Geometric Precision in Space Radar Imaging

The Case of TerraSAR-X

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A Useful Insight: Output of the SAR Detection Process

An Analysis of Geometry Model Errors

Operational Implementation: The TerraSAR-X Satellite

Registration Example

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Registration Example

Passive Remote Sensing

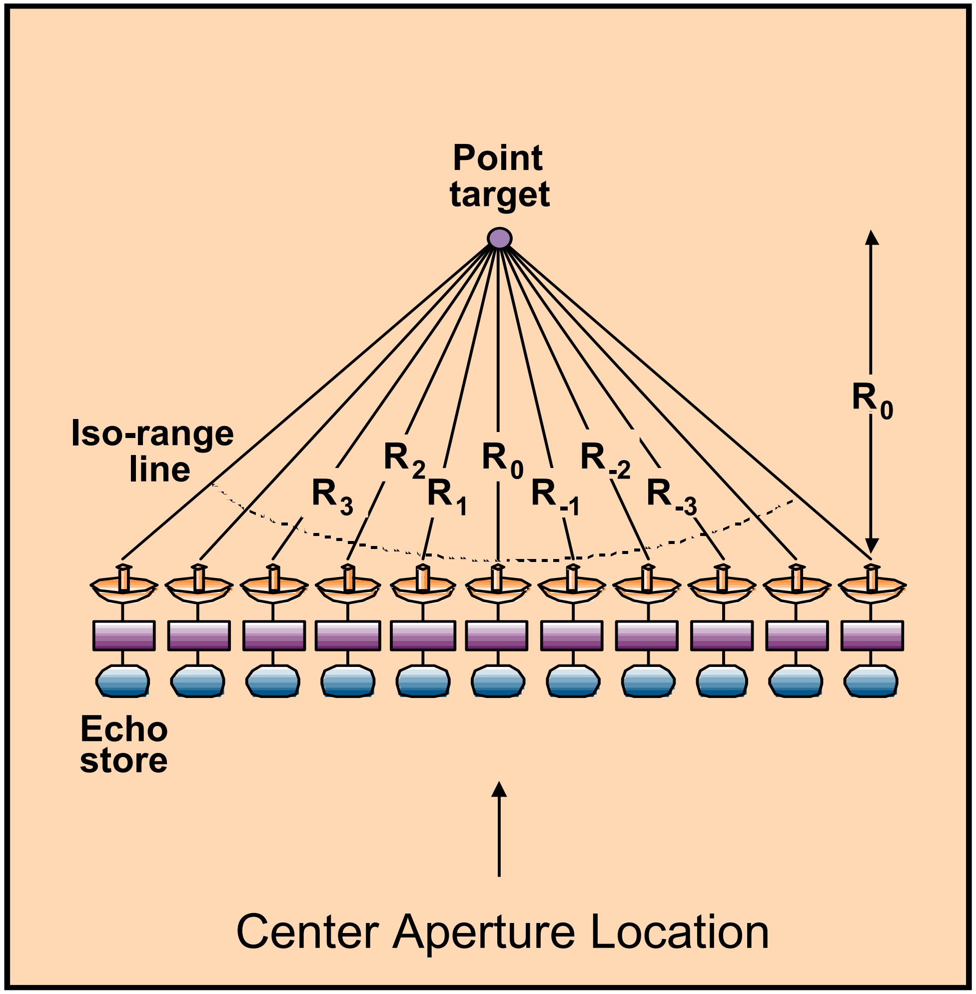
- Passive Electromagnetic Sensor
  - Measures photon intensities via linear or frame array of detectors
  - Calibrated detector locations are easily transposed to pixel coordinates
    - Straight forward process to create an image from the electrical signals output by the detectors
    - Not a direct correspondence because physical array coordinates are sometimes converted to “virtual arrays”

SAR Image Formation

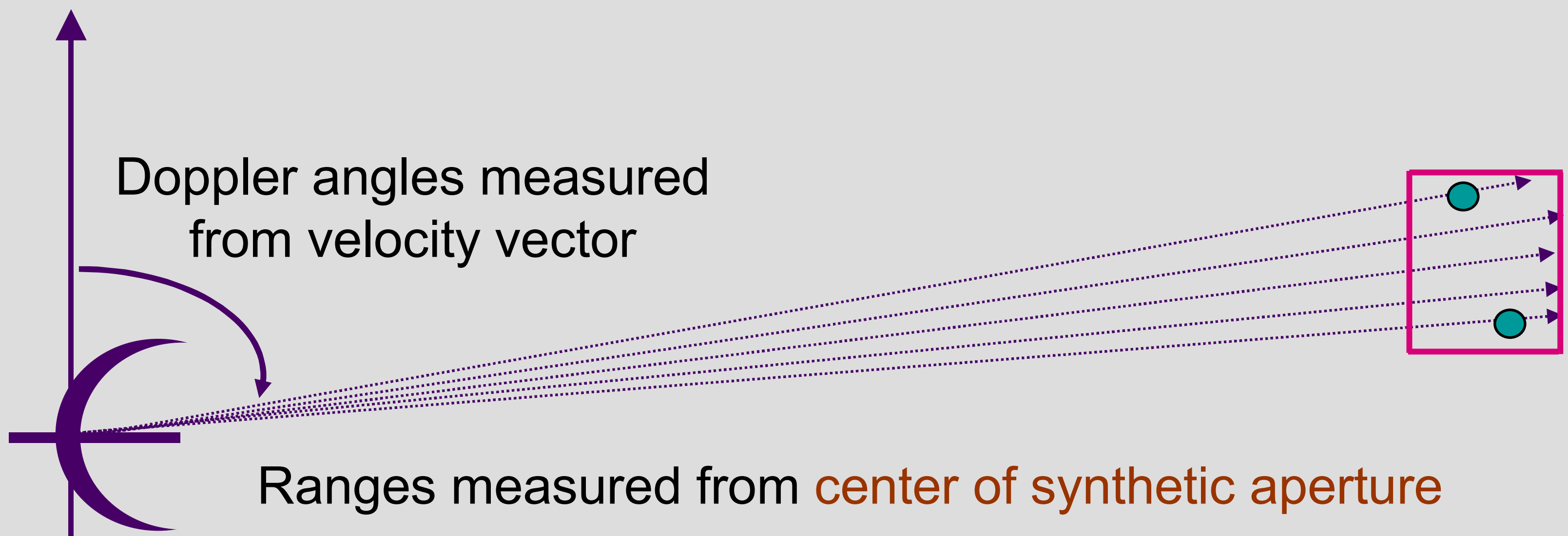
- SAR Sensor
  - Measures signal characteristics over time
    - Phase information and strength of return
  - Sophisticated image formation via Doppler Phase History Processing
    - Produces Complex Image in which phase data are available
    - SAR detection process generates simple pixel brightness values (amplitude) from a complex image
  - **USEFUL INSIGHT**
    - Output of SAR detection can be thought of as "table" of data
    - For each resolution cell in the scene:

Range, Doppler Angle, Amplitude

Consider Spotlight SAR



SAR Ranges and Angles



Center aperture location is arbitrary location

Output of Detection Process

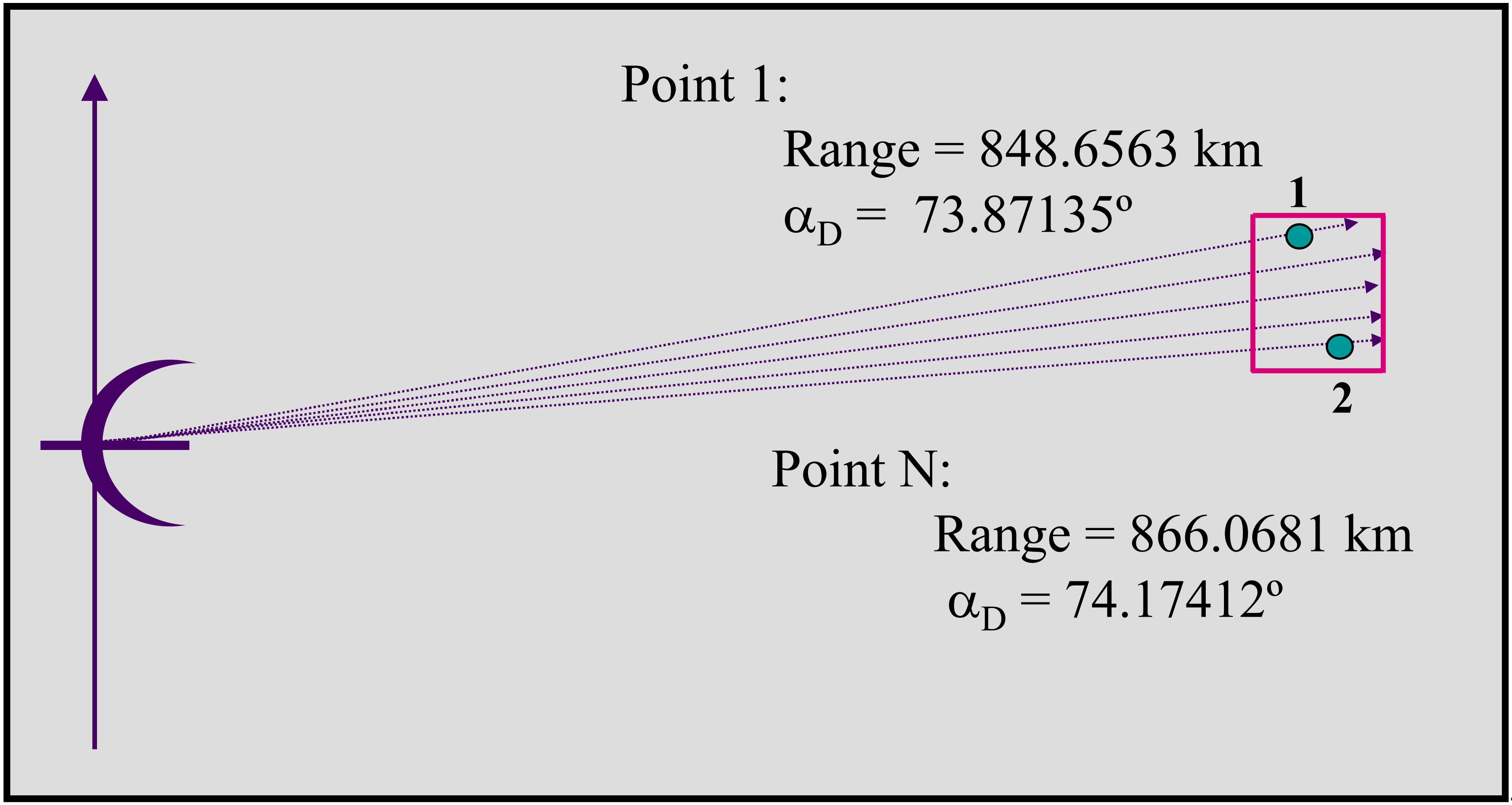
Resolution Cell	Range	Doppler	Amplitude
1	848.6563 km	73.87135^0	173
2	848.6563 km	73.87201^0	180
.			
.			
N	866.0681 km	74.17412^0	0

The SAR Geometry Model

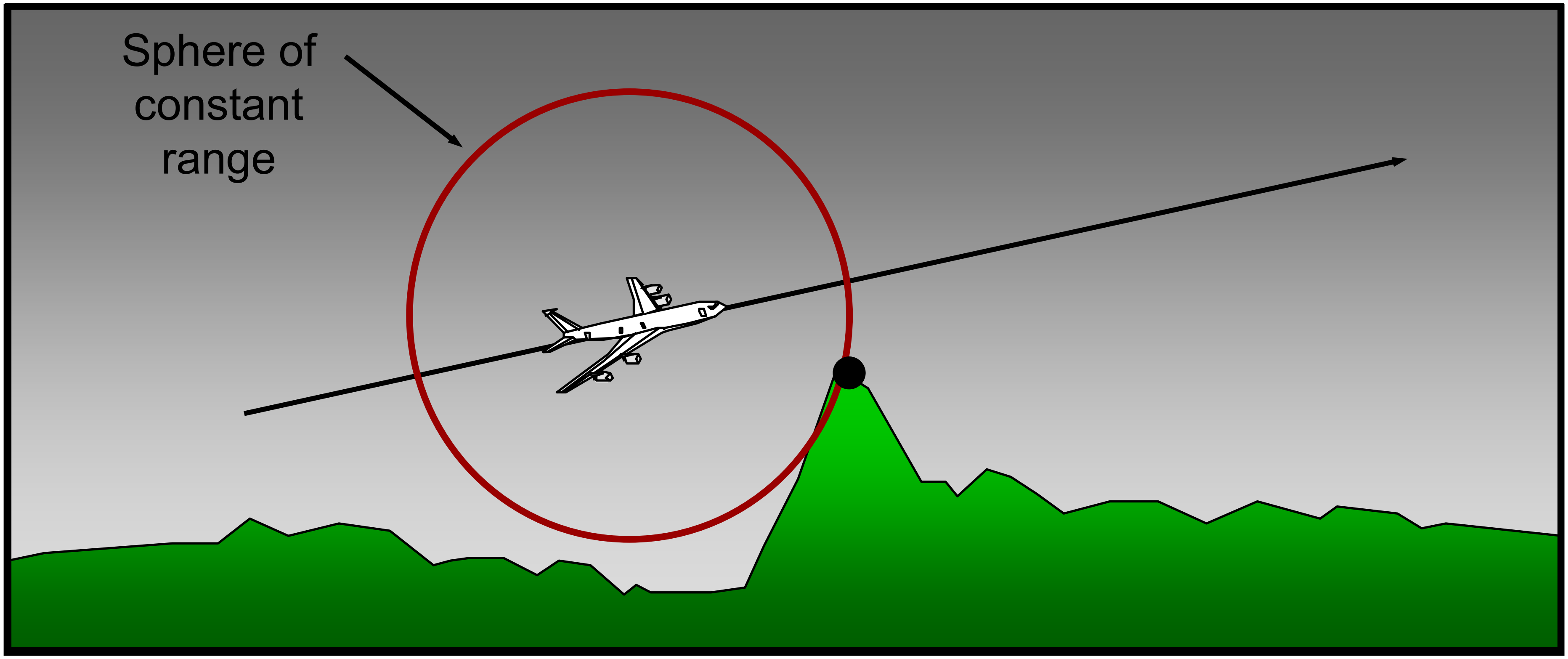
- **The SAR geometry model relates**
  - Range and doppler image coordinates
  - Sensor position at the "moment of acquisition"
  - Corresponding ground position

- **Analogous to the optical geometry model**
  - Describes the path of a photon as it traveled from the ground to the sensor array

Spotlight SAR Coordinates

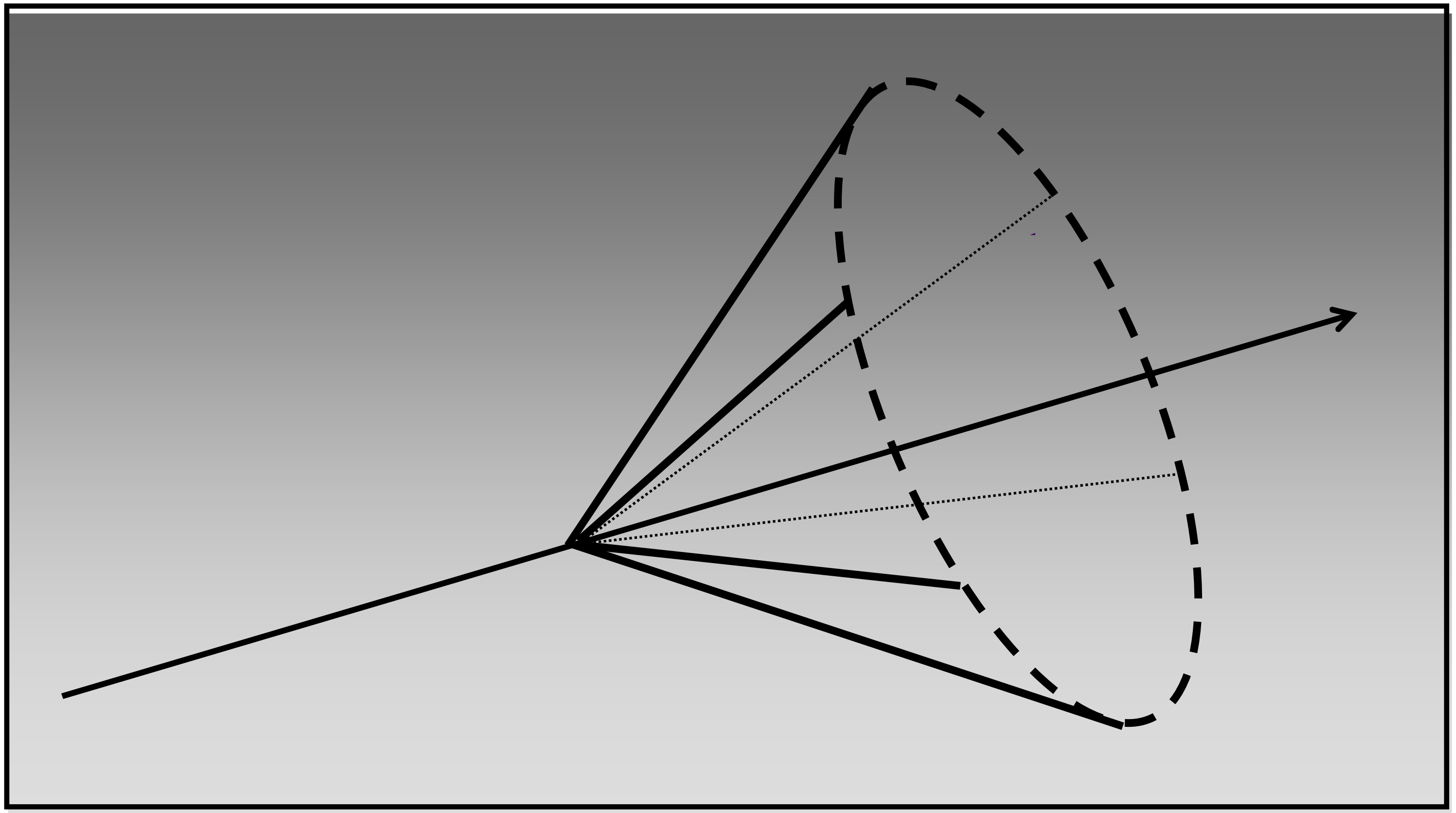


The Range Condition



- We have a known range: 848.6563 km
- In 3-D space this determines a sphere centered on the sensor position

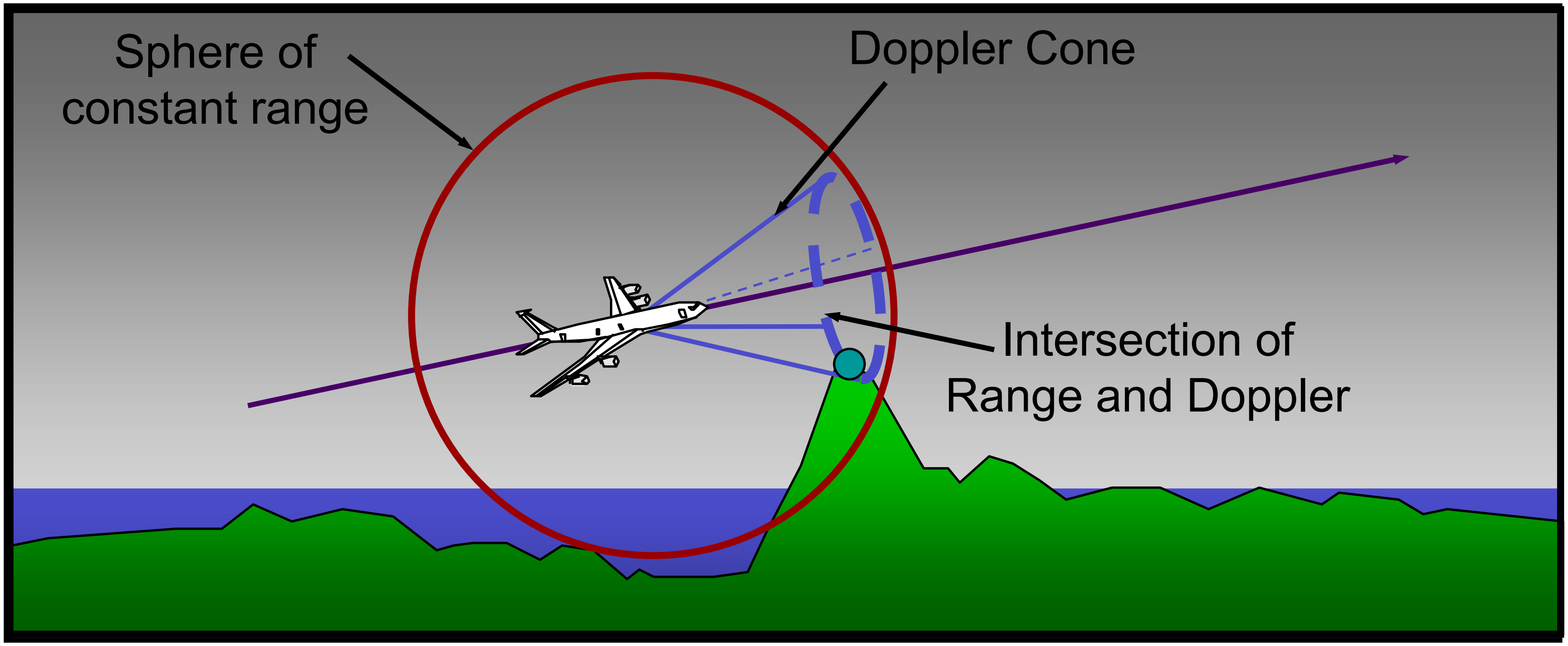
Doppler Cone



- We have a known Doppler Angle: 73.87135^0
- In 3-D space this determines a cone centered on the sensor position

SAR Geometry Model

Sphere-Cone Intersection



- Combining the range sphere and Doppler cone results in a circle of intersection
- The ground point associated with a specific image position (r, α_D) and sensor position (X_s , Y_s , Z_s) is somewhere on the circle

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Consider the Parameters

Sphere equation:

$$r = \sqrt{(X - X_S)^2 + (Y - Y_S)^2 + (Z - Z_S)^2}$$

(X_S, Y_S, Z_S)

$(\dot{X}_S, \dot{Y}_S, \dot{Z}_S)$

$r \quad \alpha_D$

Cone equation:

$$\dot{X}_S(X - X_S) + \dot{Y}_S(Y - Y_S) + \dot{Z}_S(Z - Z_S) =$$

$$\cos\alpha_D \sqrt{\dot{X}_S^{\,2} + \dot{Y}_S^{\,2} + \dot{Z}_S^{\,2}} \sqrt{(X - X_S)^2 + (Y - Y_S)^2 + (Z - Z_S)^2}$$

Velocity Vector

- **Measured accurately via GPS data**
  - Smooth satellite motion has advantage over aircraft
  - Routine GPS-derived orbits have errors of 1 m in each axis
- **Extreme precision is possible for spacecraft**
  - Gravity Recovery and Climate Experiment (GRACE)
  - NASA mission launched in March 2002
  - Dual frequency GPS with 14 channels
  - Accelerometer precision: 1 nm/s^2
  - Orbit error at 500km approximately **10 cm**
  - Velocity error incredibly small: **< 0.01 mm/s**
  - "Grace: Millimeters and Microns in Orbit" ION GPS 2002, Portland

Range Estimates

- **Raw error in range estimates can be small**
  - ΔT measured to within nano-seconds
    - Error is less than 1: 10,000,000
    - Contribution to range error is 0.1 m over distance of 1,000,000 meters
- **Perturbed by senor hardware and atmospheric refraction**
  - Delays caused by hardware can be calibrated
  - Refraction can be modeled via various schemes
  - Shallow depression angles increase refraction

Doppler Angle

- **An error here seems worrisome**
  - The angle is projected over the long range to the target
  - Angular errors pose significant problems in the optical geometry model
- **But… this angle is not directly measured**
  - Derived from Doppler frequency measurements
  - It does not contribute to ground error in any significant way

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*TerraSAR-X Performance**

- **State Vector**
  - Dual Frequency GPS and use of JPL-based GPS orbits
  - Orbital error estimate: 20 cm
    - These are provided for "rapid orbits" produced within one day of imaging
    - Science orbits with errors of 10 cm are computed for all archived data… produced one week after imaging

- **Range**
  - Calibrated hardware and compensation for refraction
  - Range error estimate: 0.5 m

- **Doppler Angle**
  - Zero doppler processing
  - Angular error estimate: No significant error

* Error estimates based on specifications, JPL orbit performance, TS-X commissioning results, and independent NGA tests.

CCAP Accuracy Evaluation of TS-X

Ground Control Points Measurement on Imagery

Average Radial Offset: 0.6 m

13 images
3 to 10 Ground Control Points per image

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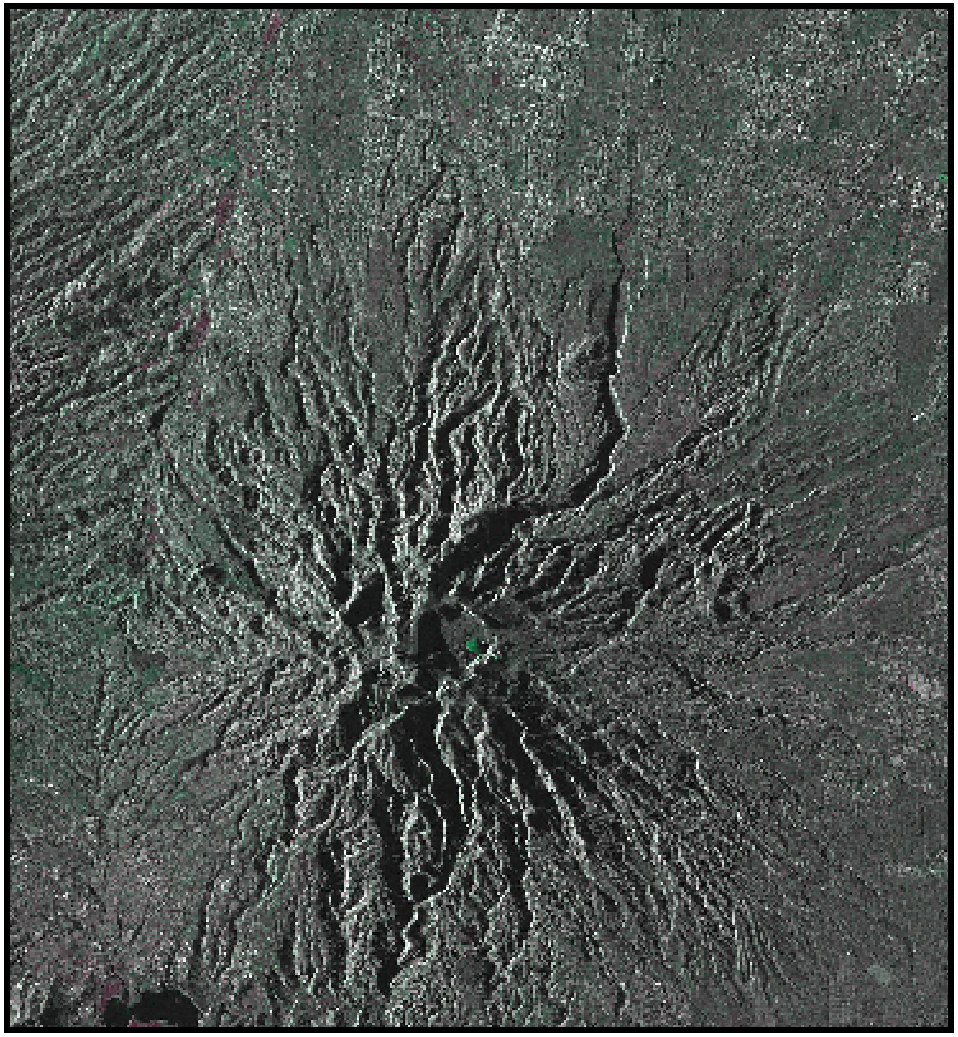
Coherent Pair

Excellent Match of Pixel Magnitude Data



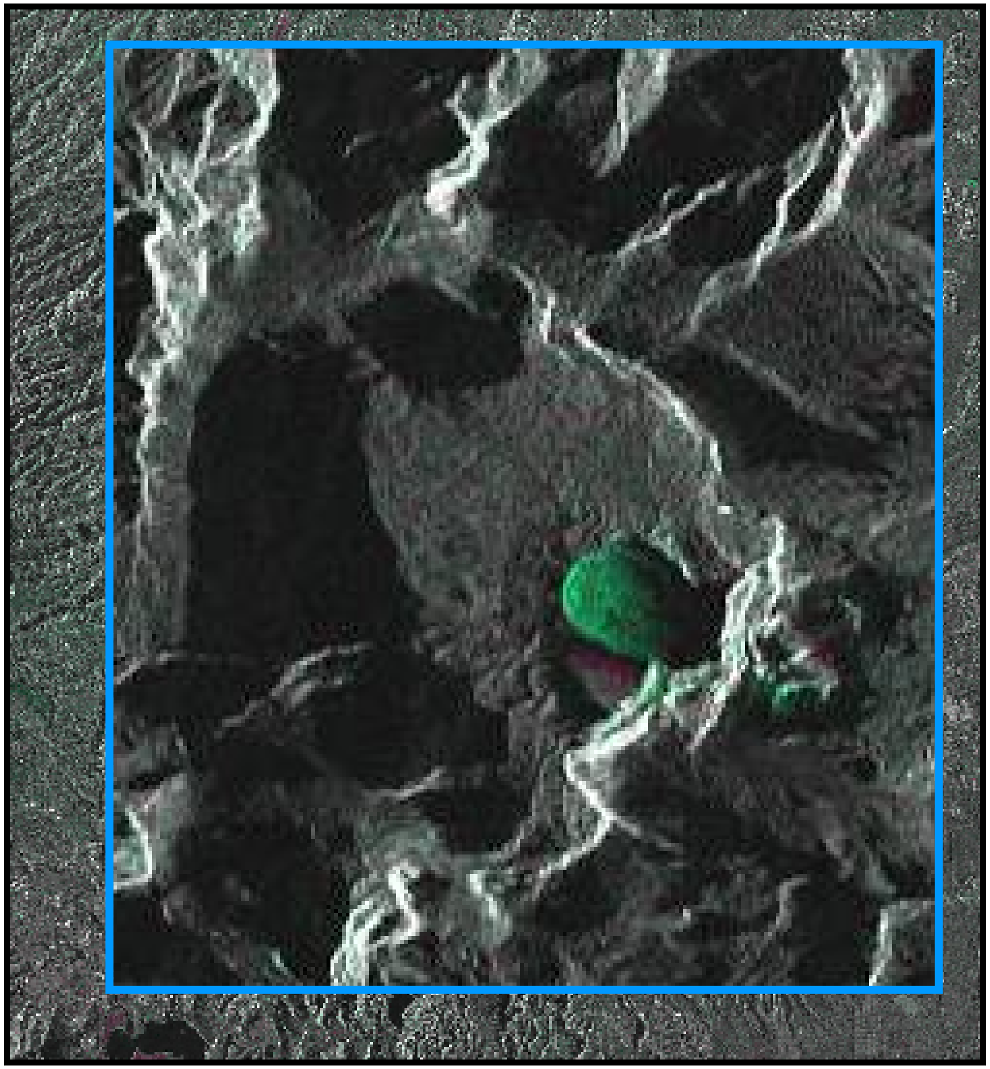
Mt. Kelud

Coherent Pair
23 Oct and 14 Nov 07

Nearly Perfect
geometric match

No warping needed
No registration applied

Amplitude Change Detection



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Courtesy
Infoterra GmbH

Mt. Kelud

Coherent Pair
23 Oct and 14 Nov 07

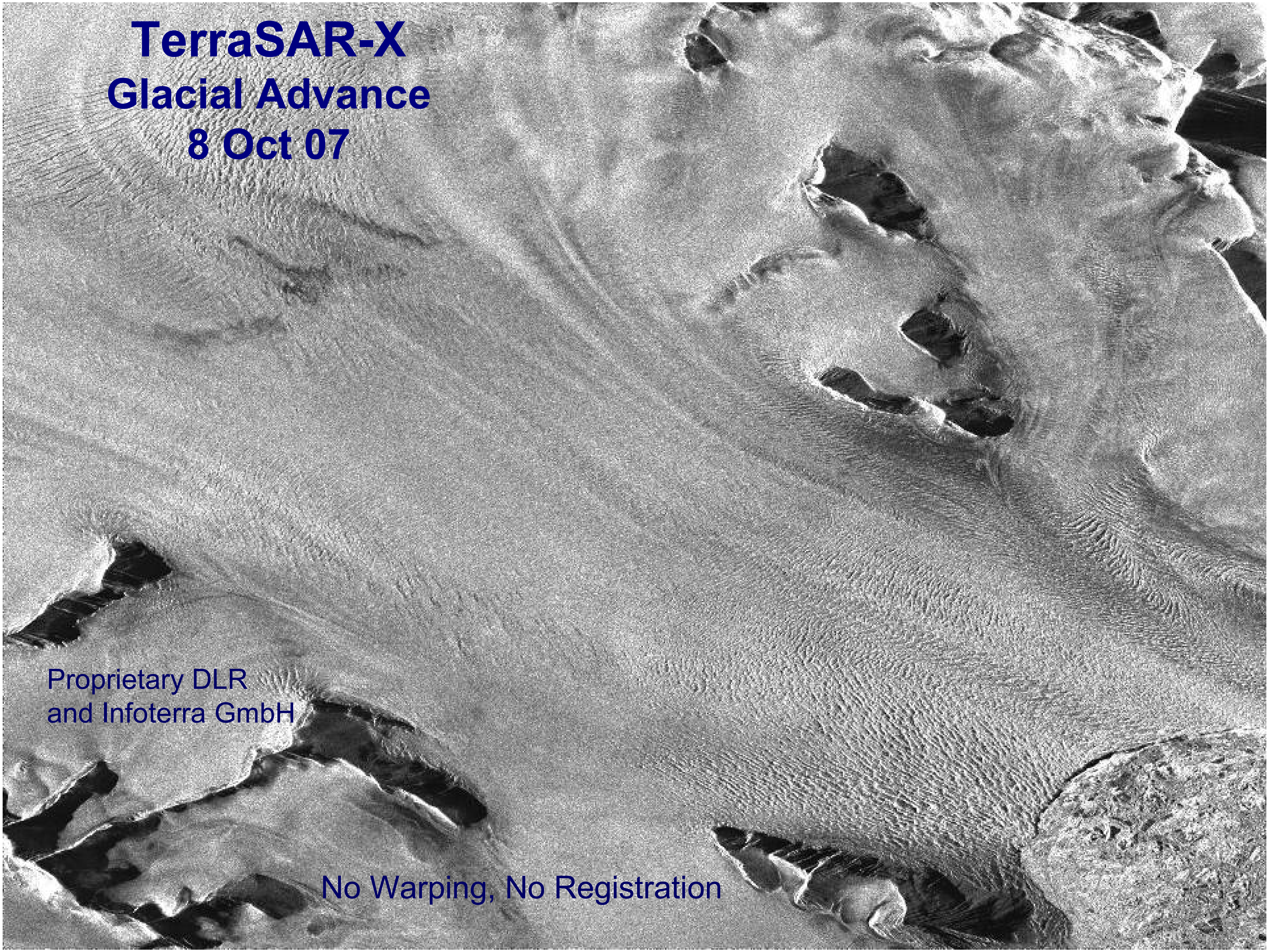
Growth in Caldera

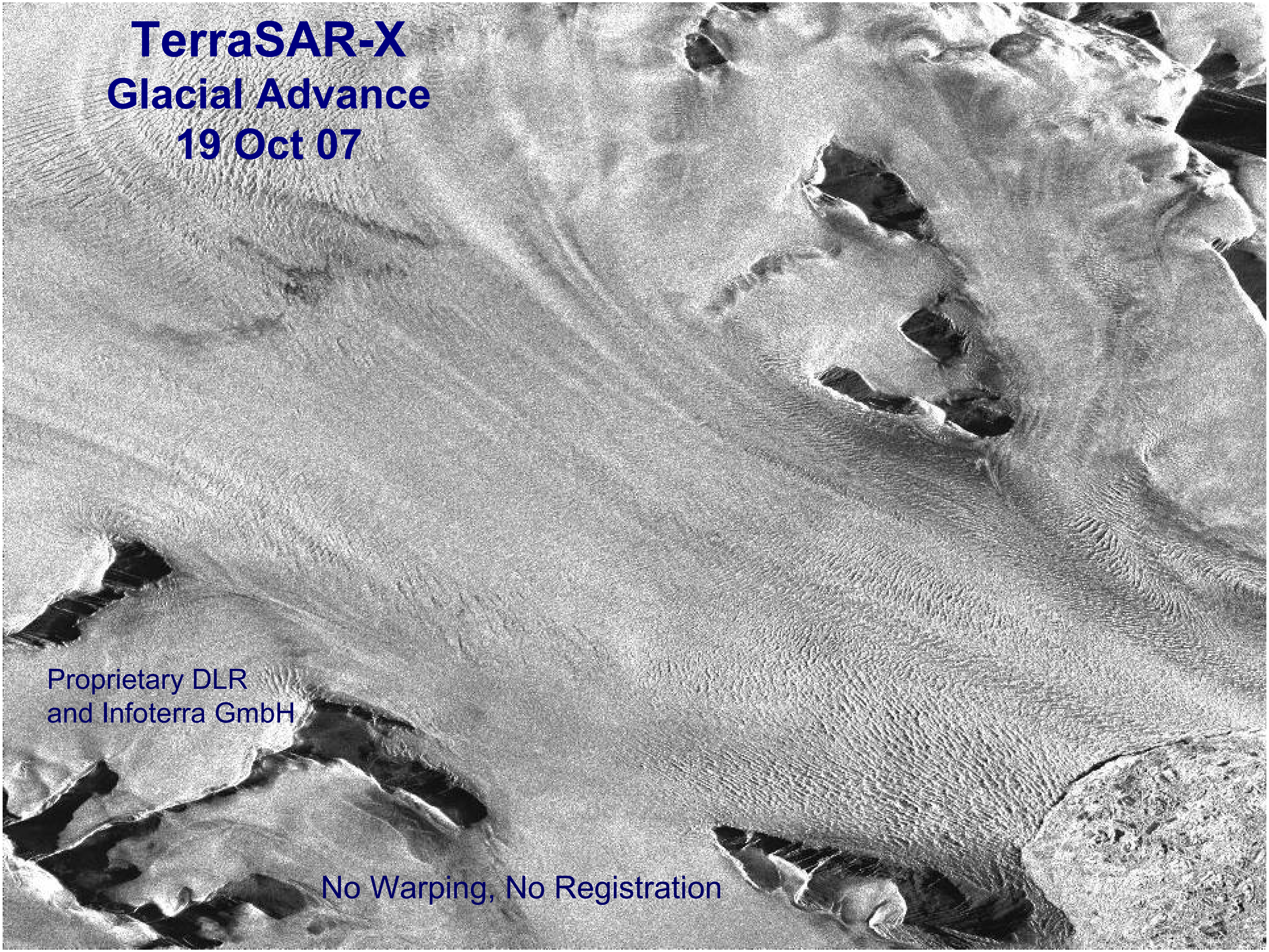
No False Changes
Caused by Parallax

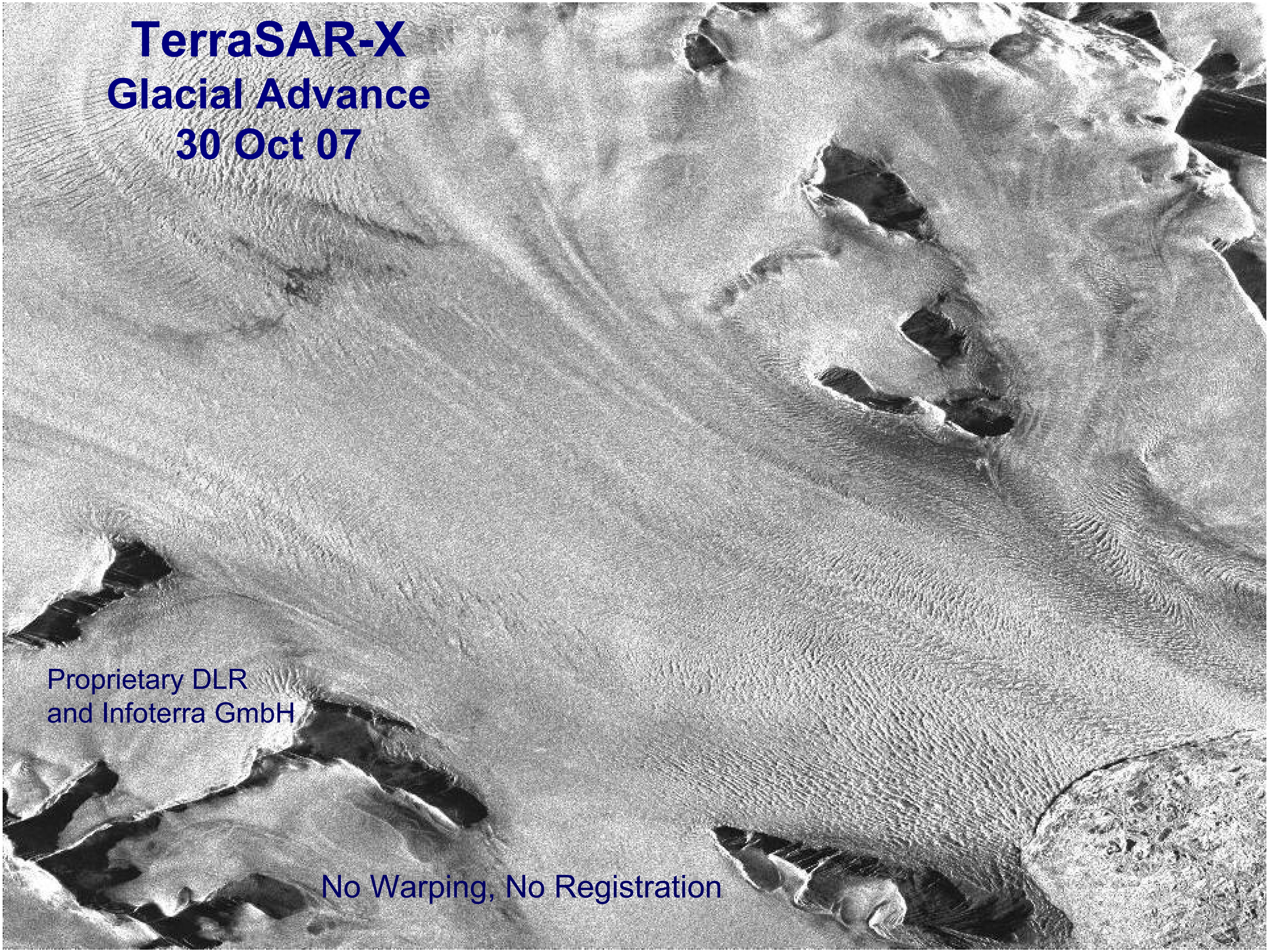
There is No Parallax

TerraSAR-X May Be
The World's Most
Geometrically Accurate
Imaging System

Environmental Monitoring


TerraSAR-X
Glacial Advance
8 Oct 07
Proprietary DLR
and Infoterra GmbH
No Warping, No Registration


TerraSAR-X
Glacial Advance
19 Oct 07
Proprietary DLR
and Infoterra GmbH
No Warping, No Registration


TerraSAR-X
Glacial Advance
30 Oct 07
Proprietary DLR
and Infoterra GmbH
No Warping, No Registration

Summary

- SAR Geometry Model
  - Has inherent accuracy advantages when compared to passive remote sensing systems
  - Both are capable of accurate determination of State Vector via GPS technology
  - SAR Range can be computed with great precision
    - Atmospheric refraction does degrade accuracy
  - SAR Doppler Angle based on Doppler frequency
    - Extremely precise frequency measurements remove affect of angular propagation over long ranges
- TerraSAR-X Geometric Precision
  - Appears to be operational implementation of these principles