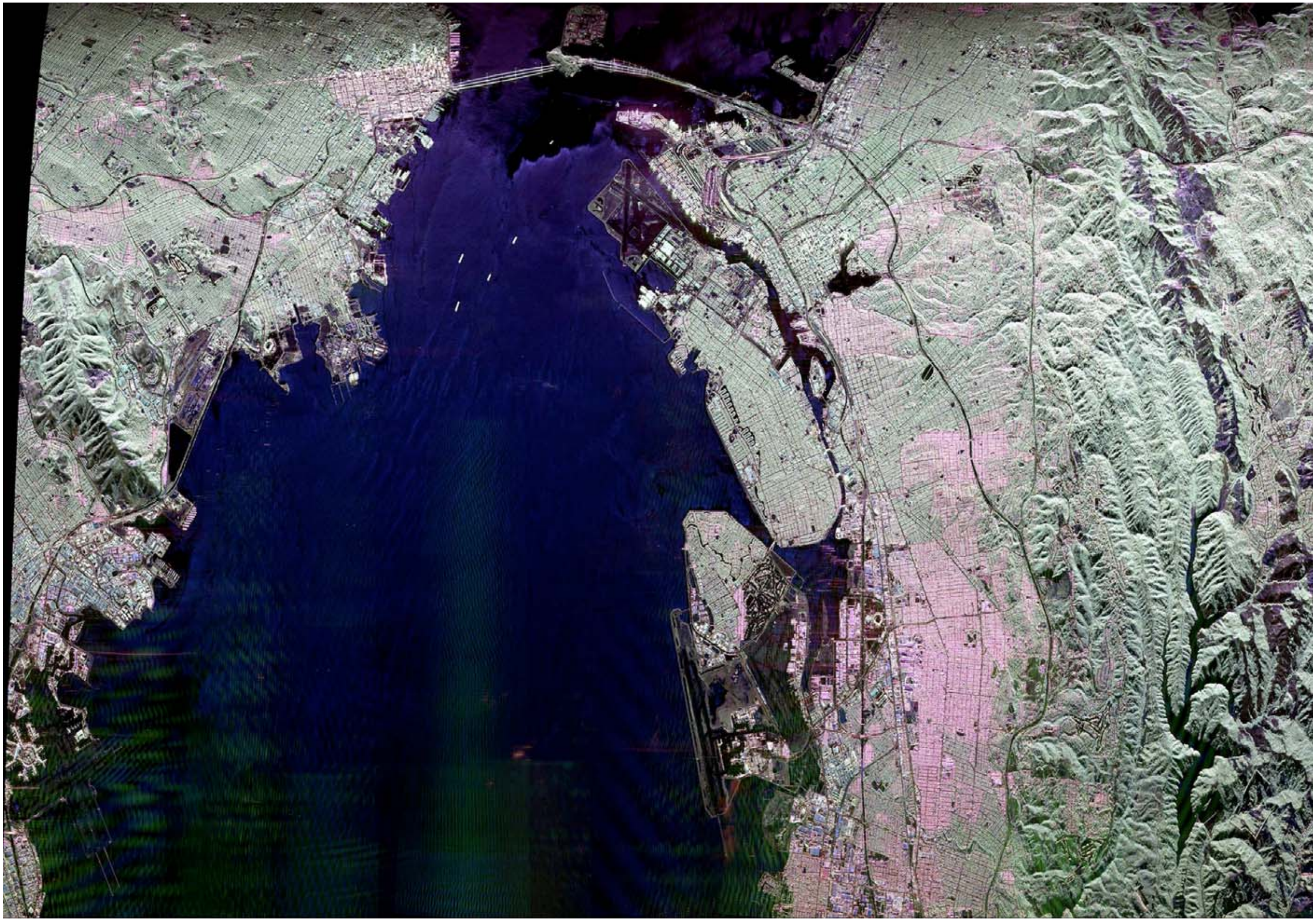
An array of 23 trihedral corner reflectors is set up on the Rosamond dry lakebed near Edwards AFB. The location of each CR's vertex is determined with high precision differential GPS. Standard engineering test flights image this array.

Full Array PolSAR Image

LHH=red
LHV=green
LVV=blue

- Data collected Dec 6 over Rosamond Lake Bed, from an altitude of 39000 ft.
- Ground swath is over 20 km

# San Francisco Bay - February 20, 2008



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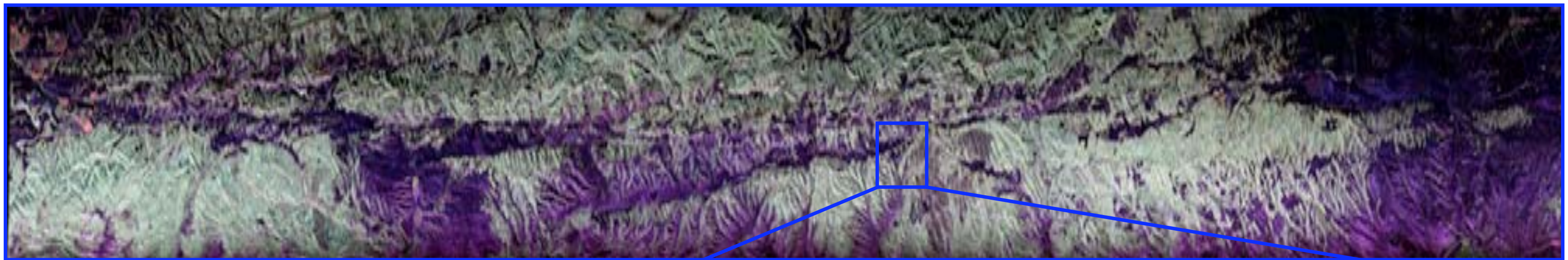

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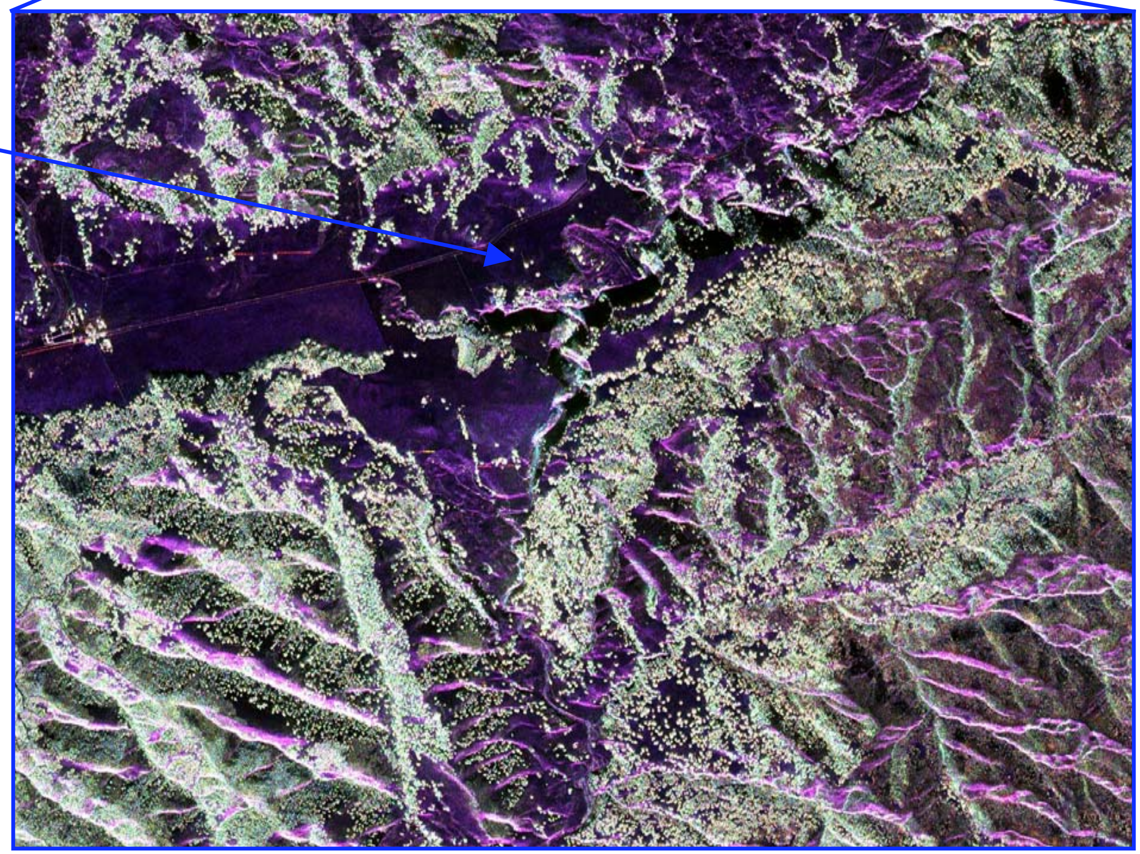

The different colors in the UAVSAR image generally correspond to different vegetation characteristics on the surface. Compensation for and projection to surface topography has not yet been applied.

1 km

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Data collected Feb 12, 2008

2x6 looks (3m resolution)

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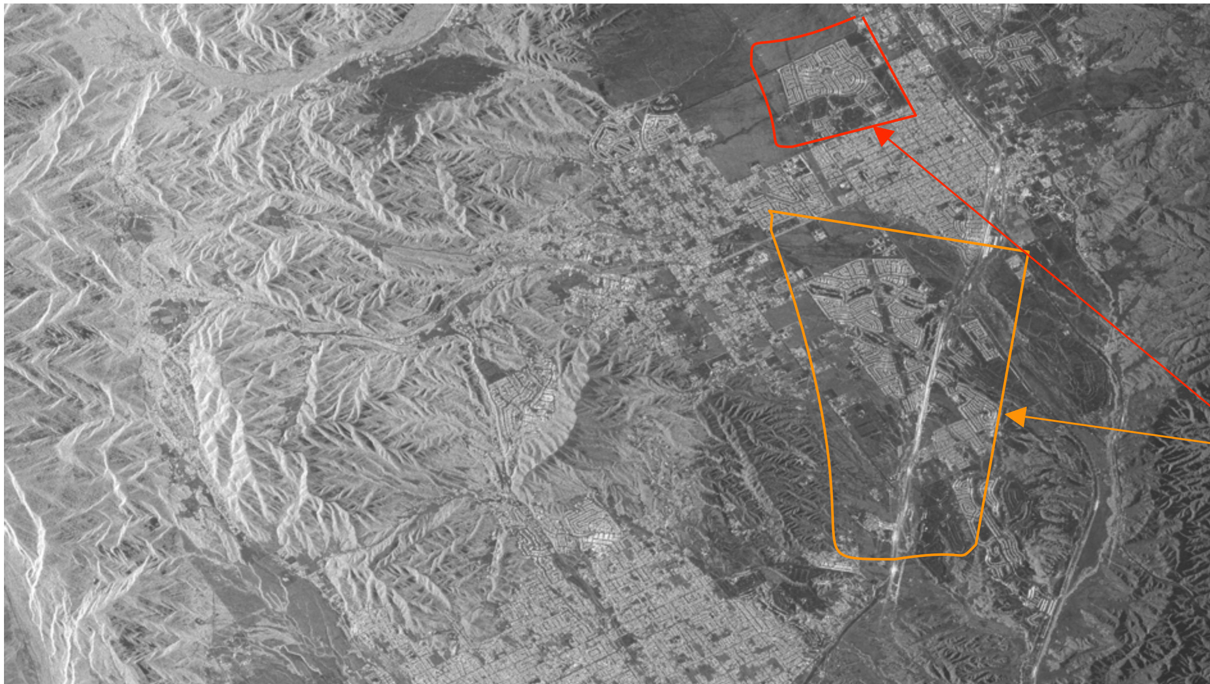

Data collected in the UAVSAR multi-squint mode, at two antenna steering angles:

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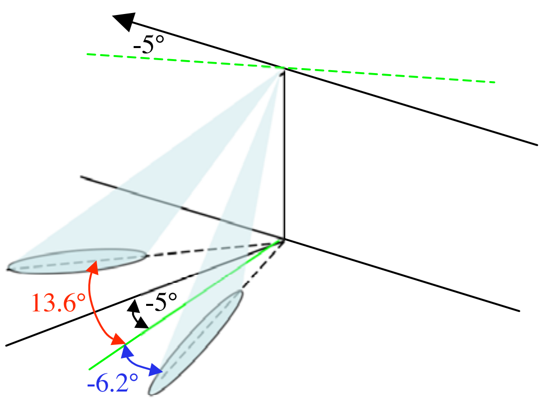
- Anthropogenic features exhibit strong viewing angle scattering signatures.

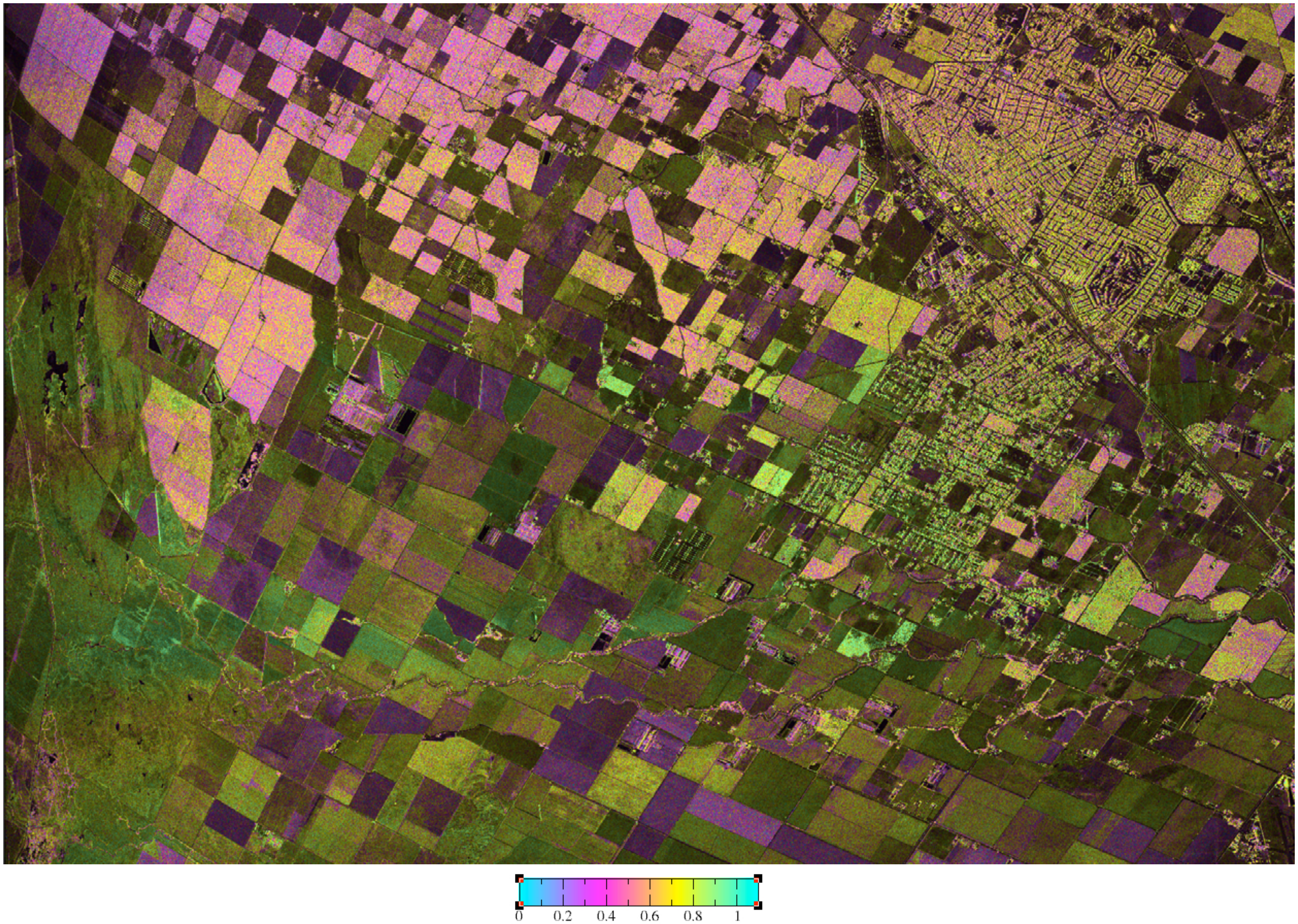
Azimuth Steering Angle: 13.6°




Azimuth Steering Angle: -6.2°

# California Central Valley Repeat Pass

- Correlation map from a portion of two passes collected over the California Central Valley on March 24 and 31 of 2008. Note changes are highly correlated with field boundaries.



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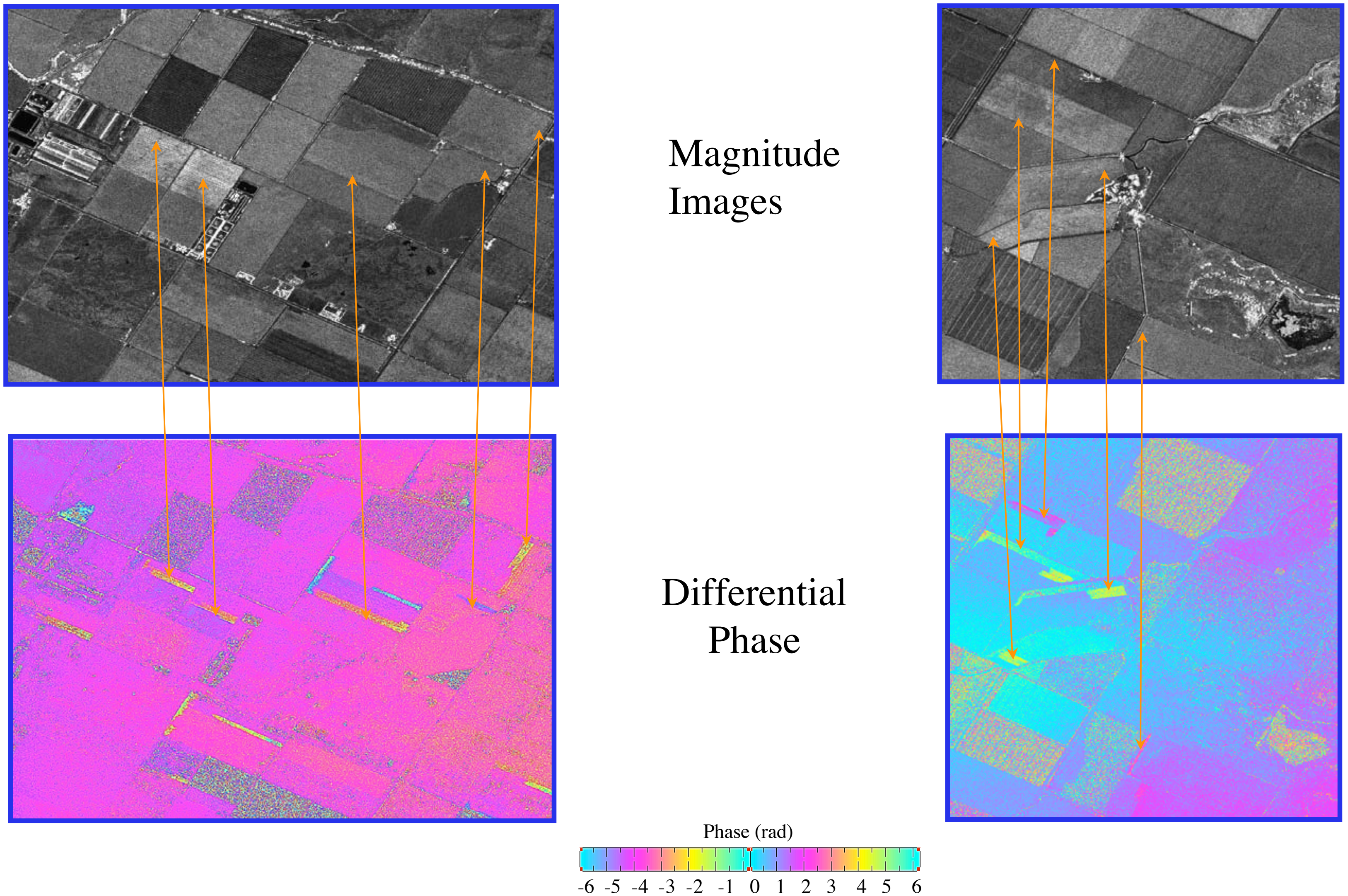
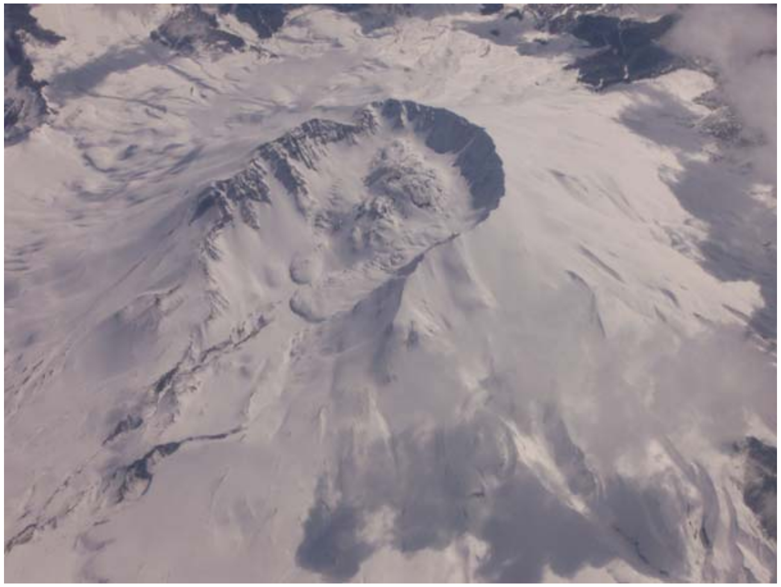
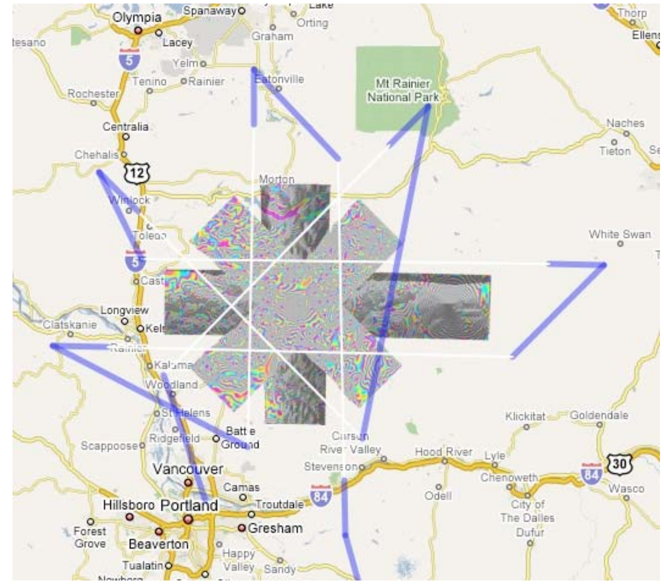


# Mt. St. Helens

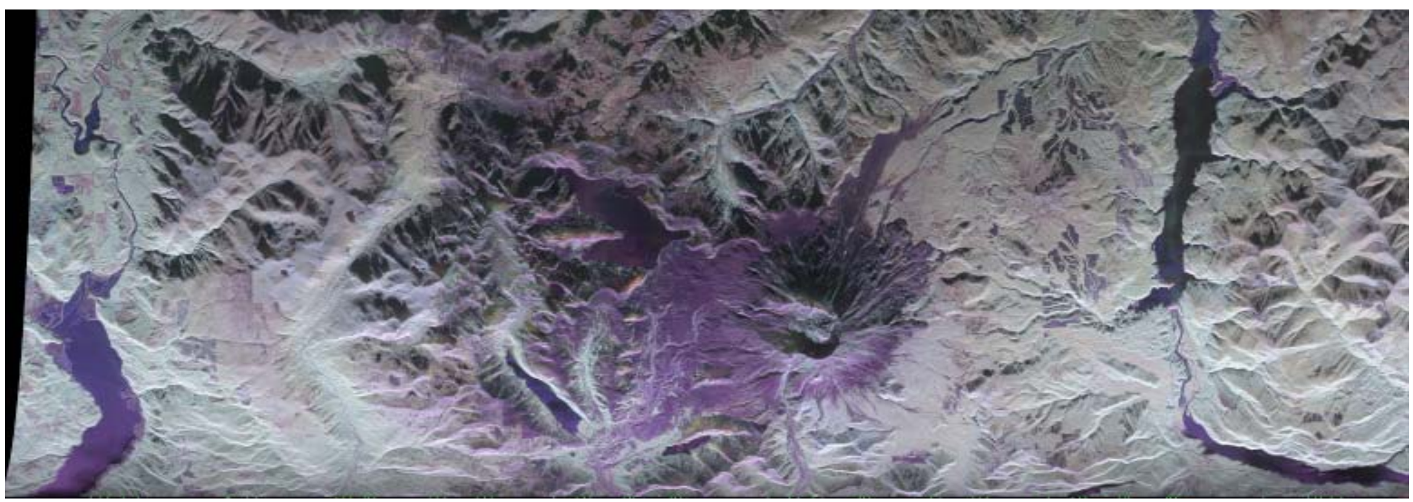


Data was collected along 6 different look directions over Mt. St. Helens.



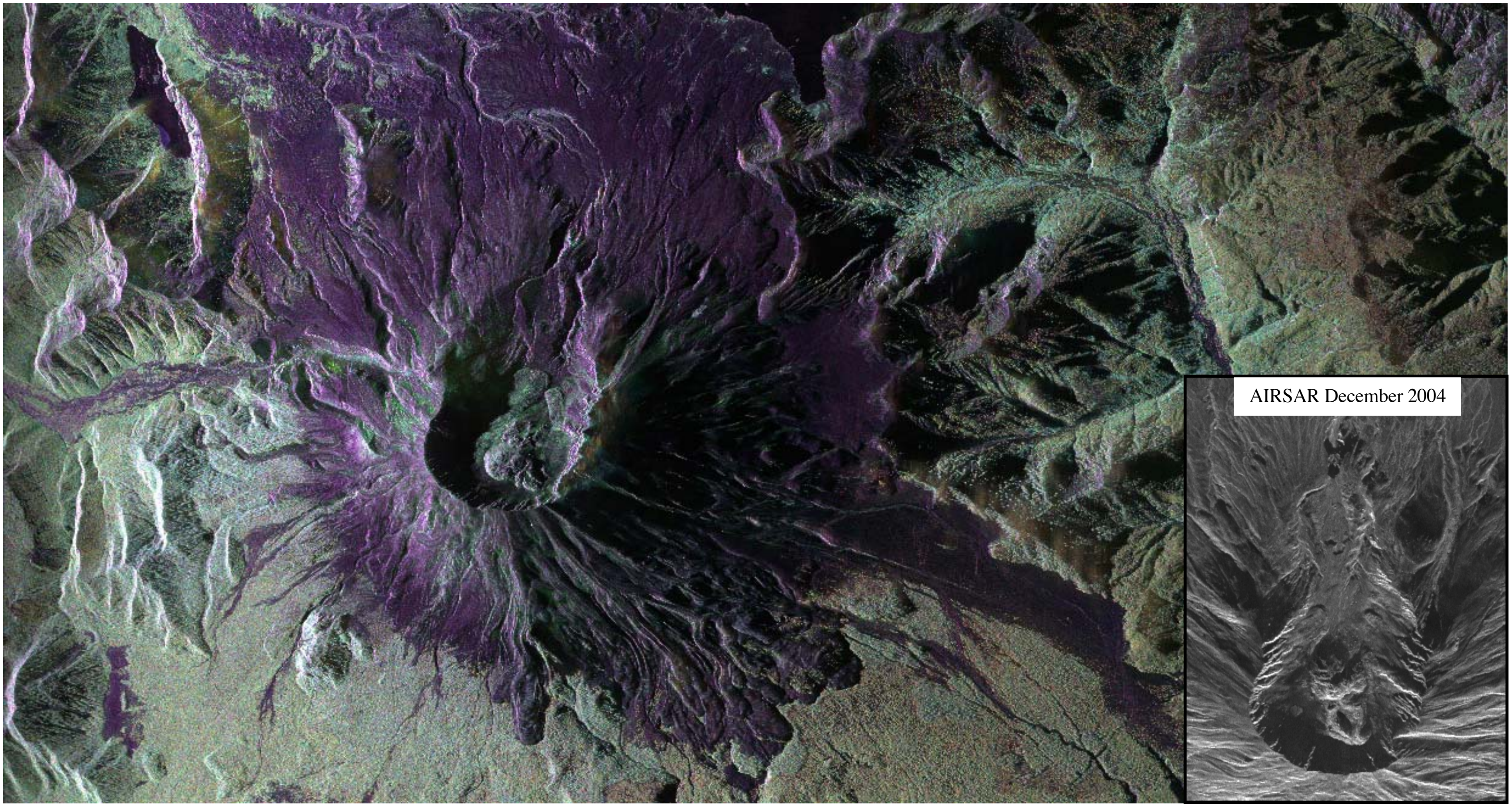

Flight Direction

Fully polarimetric image of Mt. St. Helens collected on March 24, 2008 by the UAVSAR radar. A second acquisition was collected on March 31, 2008.



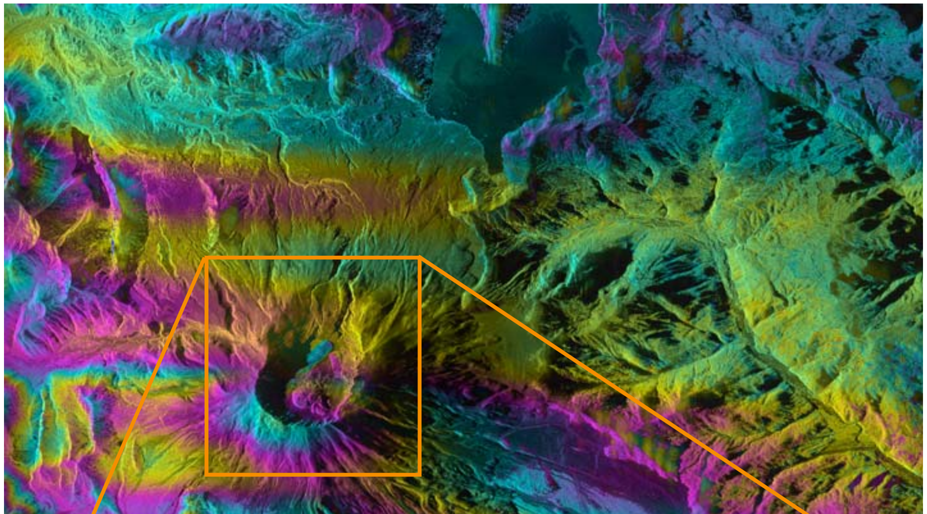
> 20 km

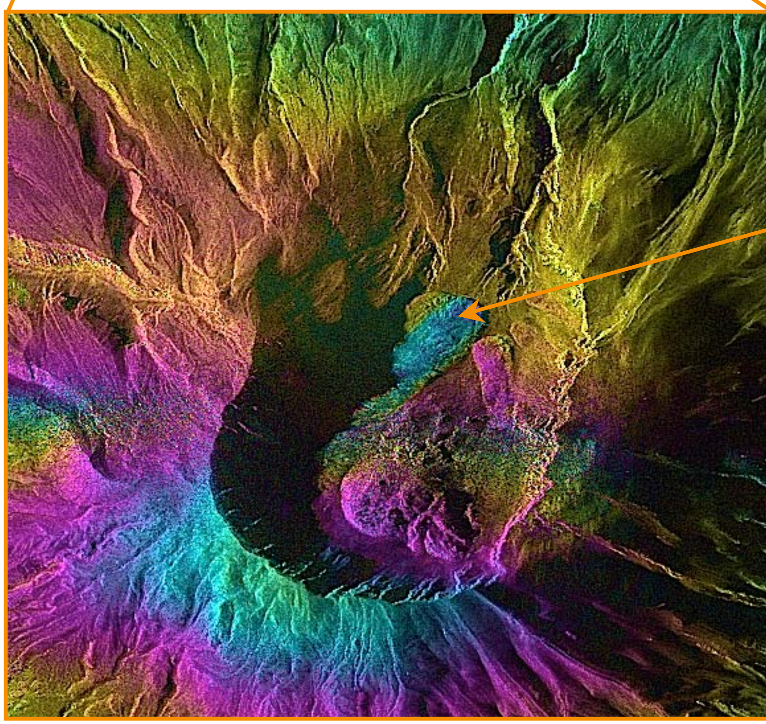
# L-Band UAVSAR Image of Caldera and Dome




LHH=red
LHV=green
LVV=blue

# Mt. St. Helens Interferogram - 4 hour Repeat





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Phase (rad)

# Conclusions

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- Results thus far from flight testing indicate:
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