Shuttle Radar Topography Mission: A National Resource

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and the SRTM Processing Team

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Descanso Seminar

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

Outline

- Introduction and Overview to SRTM DEM Production
- Calibration and Accuracy of SRTM Data
- Interesting DEM Visualizations
- GeoWall Demonstration
- Interactive Continental Tour

Acknowledgments

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- Outreach/Science
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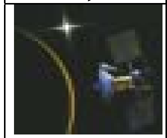
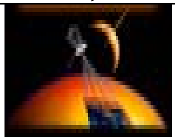
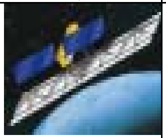
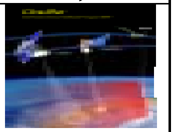
- Flight Development Team too numerous to list (> 800 people)

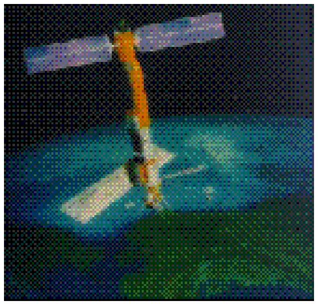
JPL Earth and Planetary Radars

	Magellan **Venus, 1989**	**SeaSAT through SIR-C/X-SAR** **Earth, 1978-1994**	**Cassini** **Saturn, 1997**	**SRTM** **Earth, 2000**	**GeoSAR** **Earth, 2000**	**Next SAR?** **Earth, 2008**	**MARSIS** **Mars, 2003**	**EORS** **Europa**	**CloudSAT** **Earth, 2003**
									
FREQUENCY (GHz)	2.4 (S-band)	1.2 (L-band) 5.3 (C-band) 9.6 (X-band)	13.8 (Ku-band)	5.3 (C-band) 9.6 (X-band)	9.7 (X-band) 0.35 (P-band)	1.2 (L-band) Possible 5.3 (C-band) 9.6 (X-band)	.0001-.0055 (0.1-5.5 MHz)	.050 (50 MHz)	94 (W-band)
POLARIZATION	HH	QUAD (L, C) VV (X)	VV	HH, VV (C) VV (X)	VV (X-band) HH & HV or VV & VH (P)	Quad (L) TBD (C, X)	N/A	N/A	N/A
RESOLUTION (m)	120	10 - 60	400-1700	30 10 Relative Vertical Accuracy	3-5 Vertical 2-4 Horizontal	3-100 Depending on Mode	100 (depth) 10,000 (horizontal)	100 (depth) 10,000 (horizontal)	1200 (horizontal) 250-500 (vertical)
SWATH WIDTH (km)	20	15 - 80	120-450	225	10-20	15- 280 Depending on Mode	10	10	N/A
ILLUMINATION CONTROL	Fixed	Electronic (L, C) Mechanical (X)	Fixed	Electronic (C) Mechanical (X)	By Flight Plan	Electronic	Fixed	Fixed	Fixed
ARCHITECTURE	Single feed parabolic dish	Distributed active phased array	Five feed parabolic dish	Distributed; Interferometer, 60 meter, fixed baseline	Conventional interferometric	Distributed active phased array	Clutter cancellation radar; dipole/monopole antenna	Subsurface sounder for water detection; Yagi array antenna	Millimeter-wave, high-precision reflector dish
MISSION DURATION	Spacecraft: Launched from Space Shuttle: 5/4/89 Mission End: 10/12/94	Space Shuttle Payload: Two 11-Day Missions: 1) 4/9-20/94 2) 9/30/94-10/11/94	Spacecraft: Launched from Titan IV: 10/15/97	Space Shuttle Payload: 11-Day Mission Launch: 2/11/00	Aircraft: 1st Flight: 3/14/99 Delivery to Industry Partner (Calgis): 11/99	Orbiting Satellite: Planned Launch: 2003, Duration: ≥5 Years	Orbiting Satellite: Planned Launch: 2003	Orbiting Satellite: Planned Launch: 2003	Co-manifested Launch on Delta-II in March 2003; Duration: 2 years
KEY FEATURES/ MEASUREMENTS	Multi-mode mapping of Venus: - radar - altimeter - radiometer	Biomass, vegetation, soil moisture, geological features, natural hazards	Multi-mode mapping of Titan (Saturnian moon) - radar - altimeter - radiometer	Digital Elevation Model (DEM) of 80% of Earth's land surface	High-resolution 3-D mapping for natural hazard and land use monitoring (above, through and below vegetation)	Surface change, forest regrowth, land hydrology, high resolution images	Subsurface & ionospheric sounding for Mars water table detection	Europa ice-thickness measurement and subsurface ocean detection	Vertical cloud profiling

(Also: Aquarius, Hydros, Topex, Jason, WSOA, Quickscat, Seawinds)

JPL Radar Interferometry Program
Research, Design, and Missions

L-band ROI

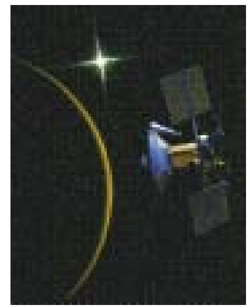


SEASAT
(1978)

L/C-band Q-Pol ROI

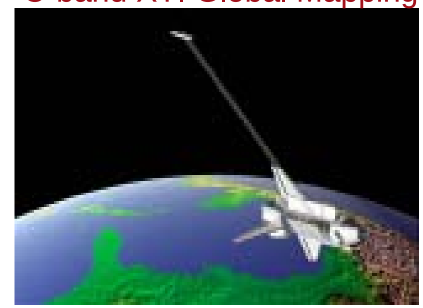
SIR-B/C
(1981-1994)

S-band ROI



Magellan
(1990-1994)

C-band XTI Global Mapping

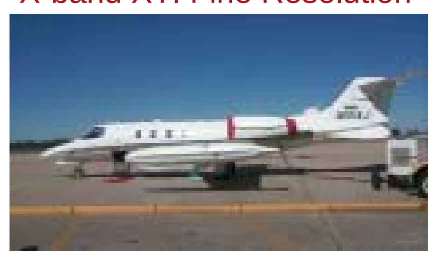


SRTM
(2000)

L/C-band XTI; P/L/C Q-Pol RTI

AIRSAR / TOPSAR
(1988-Present)

X-band XTI Fine Resolution



IFSARE (SE & Proc)
(1995-Present)

P/X-band XTI Fine Res

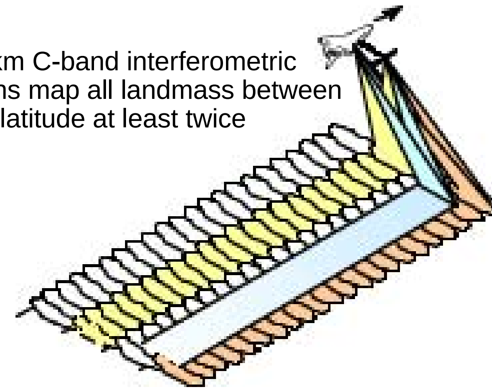
GeoSAR
(2000-Present)

Mission Overview

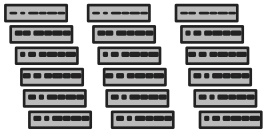
<u>Launch</u>

Feb 11, 2000 - STS99

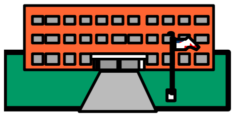
225 km C-band interferometric swaths map all landmass between ±60° latitude at least twice



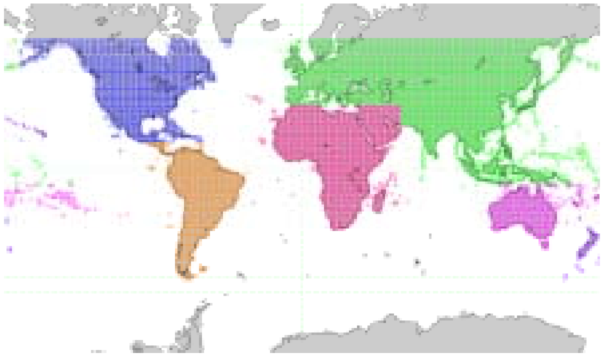
12 Tbytes data recorded on-board on 330 tape cassettes



Data returned with Shuttle to Ground Data Processing Facility



Three year processing



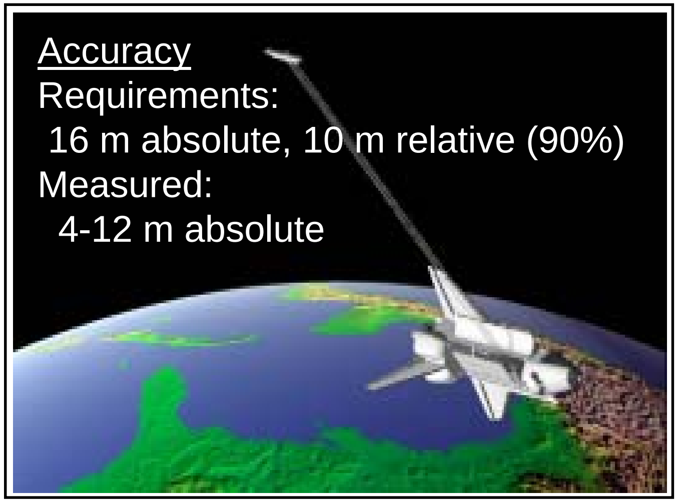
Digital elevation data delivered in 1°x1° mosaiced cells

NIMA data validation, editing and distribution to military users

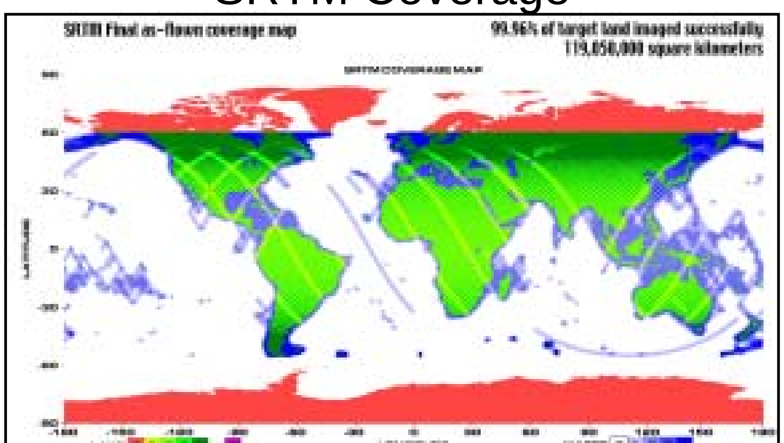
EDC for public distribution

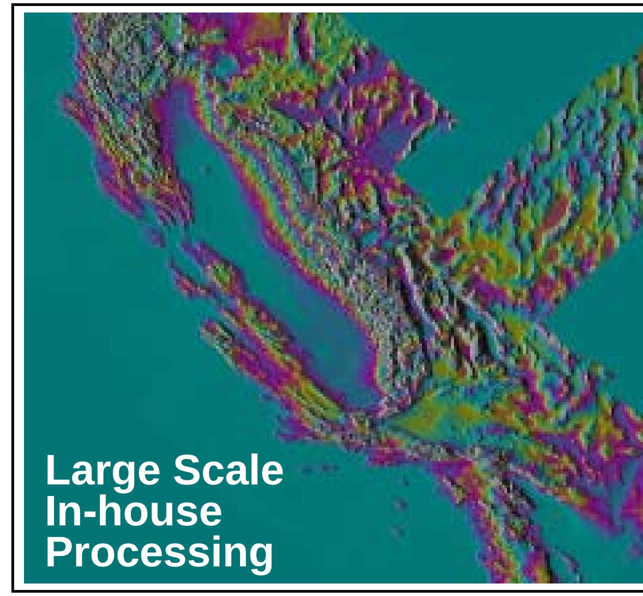
Shuttle Radar Topography Mission

Unprecedented global accuracy from innovative technologies



SRTM Coverage

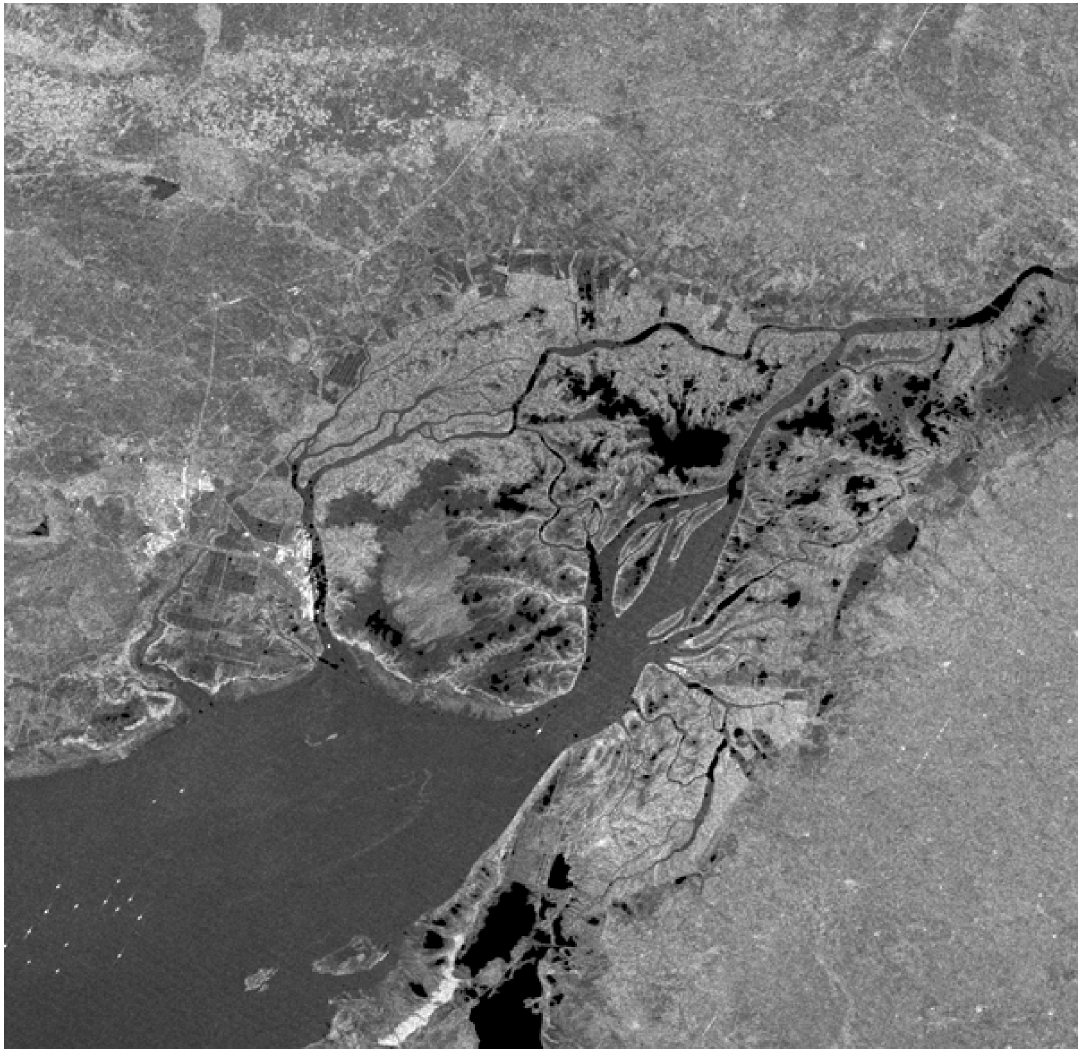




California terrain height measured by SRTM

Innovations:
- Large Deployable Structure
- ScanSAR Interferometry
- Metrology system
- Optical phase calibration

SRTM C-Band ScanSAR Imagery

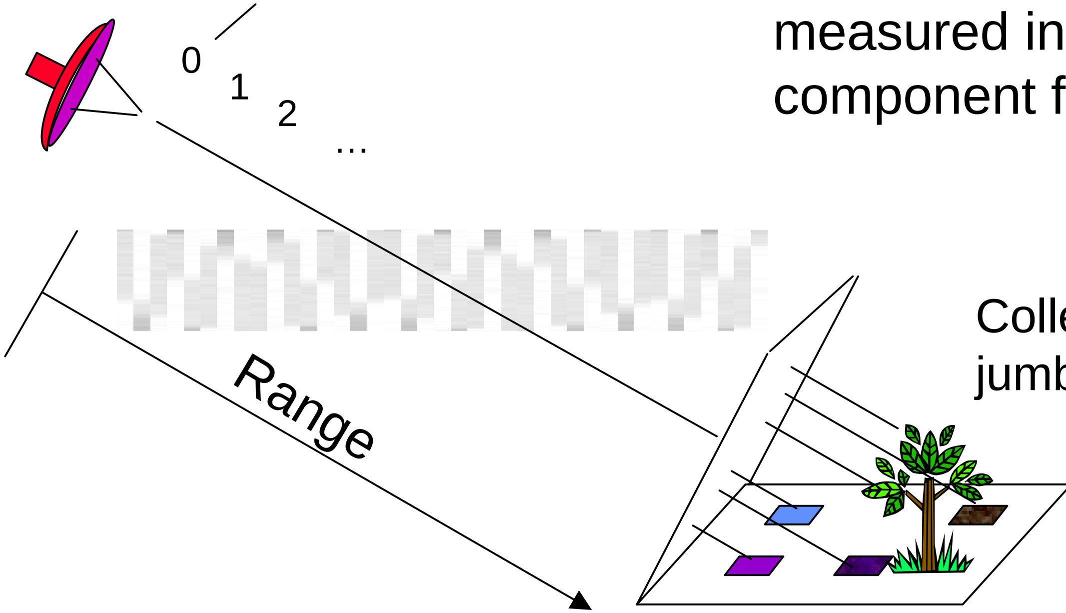


- Complete multiple coverage over latitudes flown by the shuttle (99%)
- Resolution: 25 m x 25 m pixels
- Uniqueness affirmed NASA's role in enabling technology and applications

C-band ascending image
72 km x 72 km

Phase - A Measure of the Range and Surface Complexity

The phase of the radar signal is the number of *cycles of oscillation* that the wave executes between the radar and the surface and back again.



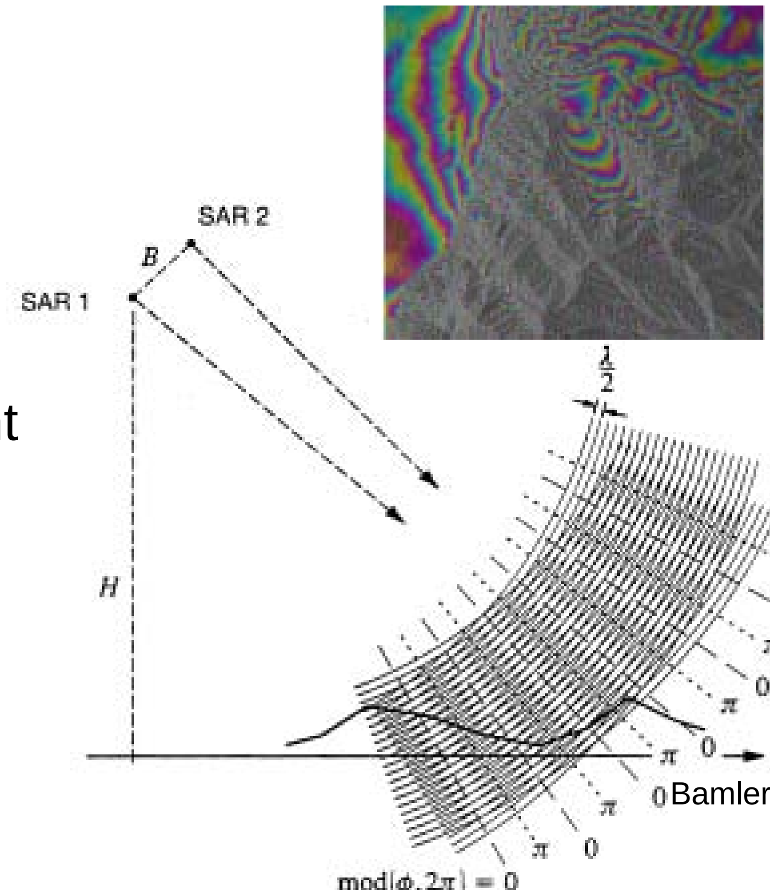
The total phase is two-way range measured in wave cycles + random component from the surface

Collection of random path lengths jumbles the phase of the echo

Radar Interferometry

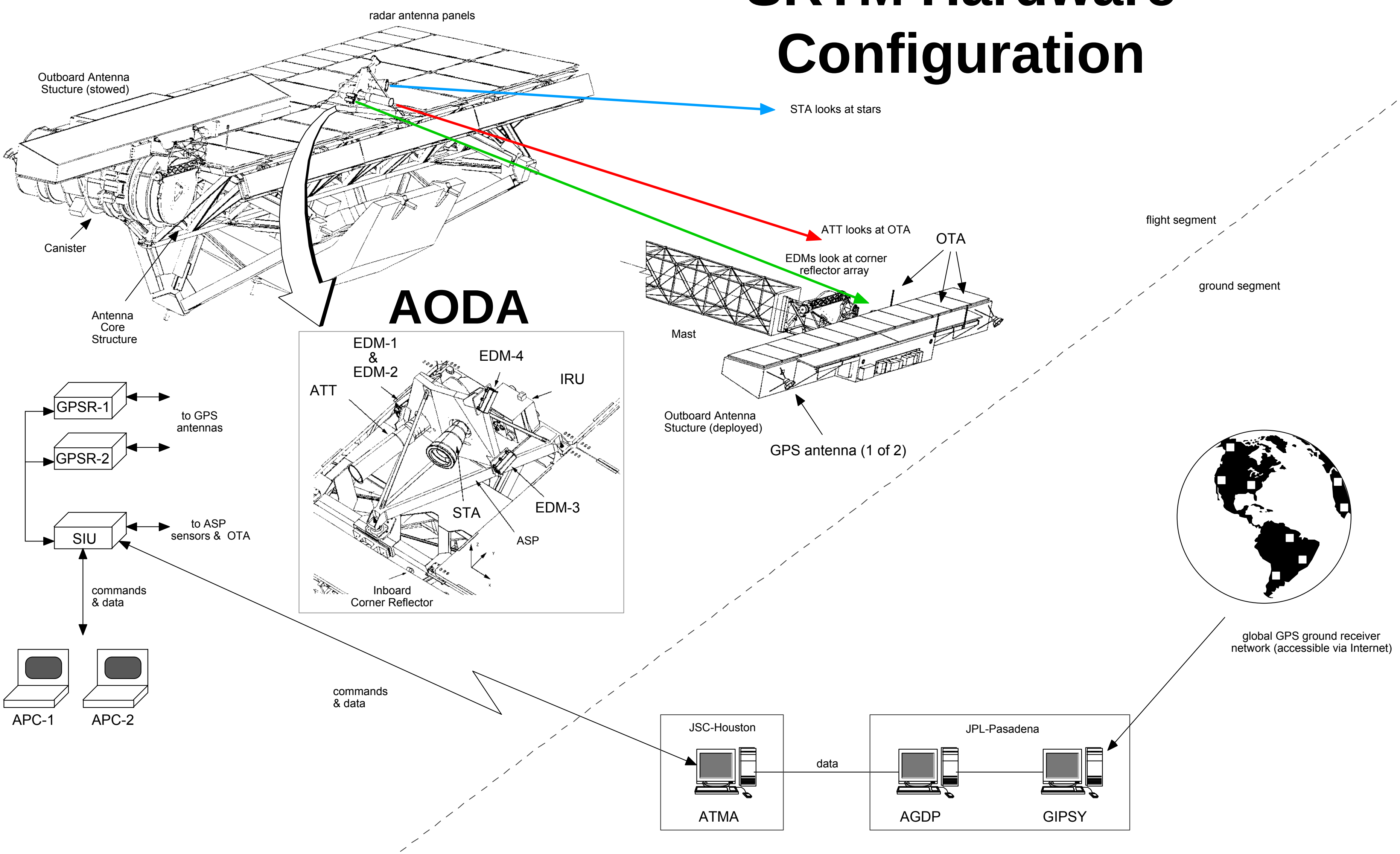
- Radar Interferometry is a simple extension of the Young's interferometry concept

- When imaging a surface, the phase fronts from the two sources interfere.
- The surface topography slices the interference pattern.
- The random surface component of the phase nearly cancels because the SAR's are very closely spaced, so the surface looks the same.
- The measured phase differences record the topographic information.



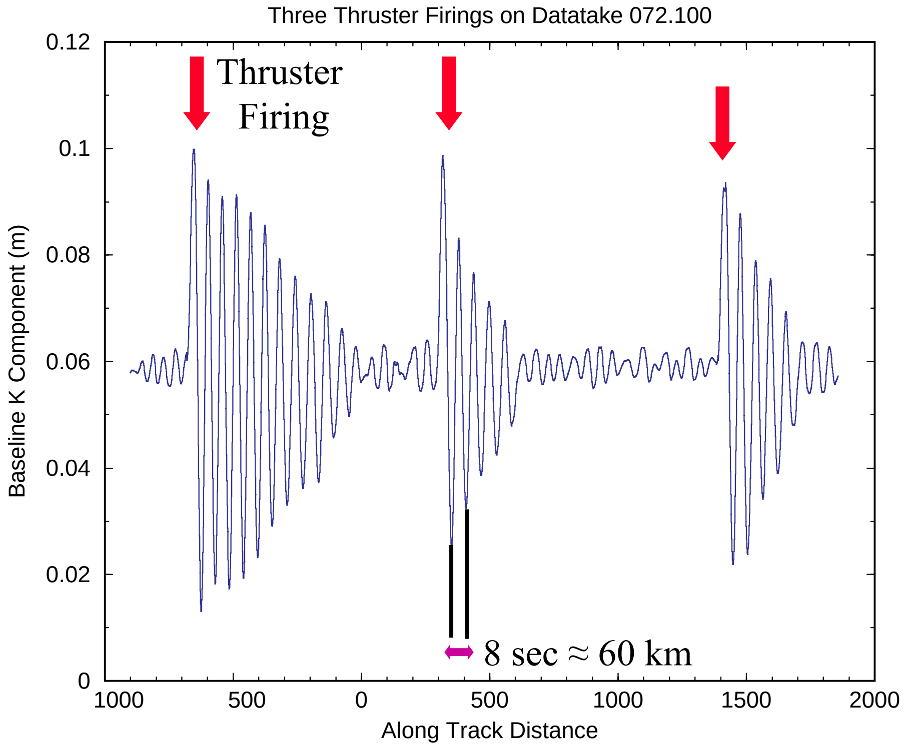
Bamler, 1999

SRTM Hardware Configuration



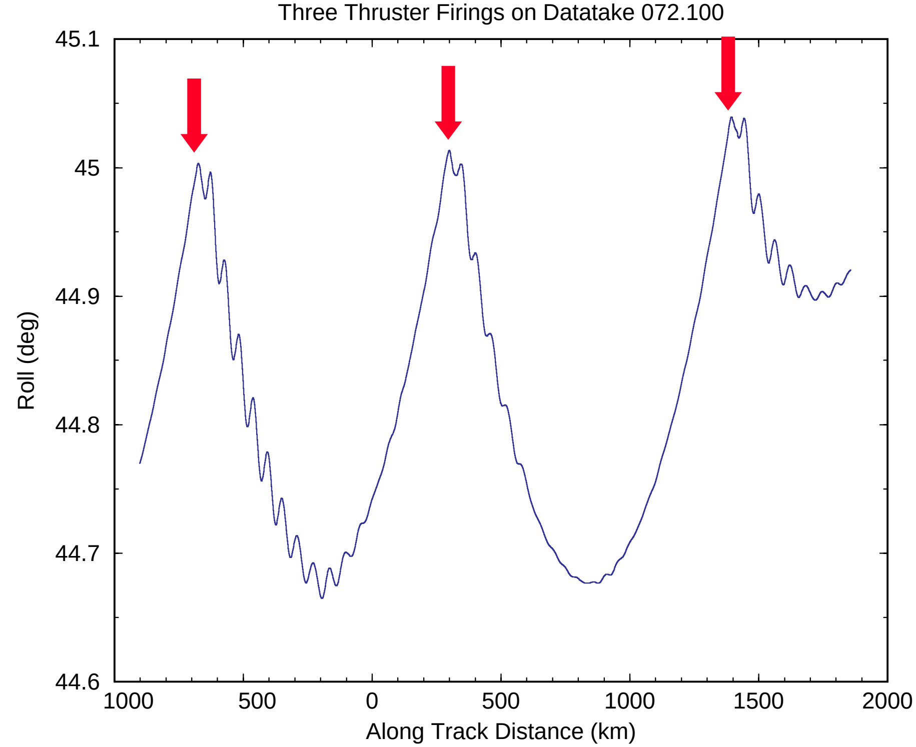
AODA Data and Need for Motion Compensation

SRTM Boom Motion



Plot of Baseline K Component

SRTM Roll Angle



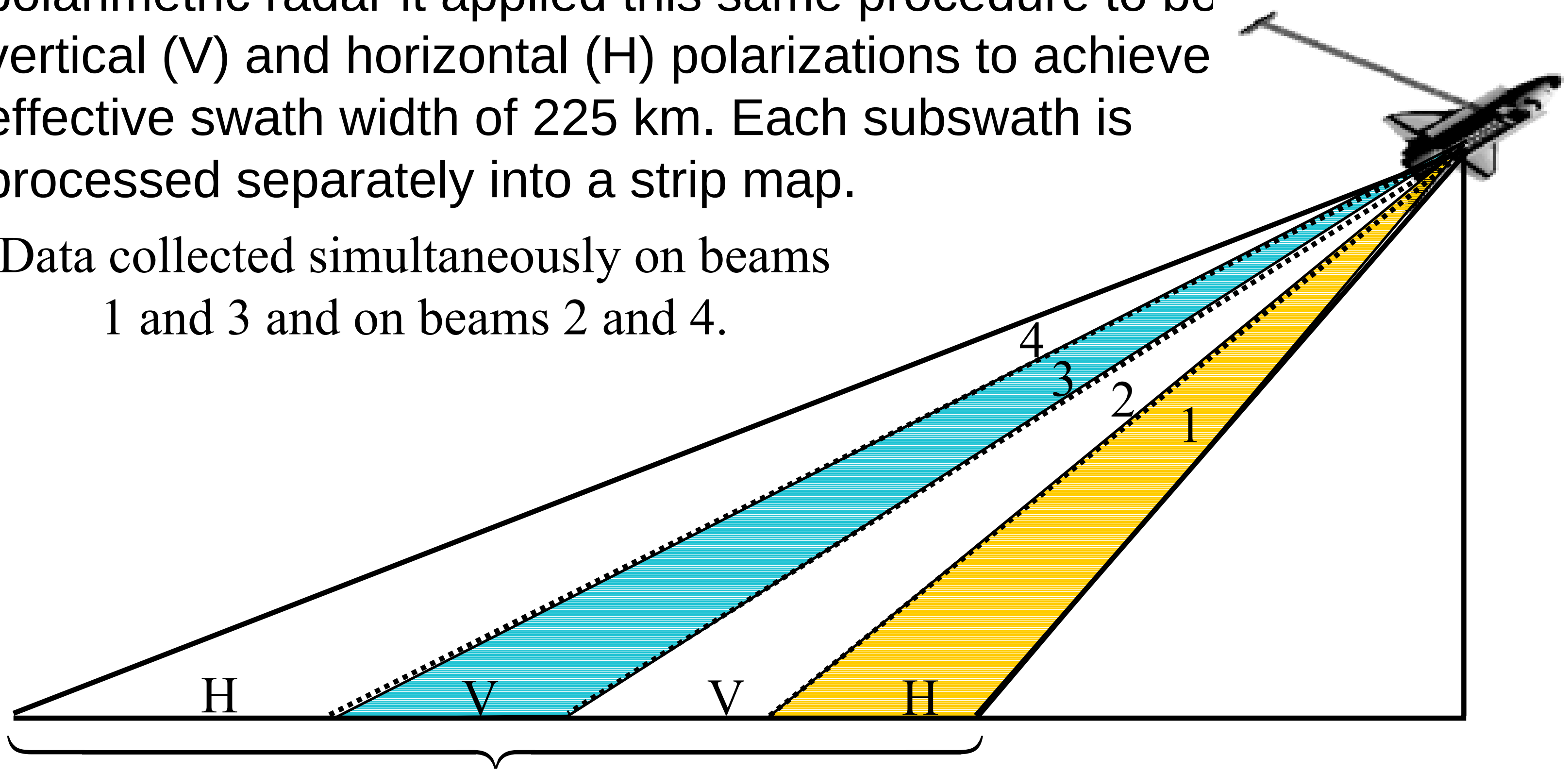
Plot of Roll Angle

- Motion compensation is required to account for boom dynamics as well as shuttle attitude changes. Left uncompensated these motions would generate hundreds of meters of height error.

Data Collection Basics

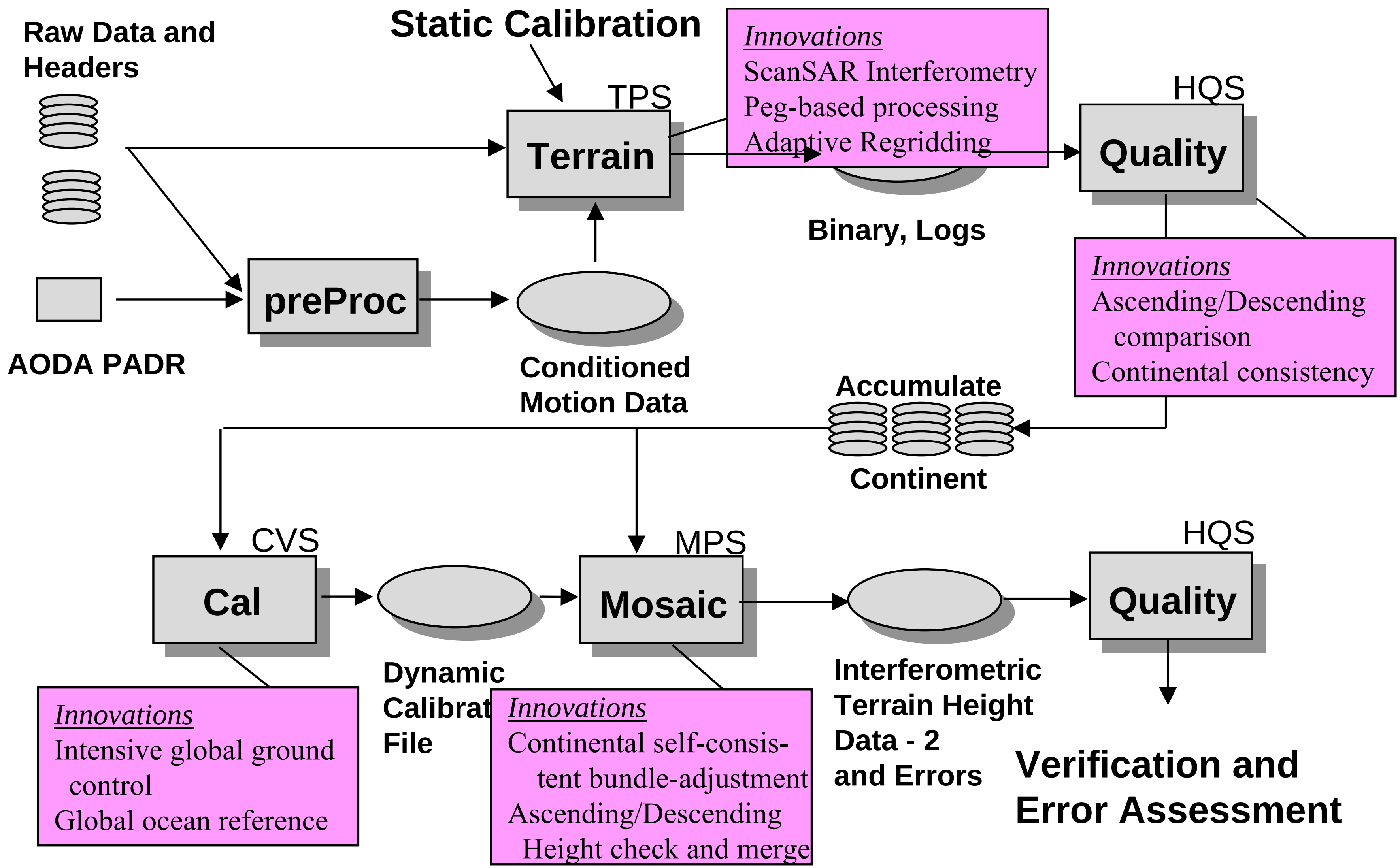
SRTM collected data in a SCANSAR mode whereby it alternately switched between two beam positions in the cross track direction to increase the swath width at the expense of along track resolution. Since SRTM is a polarimetric radar it applied this same procedure to both vertical (V) and horizontal (H) polarizations to achieve effective swath width of 225 km. Each subswath is processed separately into a strip map.

Data collected simultaneously on beams 1 and 3 and on beams 2 and 4.

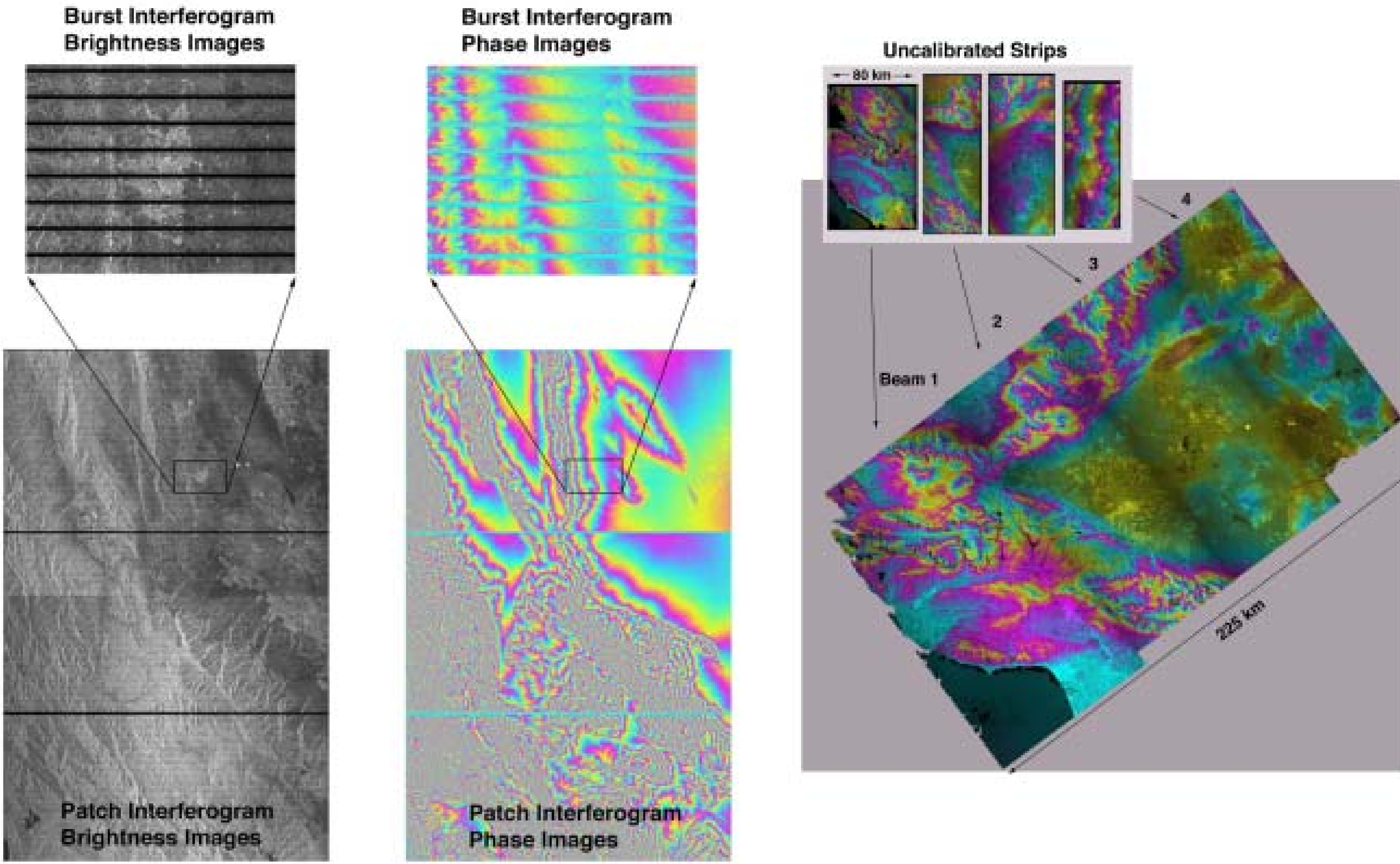


225 km swathwidth composed of four subswaths

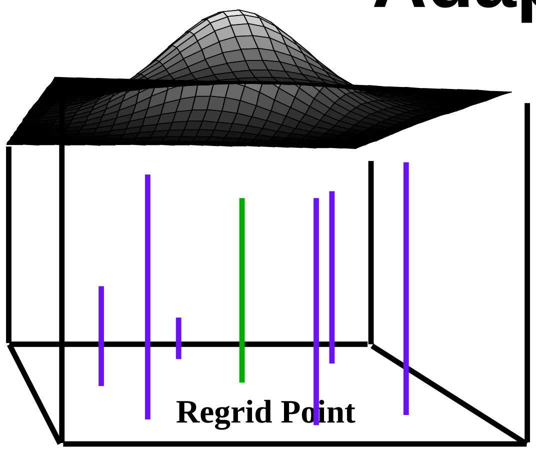
SRTM Algorithmic Flow



SRTM Patch Processing Example

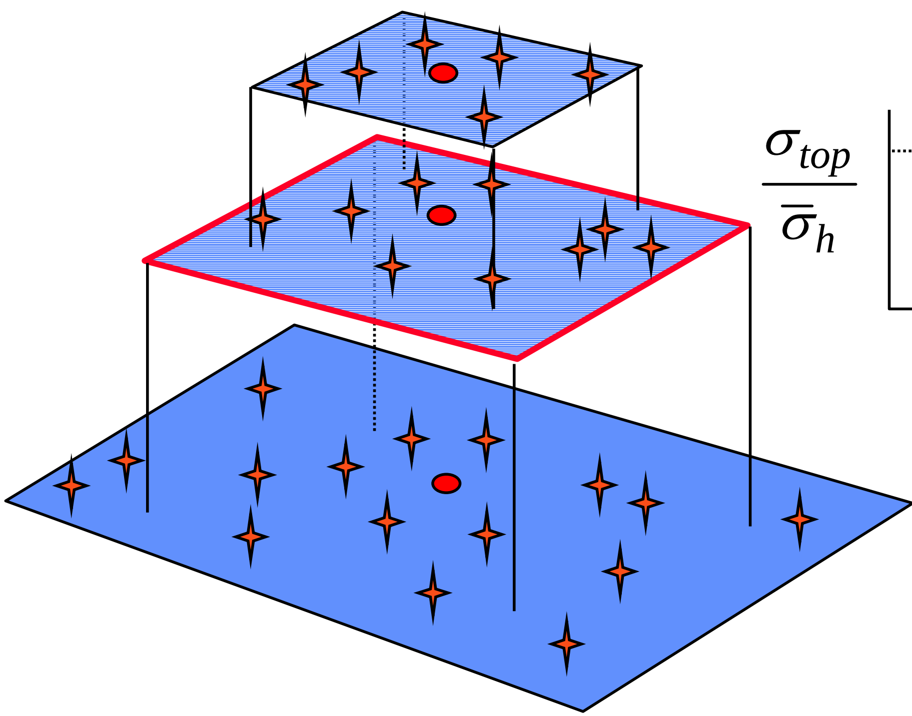


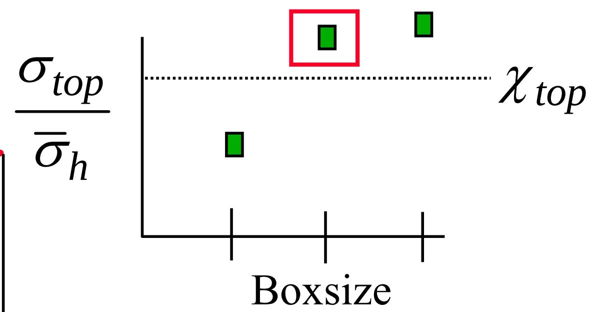
Adaptive Regridding

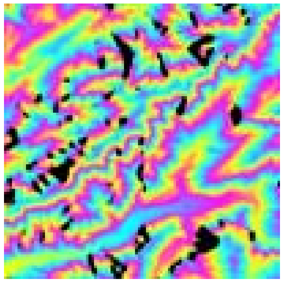


Regrid Region

Convolutional regridder uses a weighted sum of all interferometrically derived elevation values within a regrid region where the weights depend on the size of the regrid region and distance from the desired post.

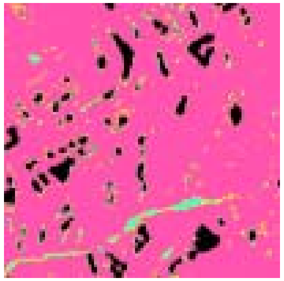






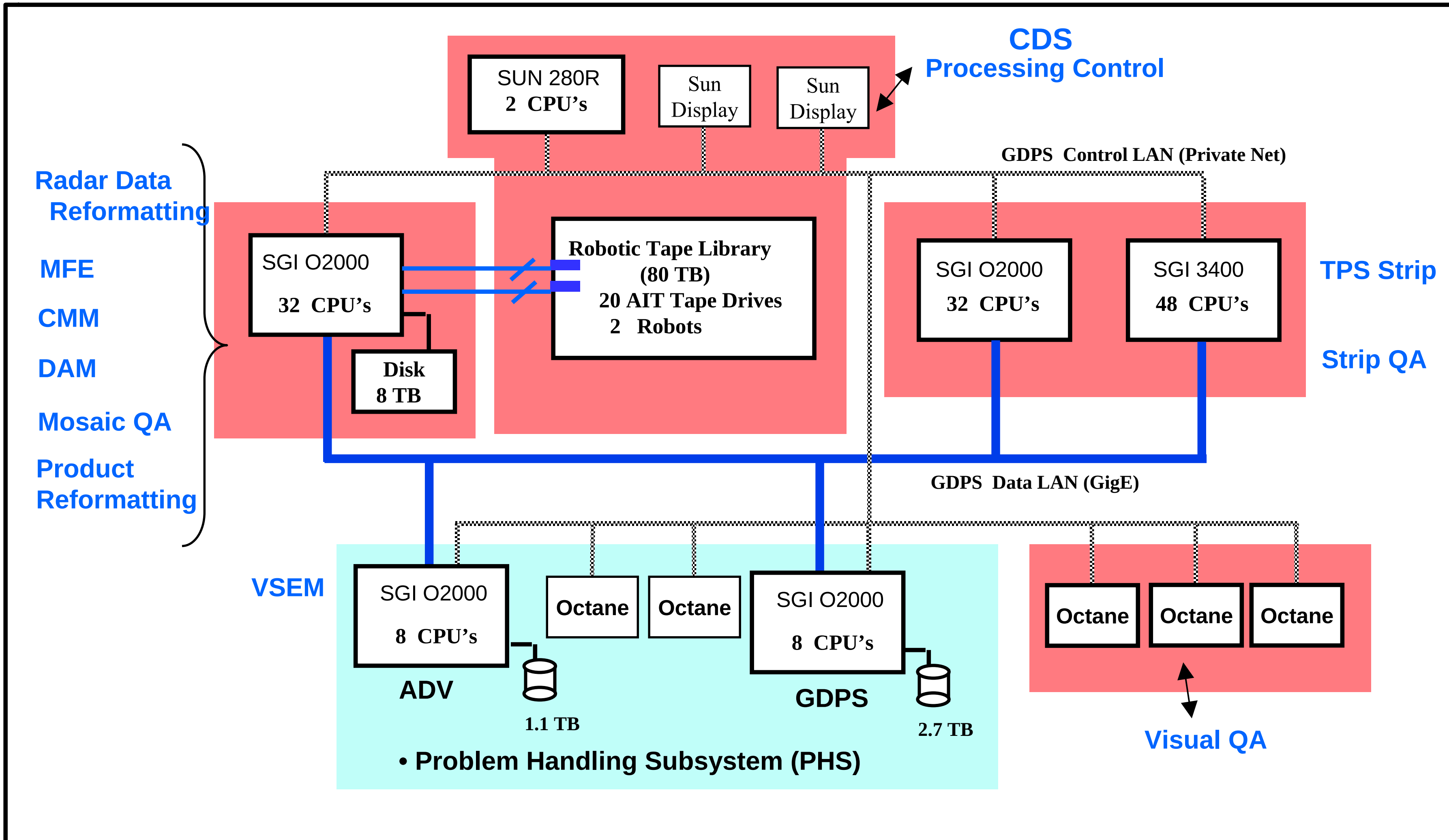
Topography

Box size is chosen to be the smallest region for which the ratio of standard deviation of the elevations values exceeds the average of the predicted height noise by a specified threshold.

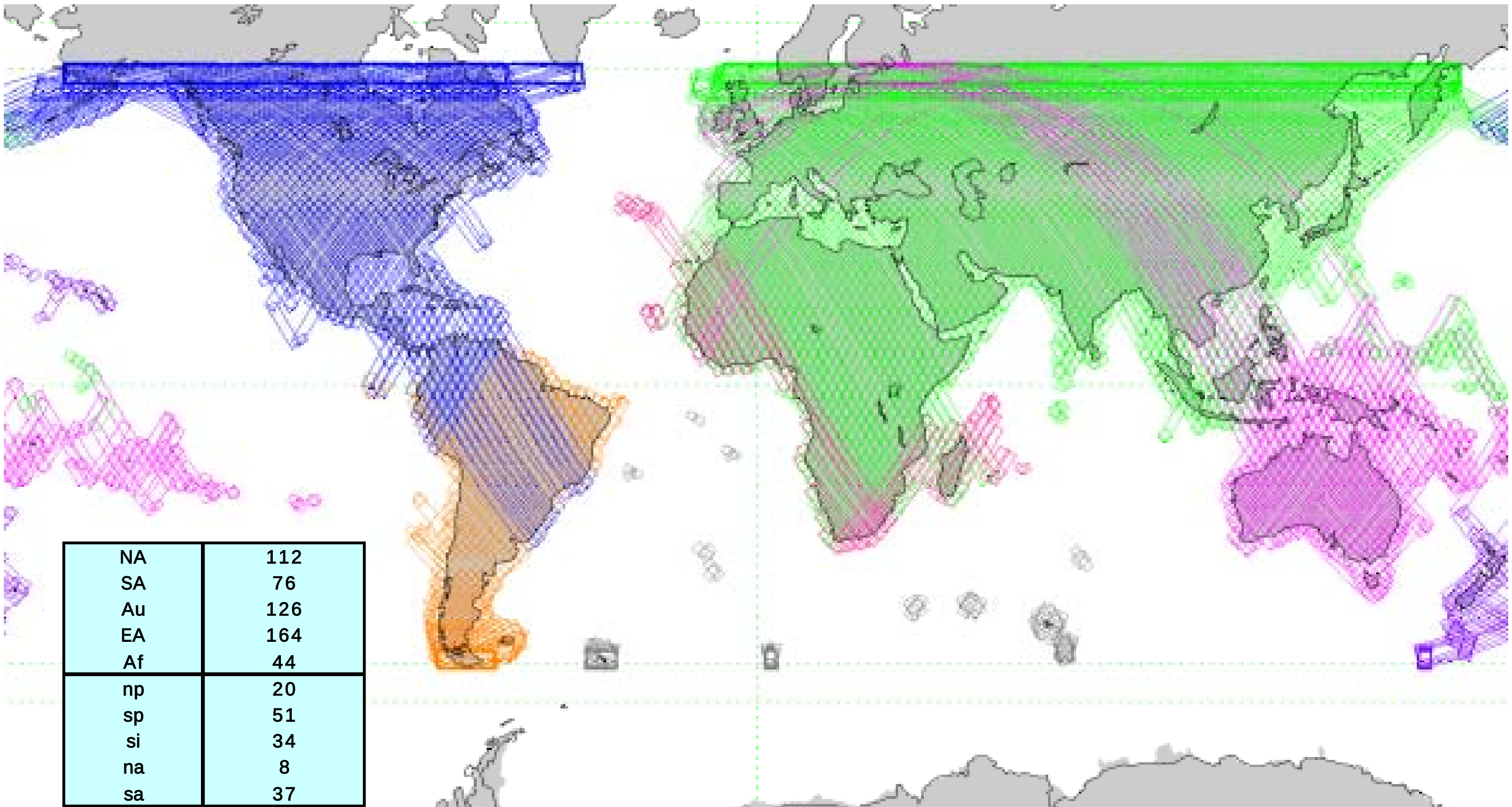


Boxsize

GDPS Production System Architecture

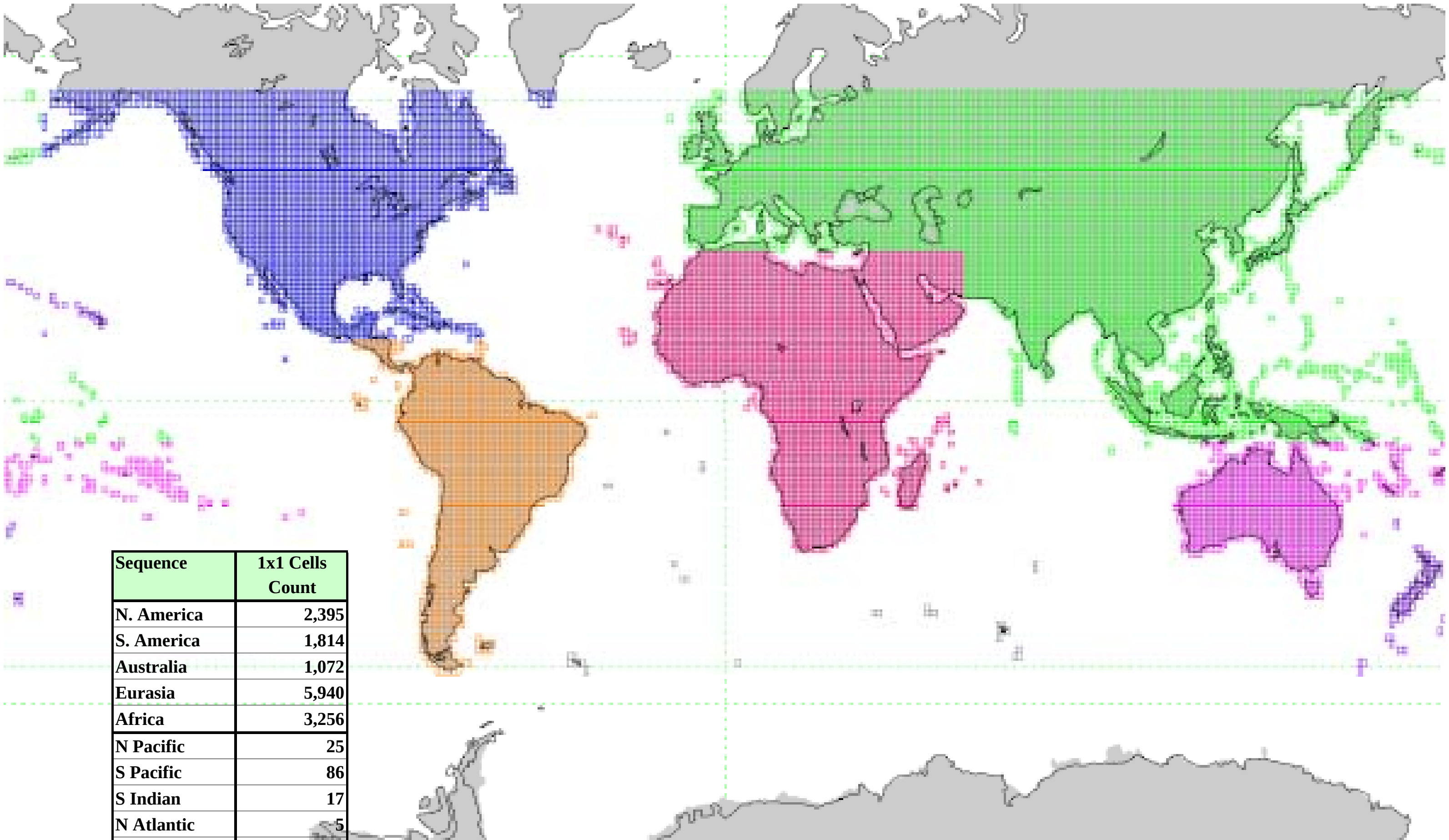


SRTM GDPS Continental Datatake Assignments



NA	112
SA	76
Au	126
EA	164
Af	44
np	20
sp	51
si	34
na	8
sa	37
Total	672

SRTM Continental Definitions and 1°x 1°Cells



Sequence	1x1 Cells Count
N. America	2,395
S. America	1,814
Australia	1,072
Eurasia	5,940
Africa	3,256
N Pacific	25
S Pacific	86
S Indian	17
N Atlantic	5
S Atlantic	11
Total	14,621

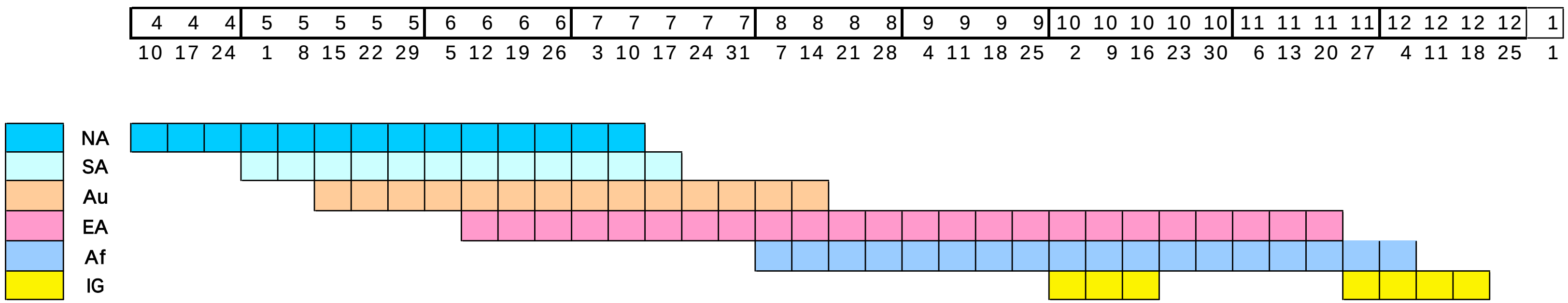
Schedule Estimation: Processor Loading Parameters

Sequence	Data Hours	1x1 Cells Count	5x5 Cells Count	Total Days
N. America	21.1	2,395	154	86
S. America	6.4	1,814	108	70
Australia	16.9	1,072	95	67
Eurasia	45.3	5,940	370	159
Africa	3.3	3,256	169	79
N Pacific	1.3	25	9	7
S Pacific	0.2	86	16	7
S Indian	0.3	17	7	5
N Atlantic	0	5	3	2
S Atlantic	0.3	11	6	2
Total	95.1	14,621	937	

Throughput Drivers

- Compute intensive tasks
  - Strip Processing – 60 x Acquisition time @ 4 nodes
  - Strip Re-processing – ≈ 50% of Strip processing time
  - Mosaic (DAM) – 6 hours per 5°x 5° Cell @ 13 nodes
- Human intensive tasks
  - Continental Correction (MFE) – 10 working days / continent
  - Visual QA (MSC) – 150 1°x1° Cells / workday
  - Vertical Systematic Error Modelling – 10 working days / 3000 1°x1° Cells
- Other applications provide smaller contribution to schedule and are often concurrent to intensive computing processes
  - Sequence generation
  - Database processing
  - Raw data input transfer
  - Output Data Product generation (Write & Verify) (2 sets of tapes per day)
    - Topographic pre-processing
    - Strip QA
    - Mosaic QA

Production Processing Schedule



Group	Deliver On or Before
NA	July 10
SA	Aug 6
Au	Aug 13
EA	Nov 17
Af	Dec 6
IG	Dec 16

Au delayed to fill the "Shaffer gap". All other Groups on schedule

- Project schedule:
  - Post-processing support phase (January 1, 2003 - March 31, 2003
  - NASA data archival phase (April 1, 2003 - May 31, 2003)

C-Band Processing Systems and Data Products

- JPL Production System to
  - Process
  - Archive
  - Deliver to NIMA

  the global DEM and Mosaicked Image data set in DTED format
- JPL prototype processor developed to
  - Develop and test algorithms
  - Deliver preliminary data products to NASA investigators
- NASA products are:
  - Mosaicked DEM at 90 m resolution globally
  - Mosaicked DEM at 30m resolution in US, and at selected non-US sites upon NIMA approval
- DEM Data Availability:
  - US at 30 m and 90 m resolution available now from EDC
  - World at 90 m available upon completion (May 2003)
  - World at 30 m available selectively to investigators upon approval by NIMA upon completion and negotiation

Calibration and Accuracy Assessment

SRTM Error Contributors

- Random error: decorrelates within a few pixels, depending on surface smoothness
- Residual Processing Errors: Random error with wavelengths on the order of 1-10's of kilometers. Estimated RMS: 1m
- Residual 7 second ripple errors (50km wavelength), RMS ~1m
  - Much reduced in the final production data since the source of this error was located and mostly removed from the motion data
    - Source of ripple was an instrument anomaly in the star tracker
- Residual PADR errors (dominant periods > 100 seconds, or 700 km)
- Residual mosaicking errors
- Other "unknown" errors

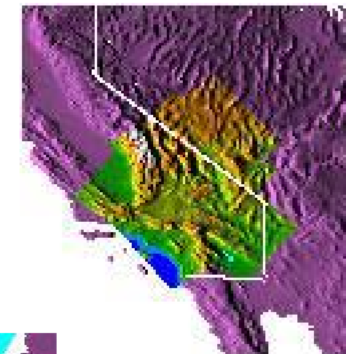
Ground Truth Data Used for System Validation and Accuracy Assessment

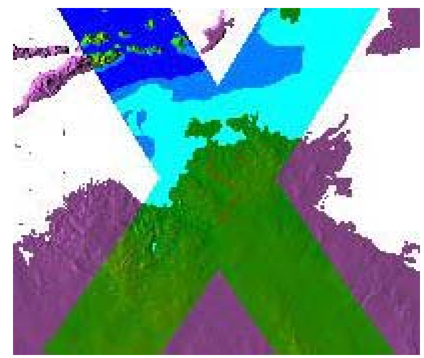
- Kinematic GPS tracks
  - Thousands of kilometers of kinematic GPS tracks in North America, South America, Australia, Europe and Africa
- Corner Reflectors
  - United States and Australia - Arrays covered 225 km in the cross track direction for baseline and common range delay calibration
- Other NIMA and JPL derived GCP’s
  - Data base of control points consists of tens of thousands of points on all continents with varying densities
- DEM “Chip” data generated by NIMA from optical imagery
- Altimeter derived GCP’s (JPL)
- Ocean GCPs - ocean heights corrected for tides used as ground control at all ocean crossings

Static Calibration Activities

- Corner Reflector Arrays and Short Ocean Data Takes
  - Absolute and relative channel delays
  - Timing constants
  - Roll constants
- Long Ocean Data Takes
  - Systematic trends
  - Radar state changes

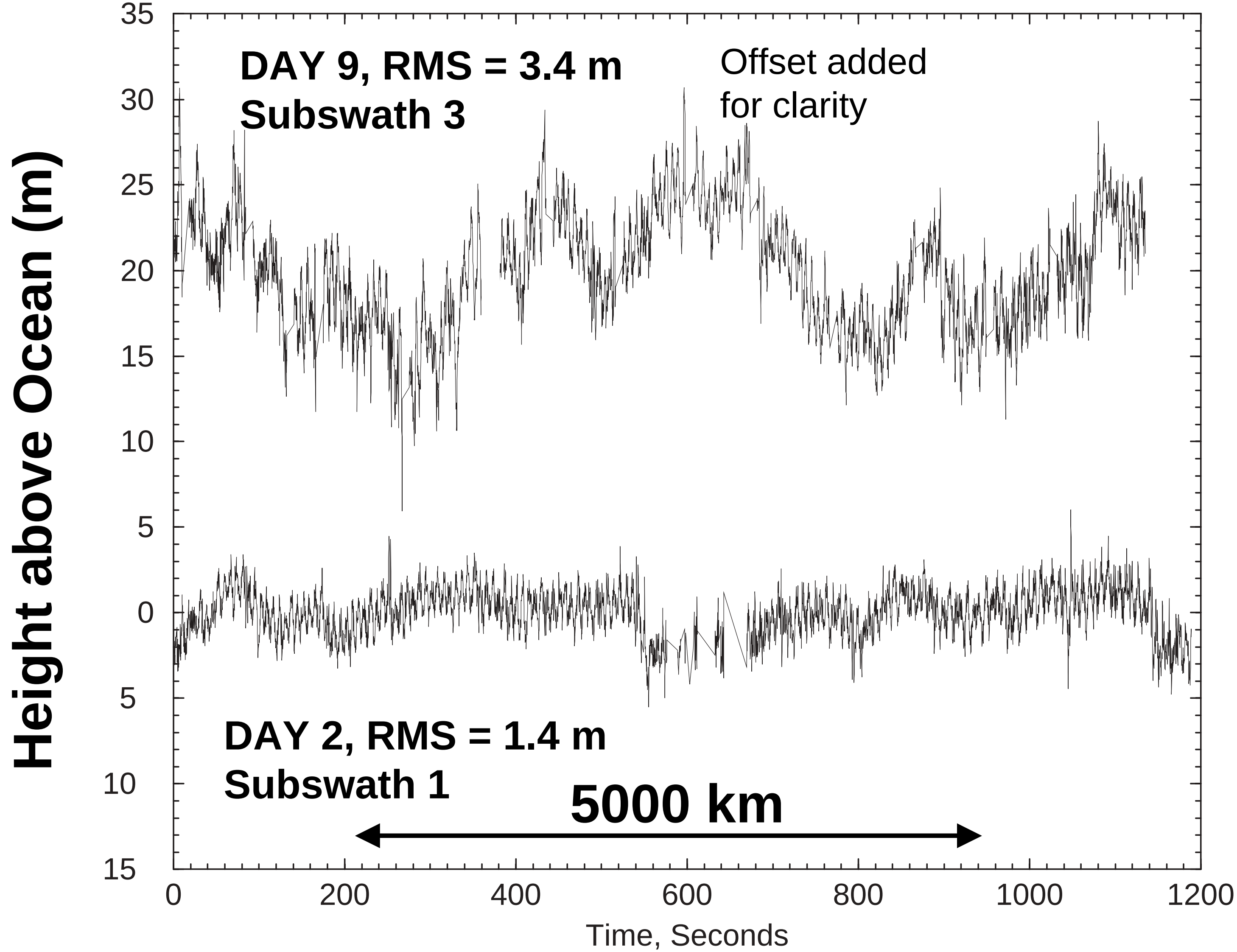
CA



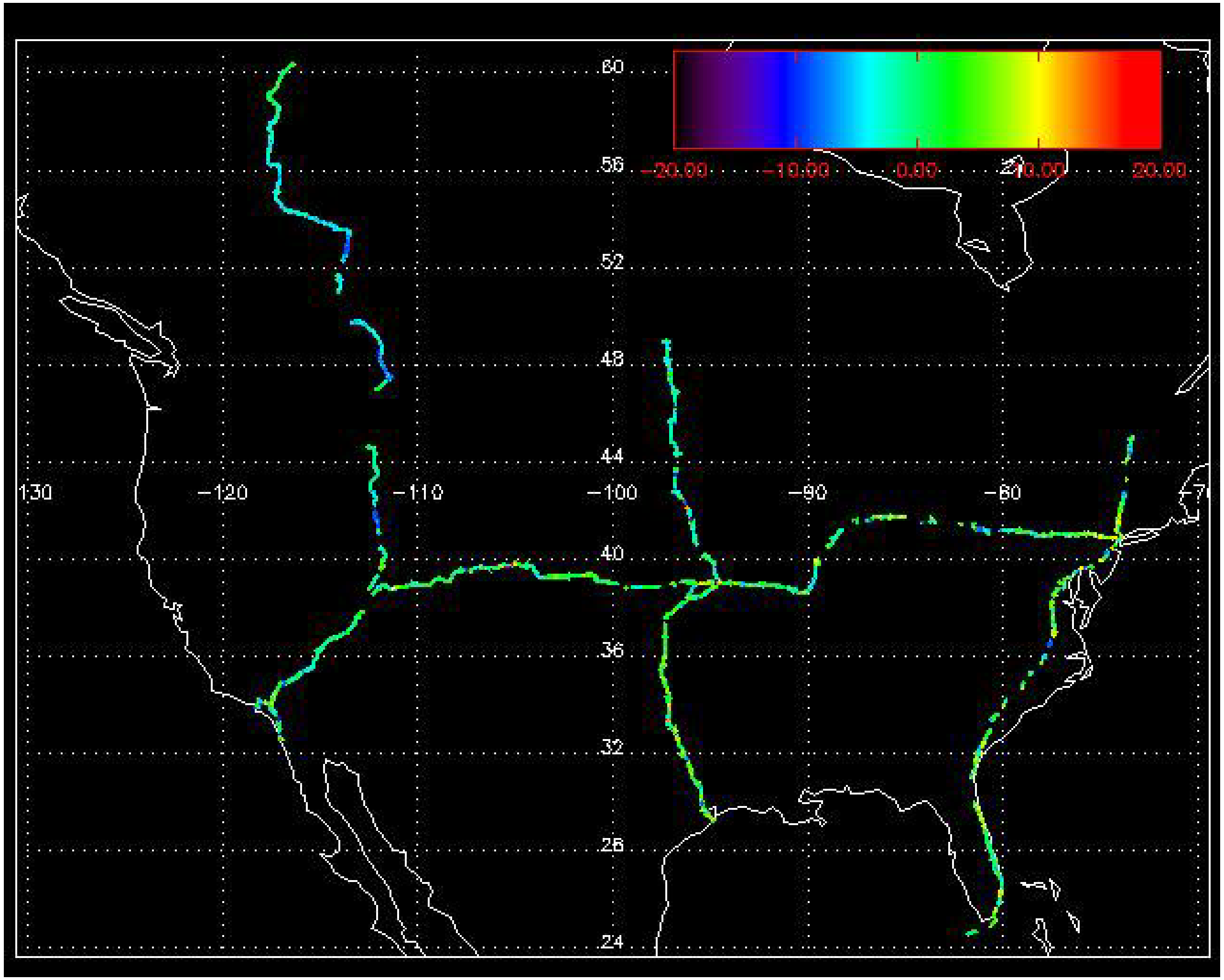


Oz

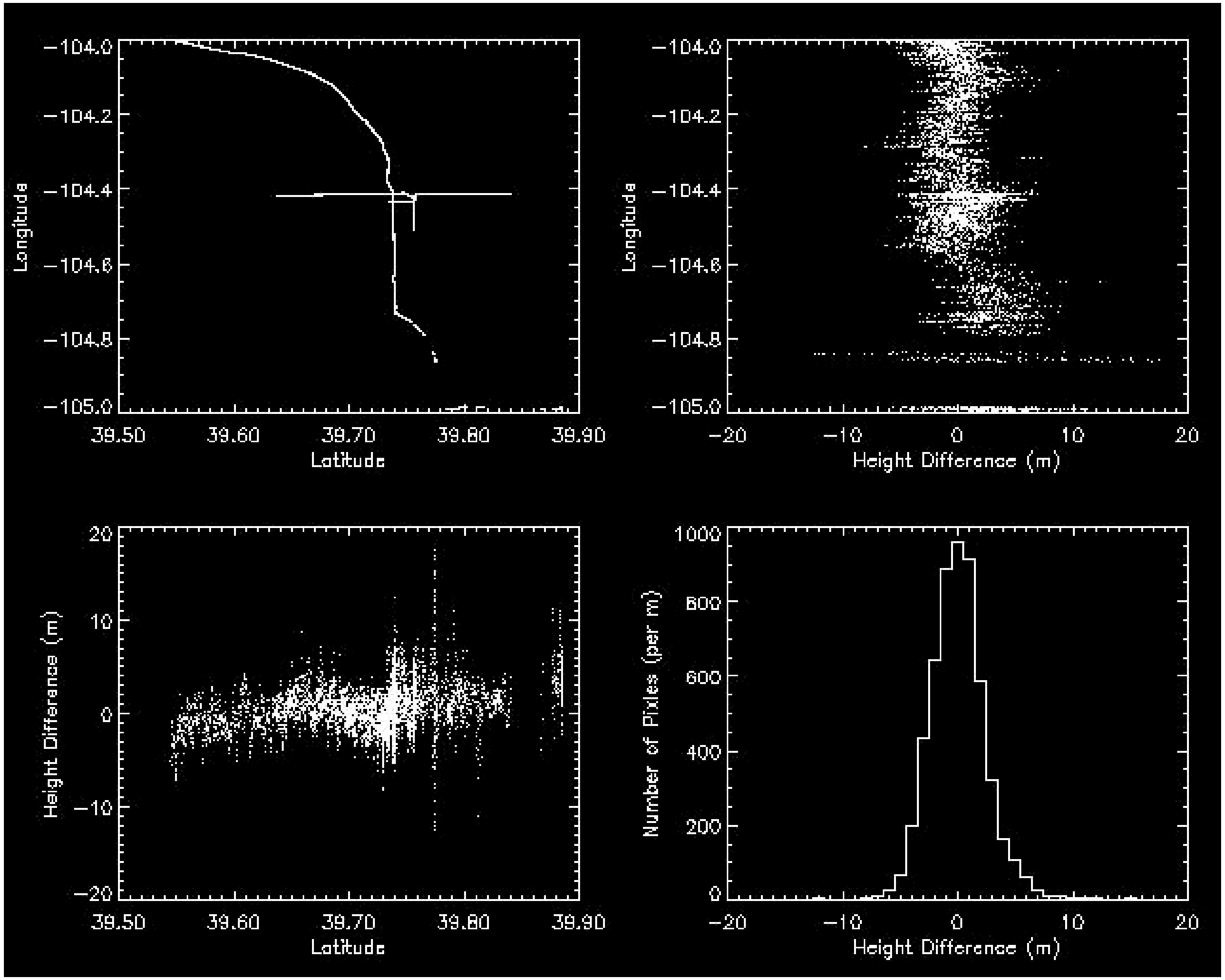
Long Ocean Data Takes Results



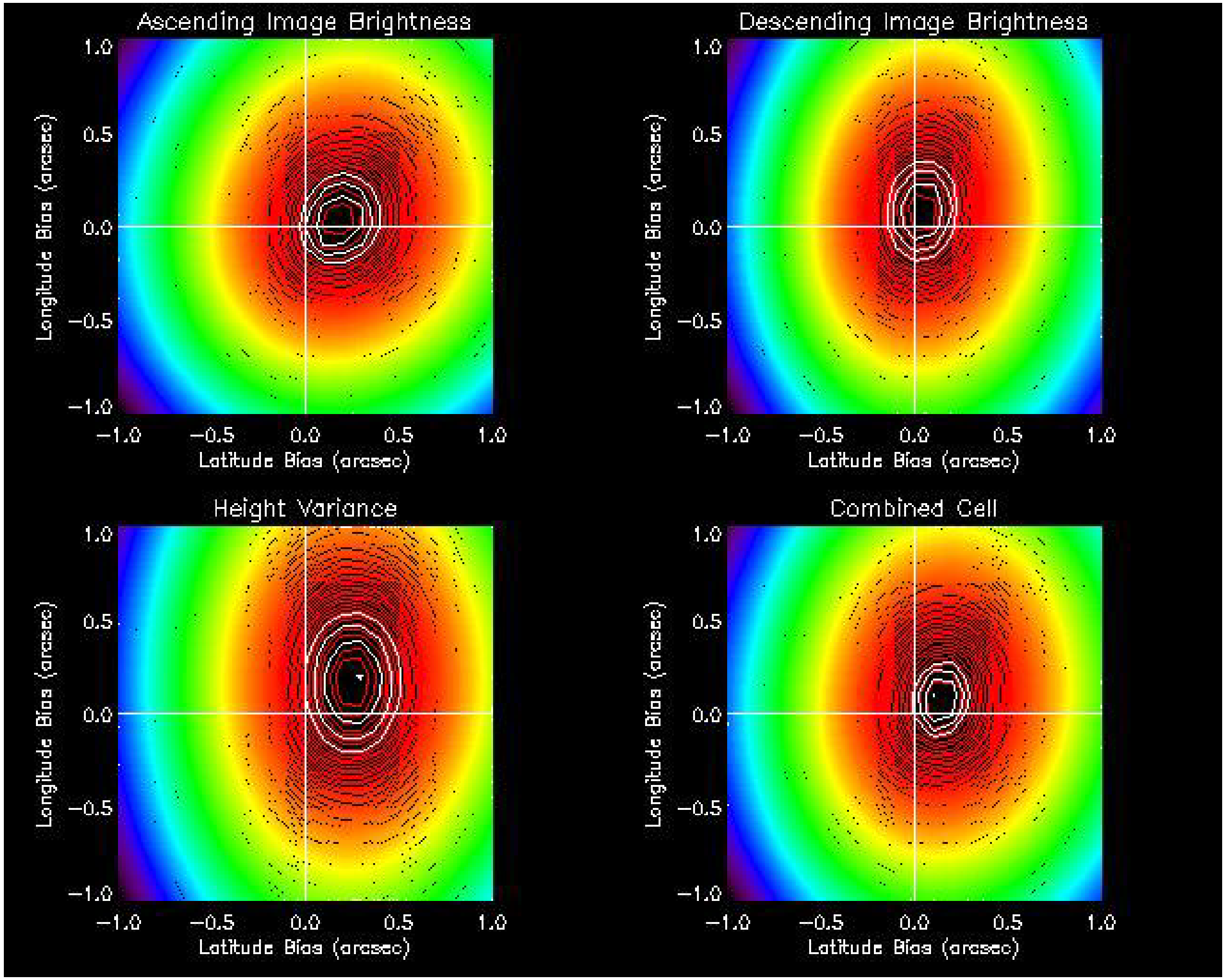
North America Kinematic GPS Data



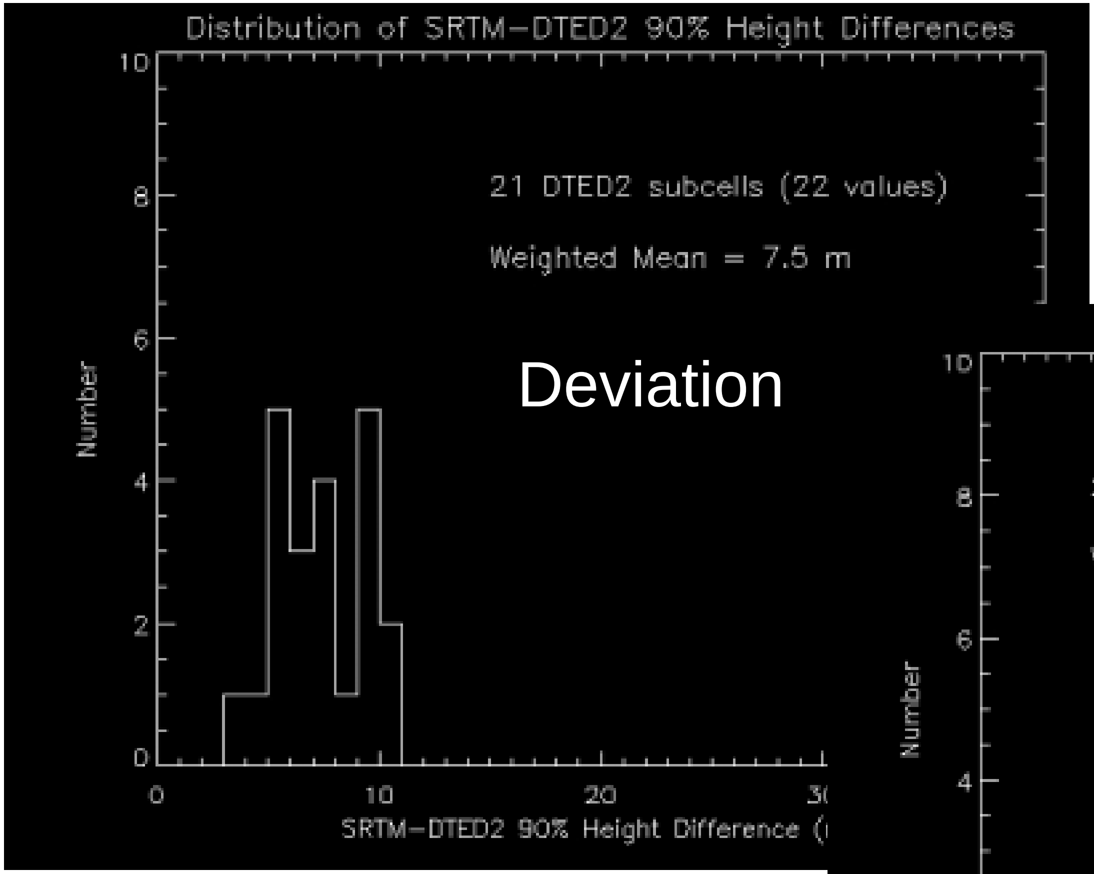
Errors Distribution for 1 Cell of Kinematic GPS Data

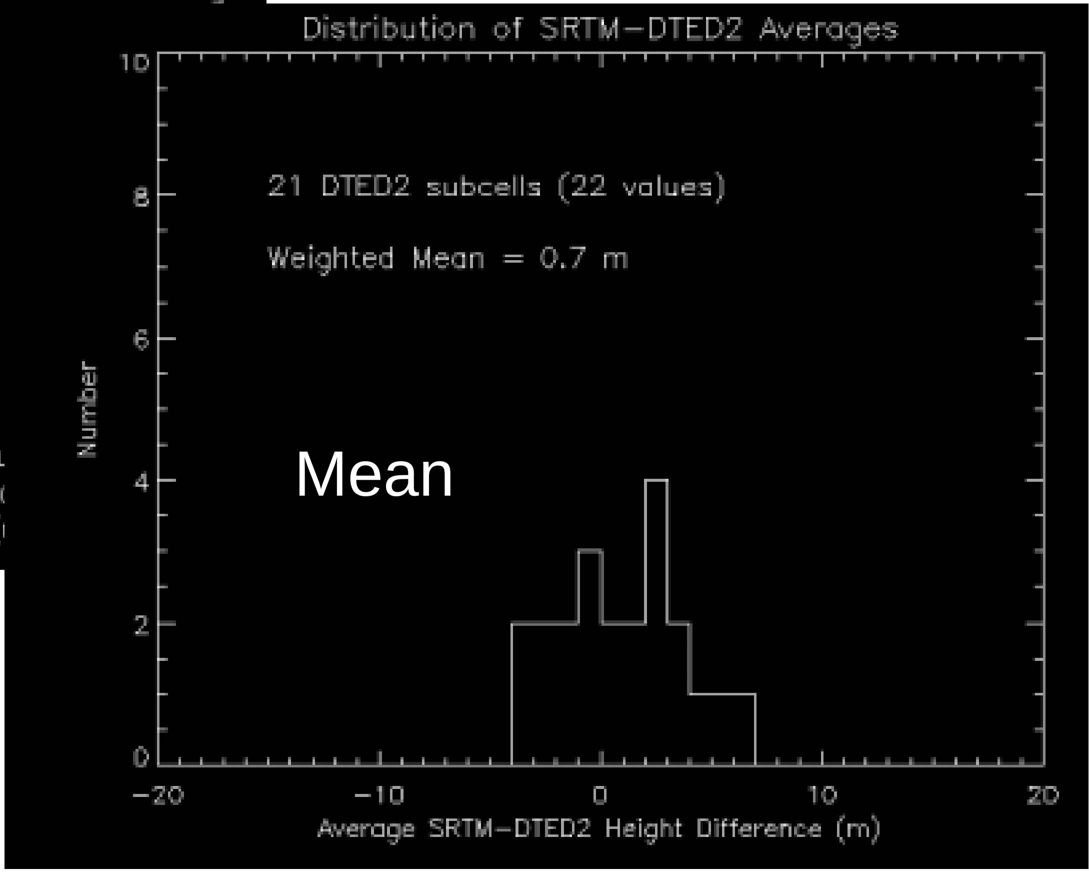


Planimetric Accuracy Assessment based on North America Kinematic GPS Data

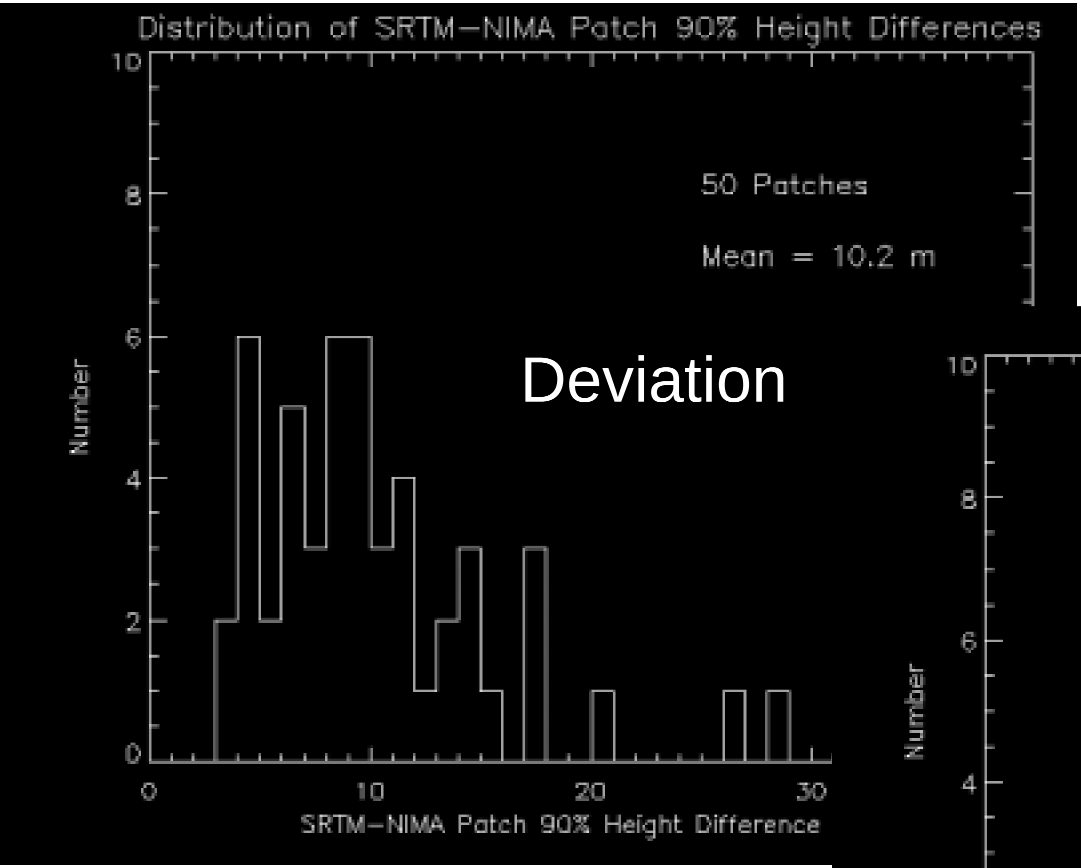


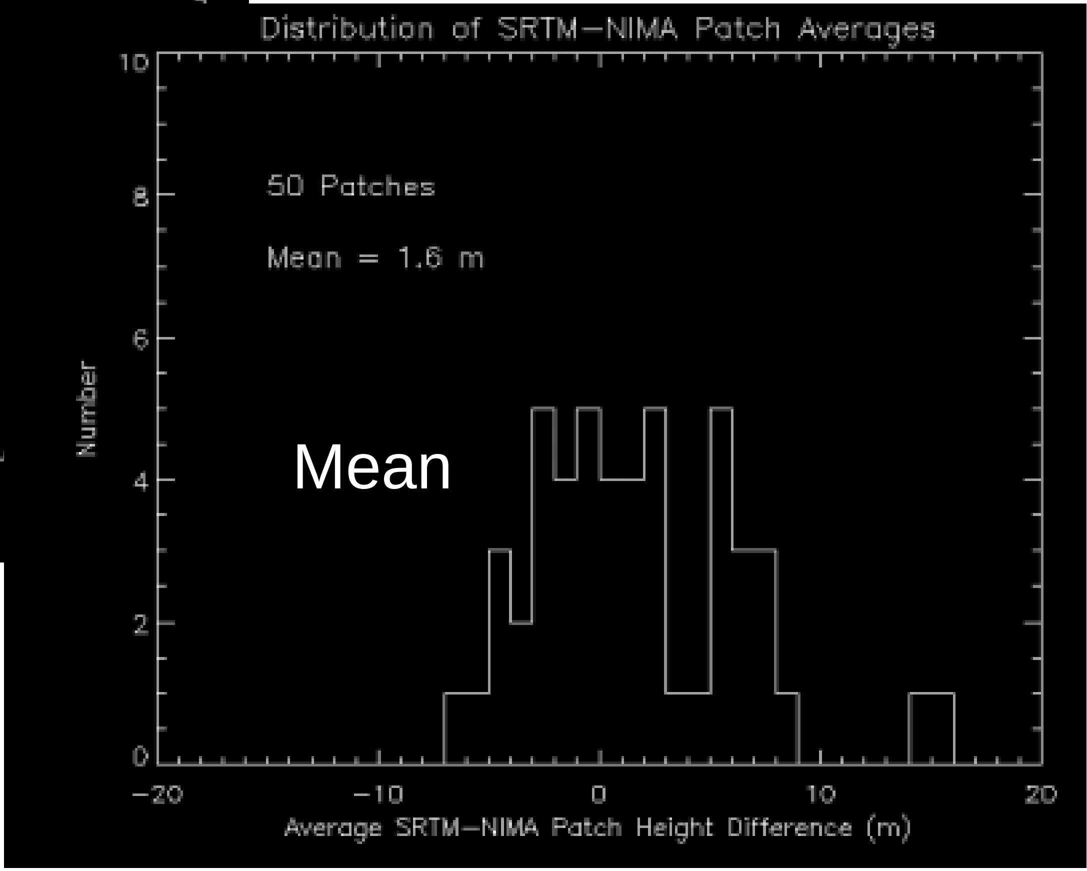
Mean and Deviation of SRTM data relative to other DTED-2 samples

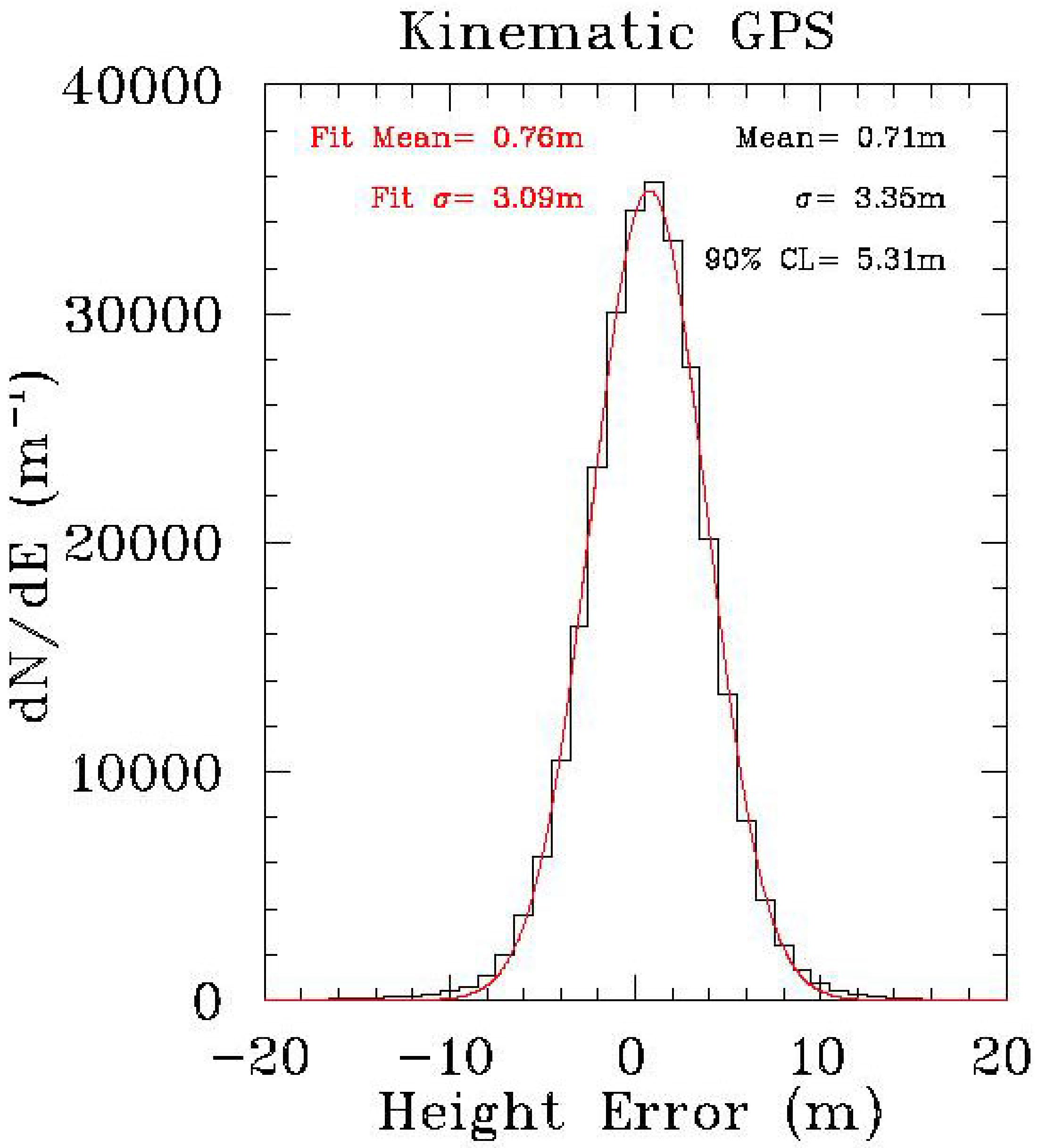




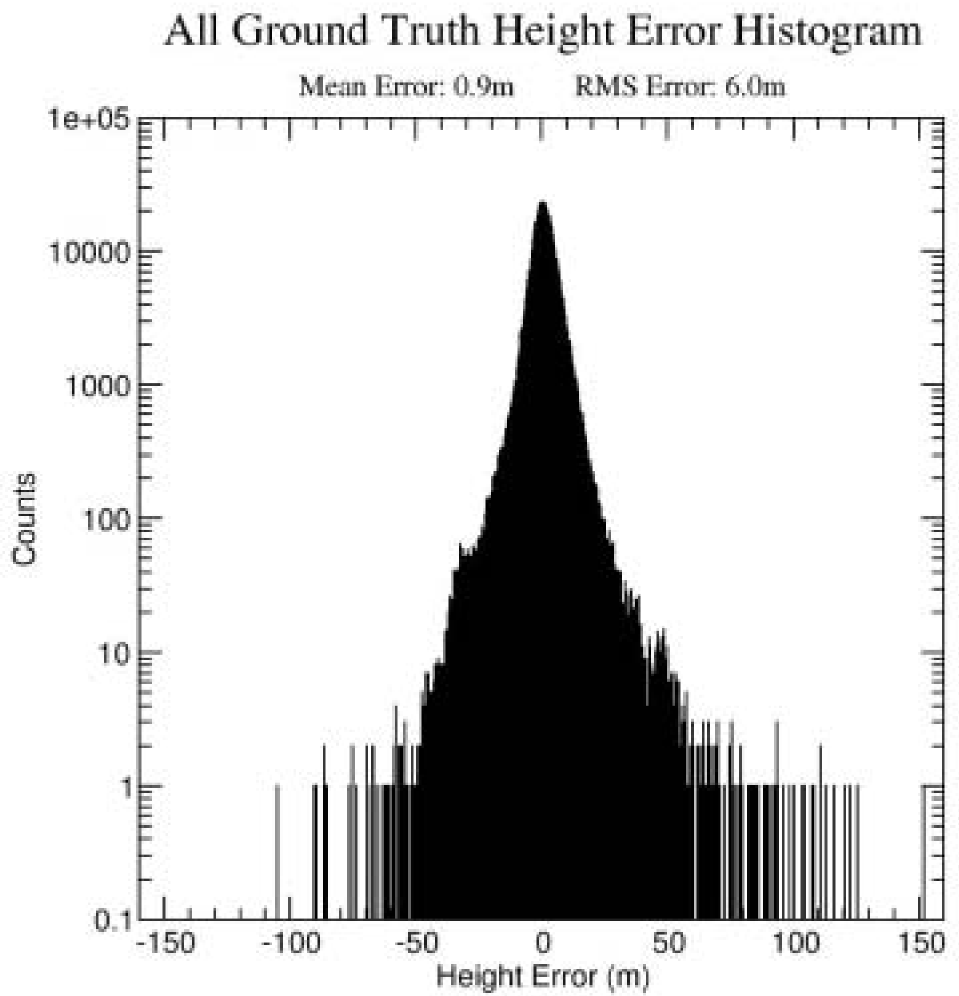
Mean and Deviation of SRTM data relative to other NIMA samples





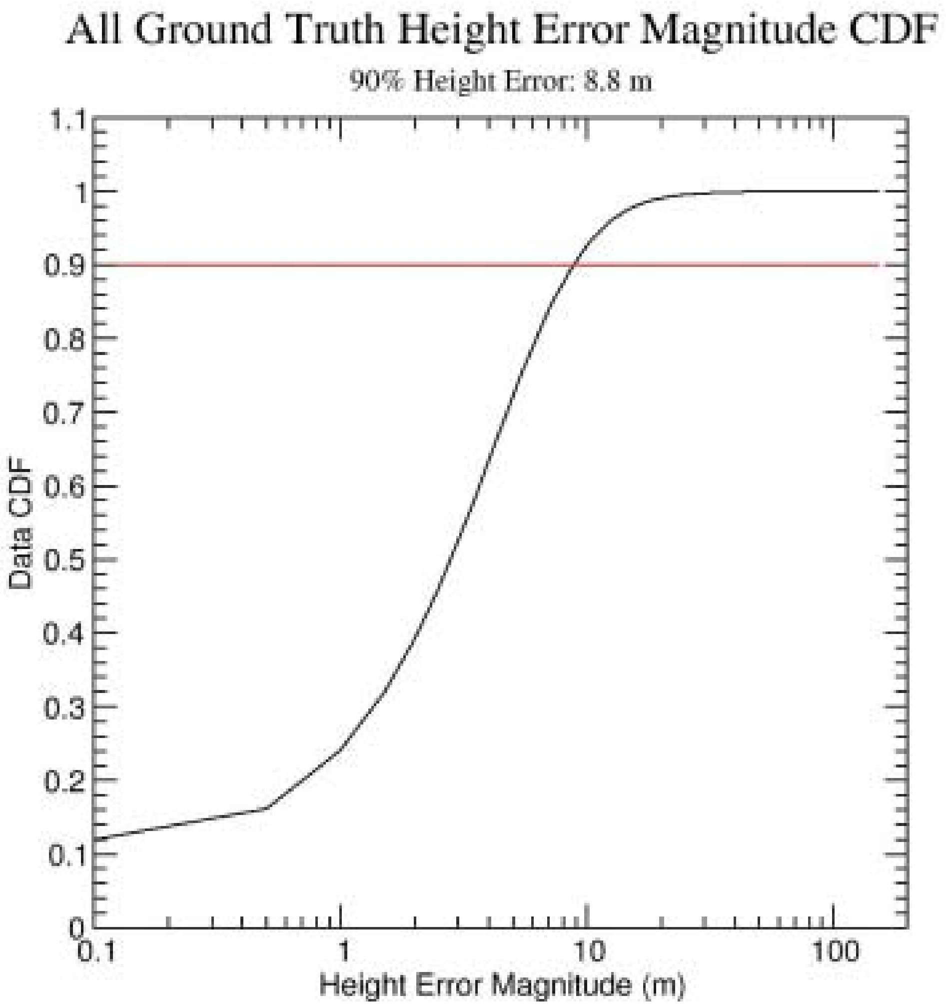

Kinematic GPS
Fit Mean= 0.76m
Fit σ= 3.09m
Mean= 0.71m
σ= 3.35m
90% CL= 5.31m
40000
30000
20000
10000
0
dN/dE (m⁻¹)
−20
−10
0
10
20
Height Error (m)

Summary Height Error Histogram



Data used: all GCP's, NIMA Chips, Kinematic GPS

Summary Absolute Error Cumulative Distribution Function



- Data using all GCP's, NIMA Chips, Kinematic GPS for several continent sized region.

SRTM Performance Summary

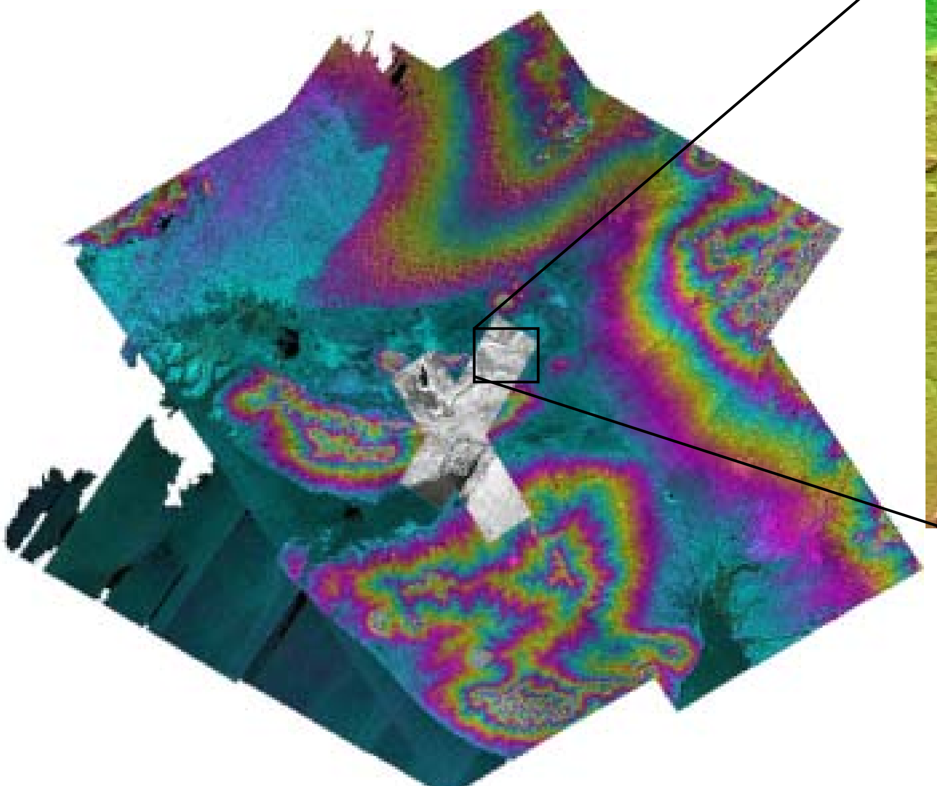
- Based on over hundreds of millions of comparisons, SRTM has a absolute height accuracy of 9.0m or better over a $1^o x 1^o$ cell, at the 90% confidence level.
- Using the kinematic GPS data, probably the best ground truth data available, SRTM meets the absolute height requirement by a factor of 3.
- **Both the absolute and relative SRTM height accuracy requirements are met.**
- Using the kinematic GPS data, SRTM's horizontal accuracy is better than 10 meters and we believe the results are consistent with no horizontal offset.
- **Both the absolute and relative SRTM horizontal accuracy requirements are met.**

SRTM Summary

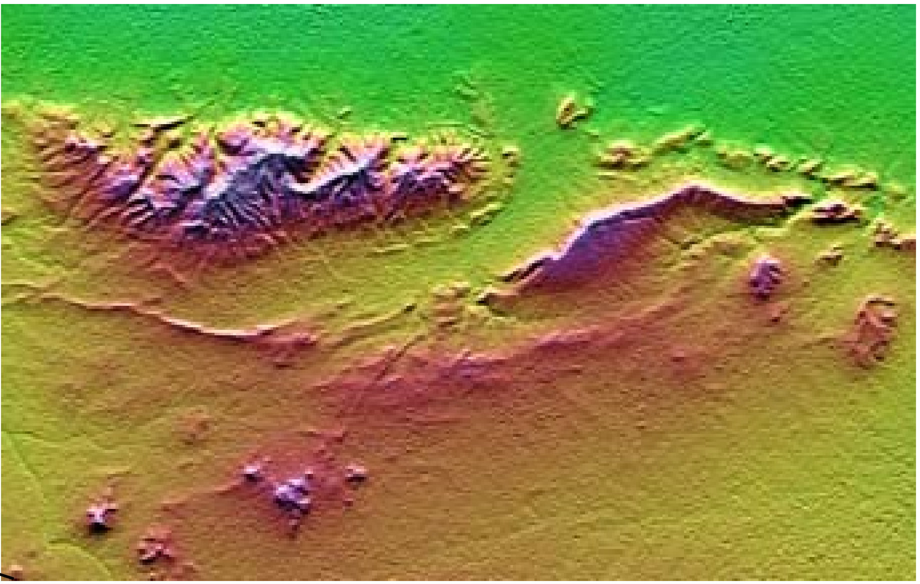
- Have processed 2/3 of DEM cells in the world and analysis of data shows that
  - Vertical accuracy is better than 2 times the requirement
  - Horizontal accuracy meets or exceeds requirements
- Global production began on April 10, 2002 with the processing of North America.
  - Data is delivered on a continent by continent basis with each continent taking approximately 6 weeks to 2 months to complete.
  - Strip map processing is complete expect for some minor reprocessing work.
  - North America, South America, (Australia,) Africa are complete.
  - Mosaicking of Eurasia and Pacific Islands are in progress.
- Planned completion of all data processing at end of calendar year.

X-SAR: an X-band interferometer on SRTM
Example Gujarat Earthquake area, India

Full ScanSAR map with X-band overlay

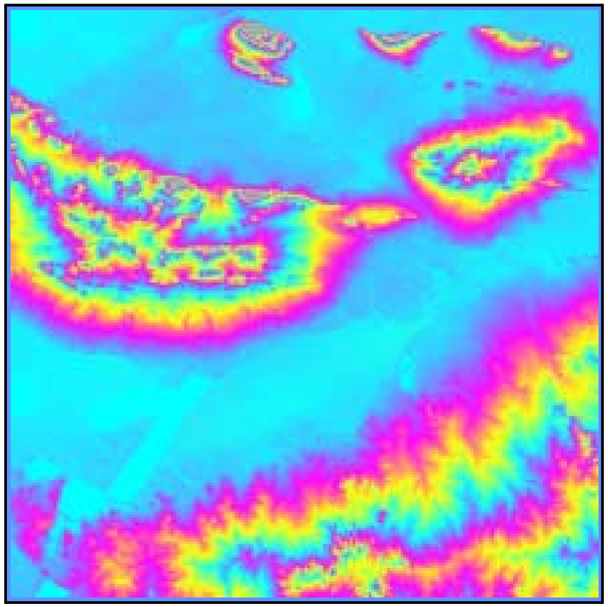


C-band DEM Northeast of Bhuj
Haro and Kas Hills - 300 m relief



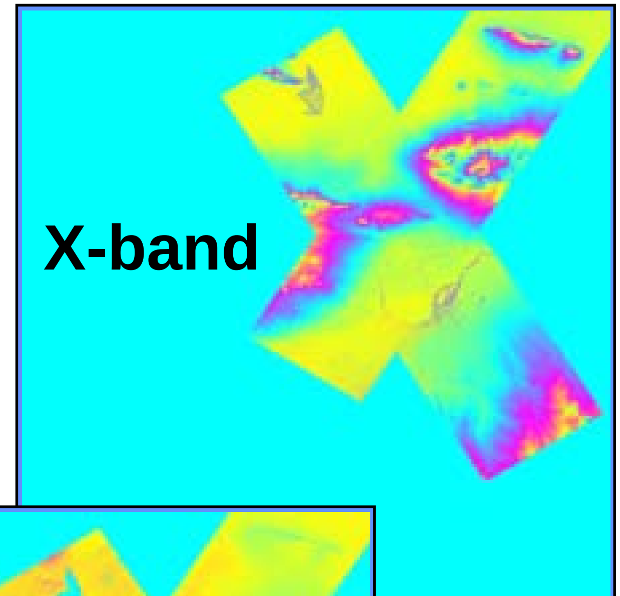
DLR designed and built X-SAR

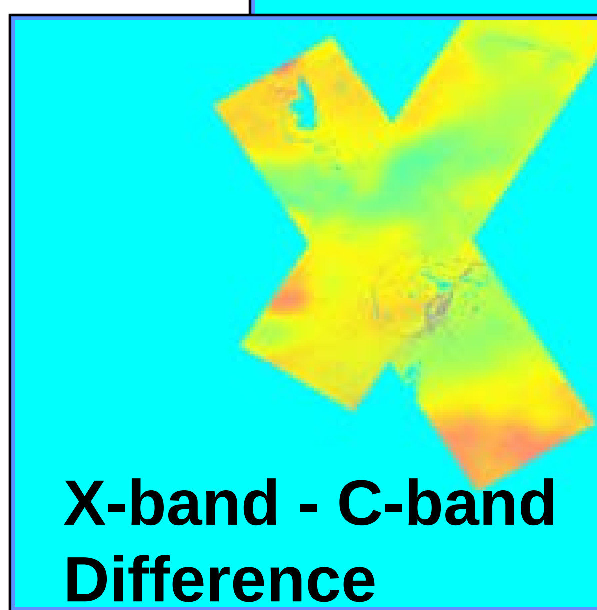
C-Band and X-band DEMs Compared



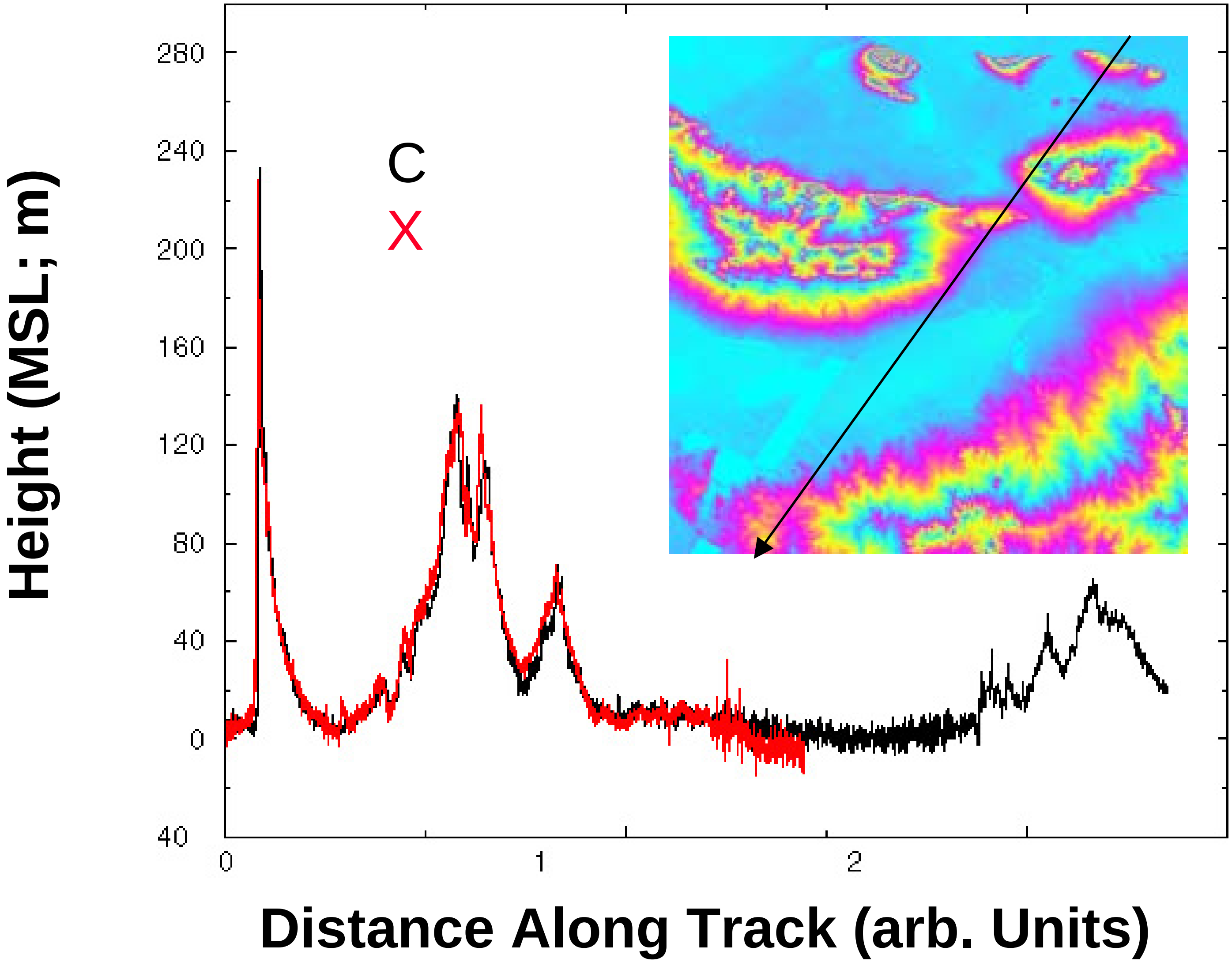
C-band
2 deg x 2 deg

100 m per contour





Preliminary C-Band and X-band DEM Profiles

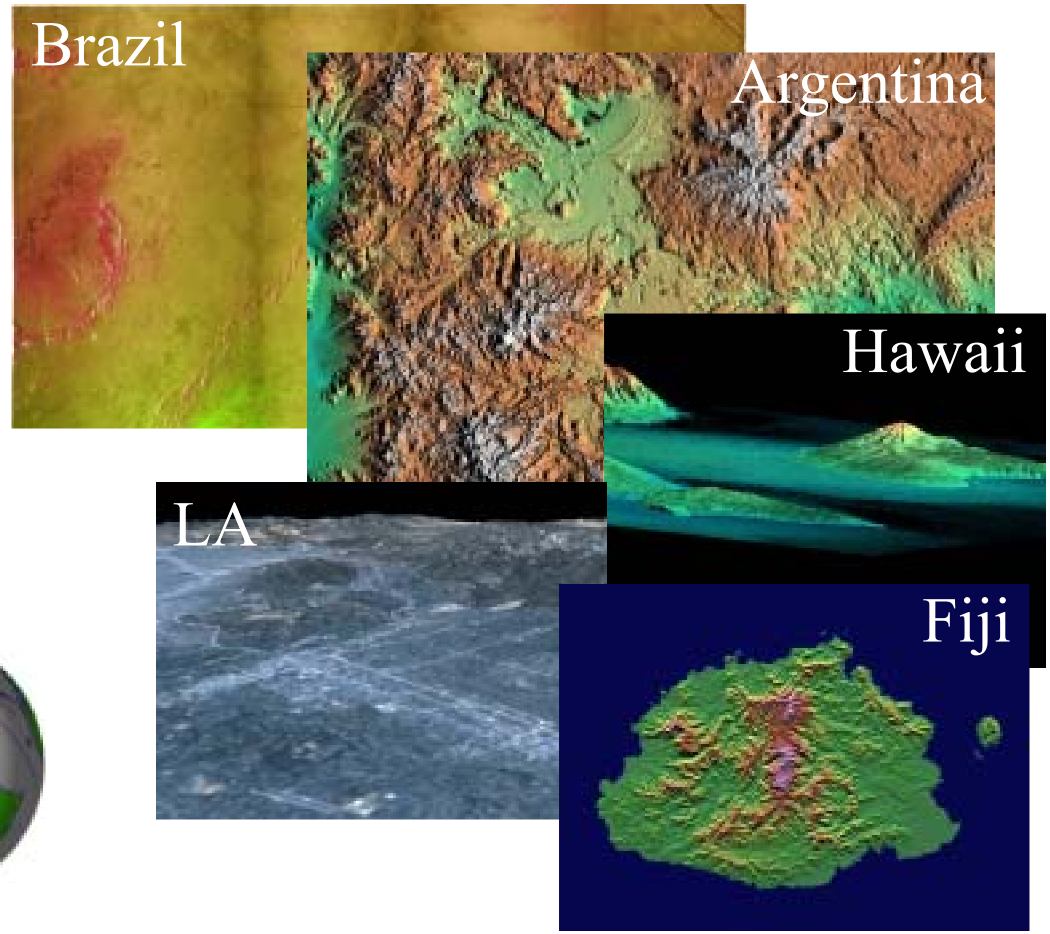


Some SRTM Results

SRTM Mission Success: Feb 11-22, 2000

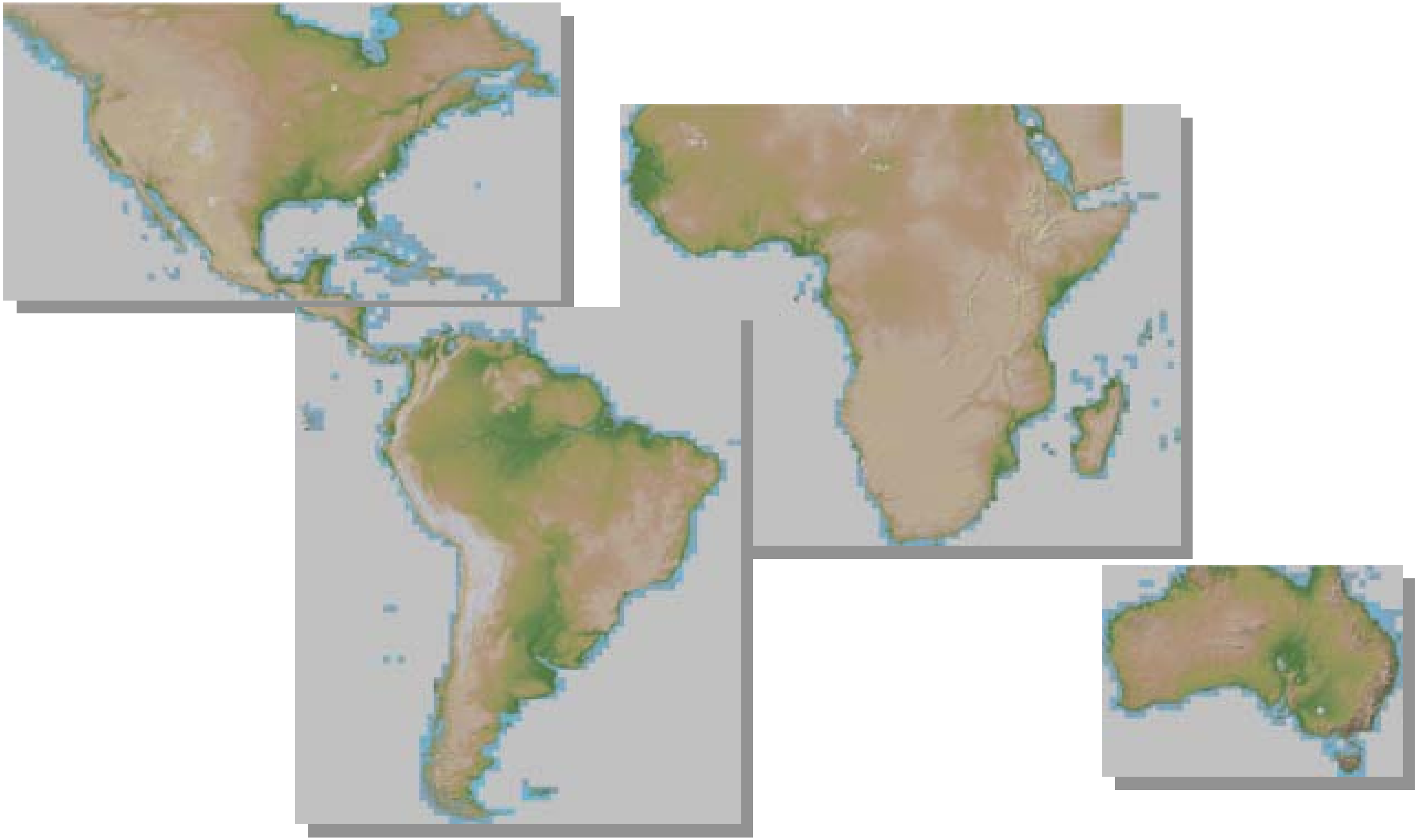
Real-Time products during the mission

99+% coverage of the planned area



SRTM Global Production

Continent by Continent*

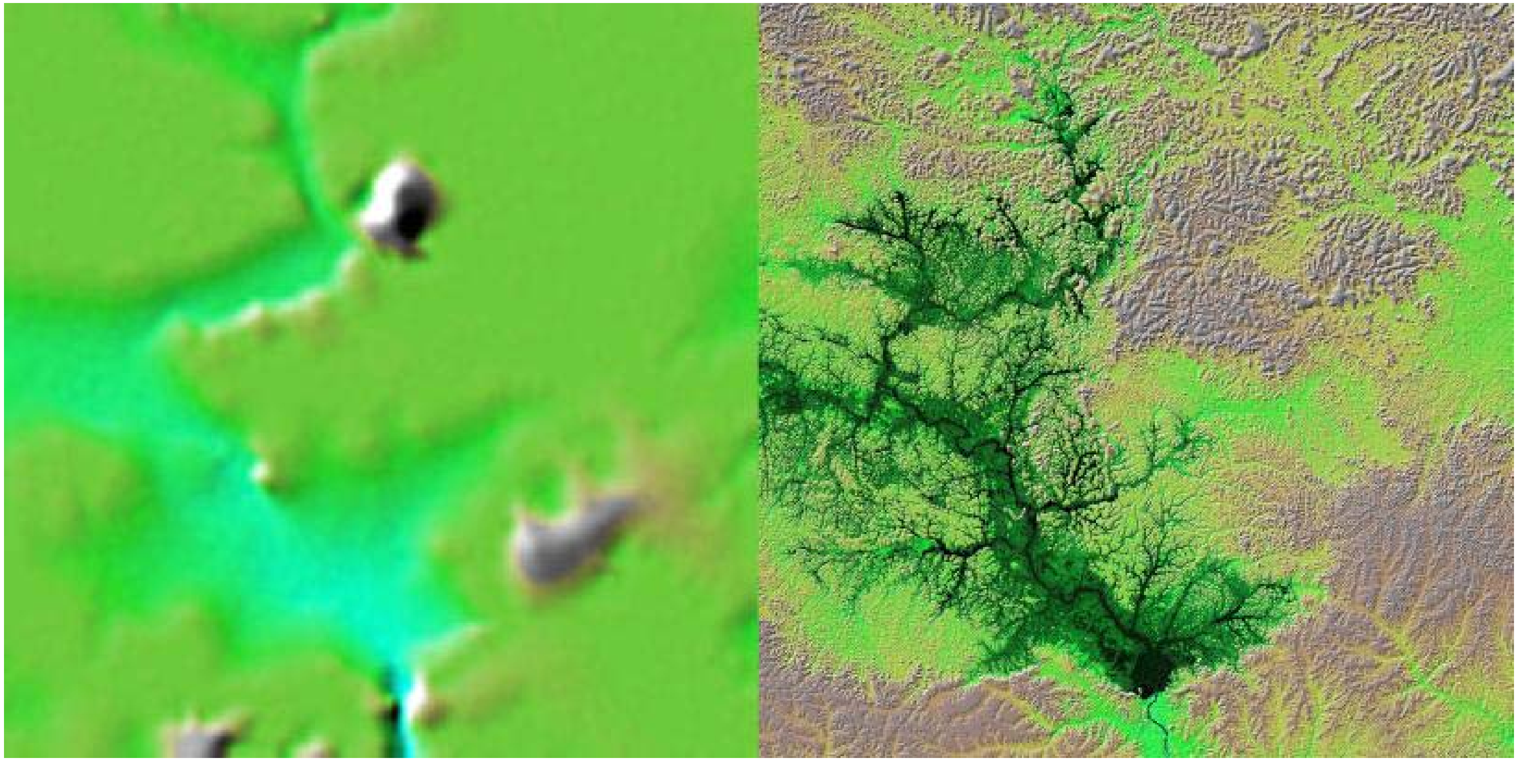


*** "Continent" defined by processing convention, not geography.**

DESCANSO

SRTM Look at Central America

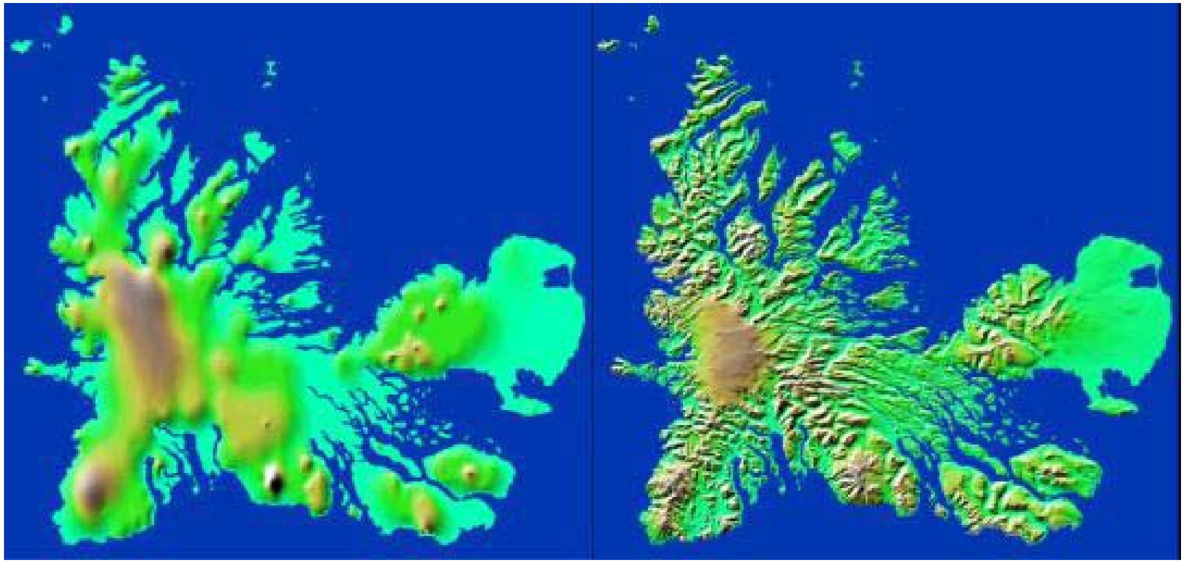
SRTM Resolution Improvement



GTOPO30 DEM SRTM DEM with radar image overlay

Lake Balbina, Brazil

SRTM Resolution Improvement

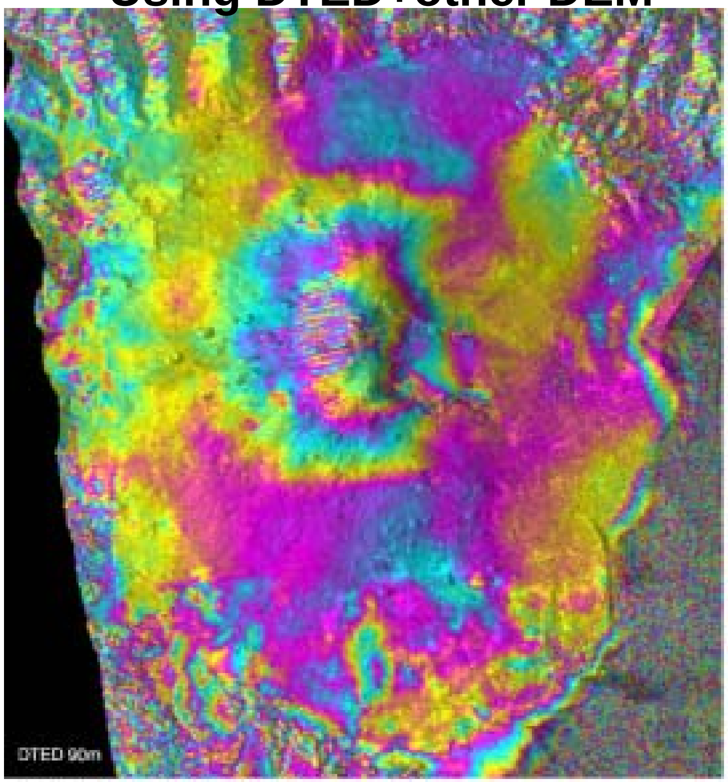


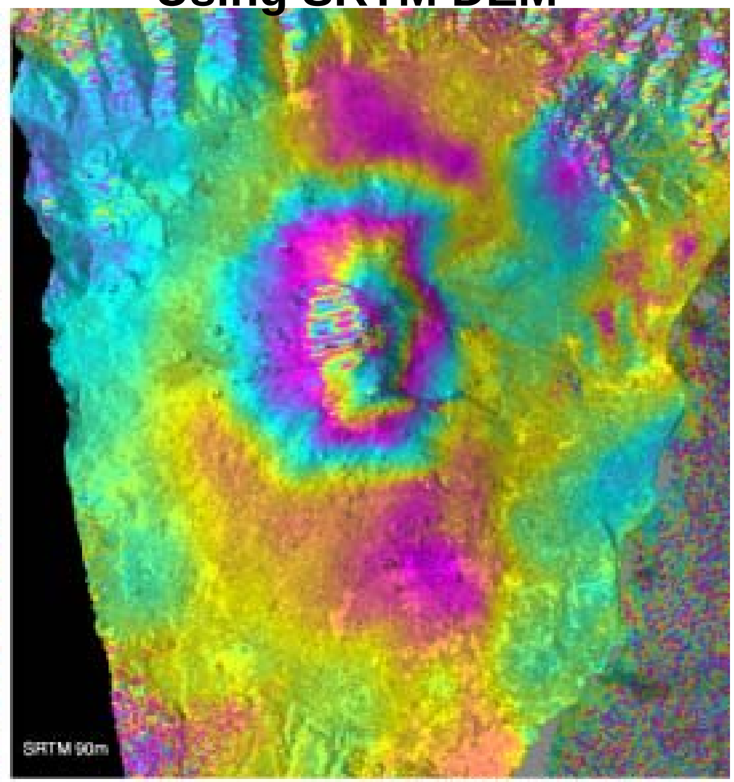
GTOPO30 DEM SRTM DEM

Kerguelen Island

Example of SRTM DEM Improvement
Differential Interferometry

Using DTED+other DEM **Using SRTM DEM**



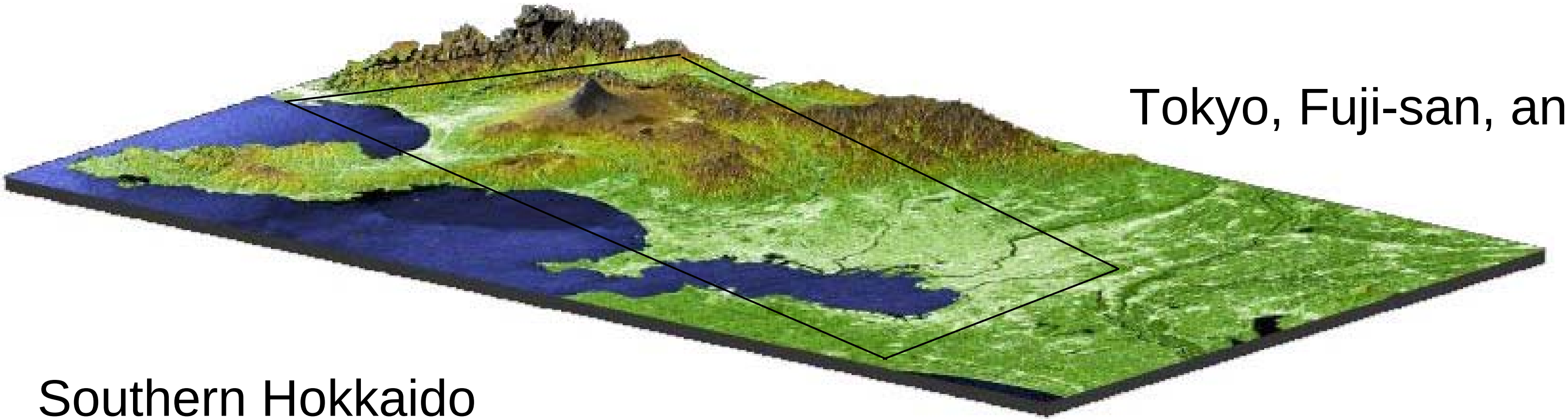


2000/10/04 - 2000/11/08 ERS Mt. Etna B_perp = 152m

ERS data courtesy ESA. P. Lundgren, JPL

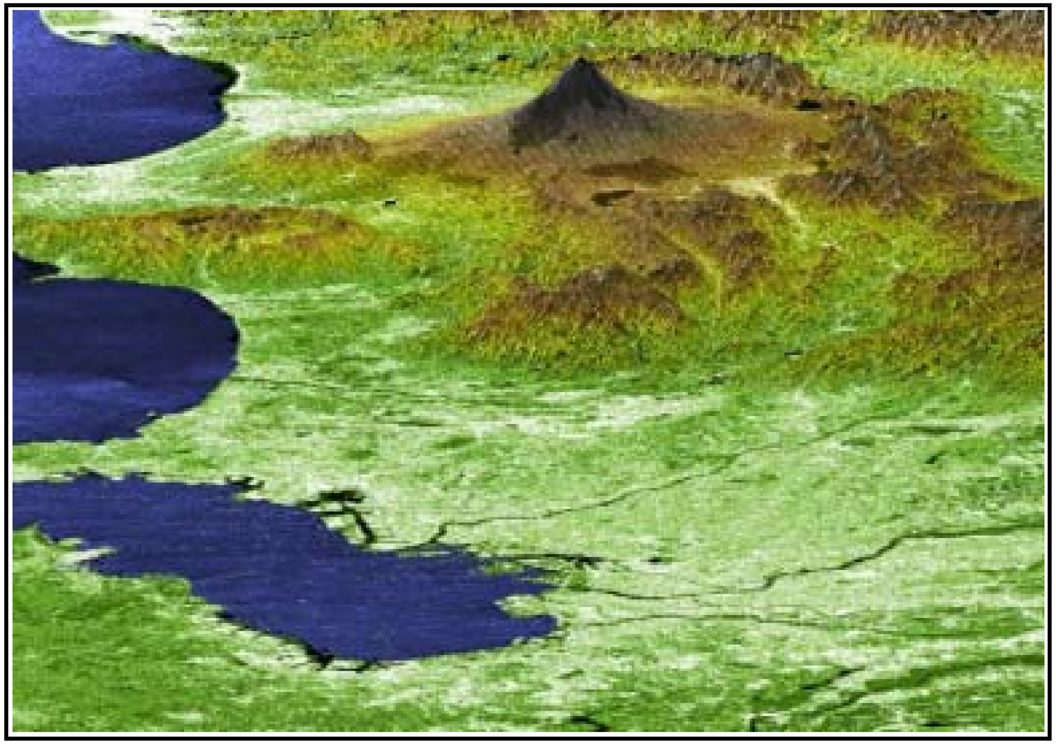
Mount Etna inflation signature cleaned up considerably by using SRTM data to remove topographic signature.

SRTM Views Japan

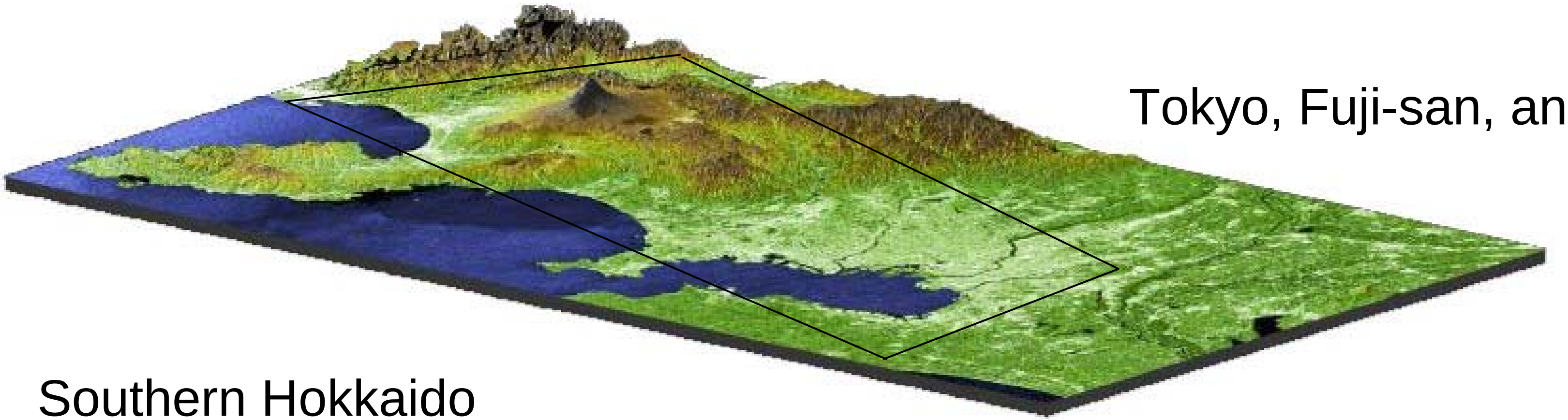


Tokyo, Fuji-san, and Izu

Southern Hokkaido



SRTM Views Japan



Tokyo, Fuji-san, and Izu

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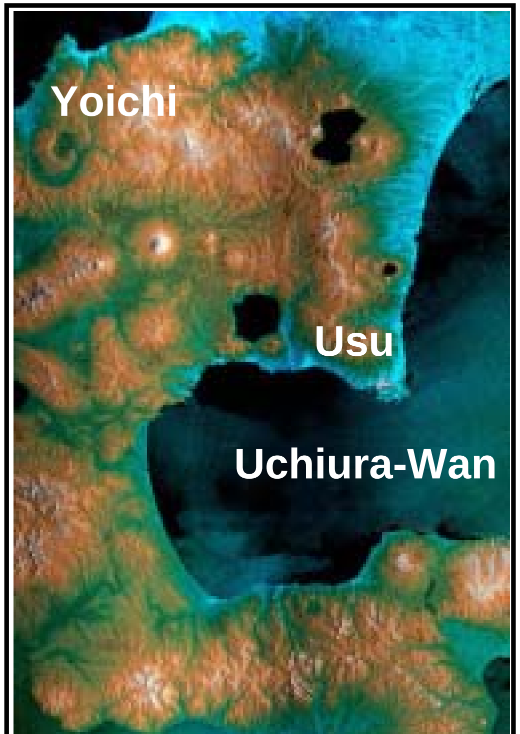
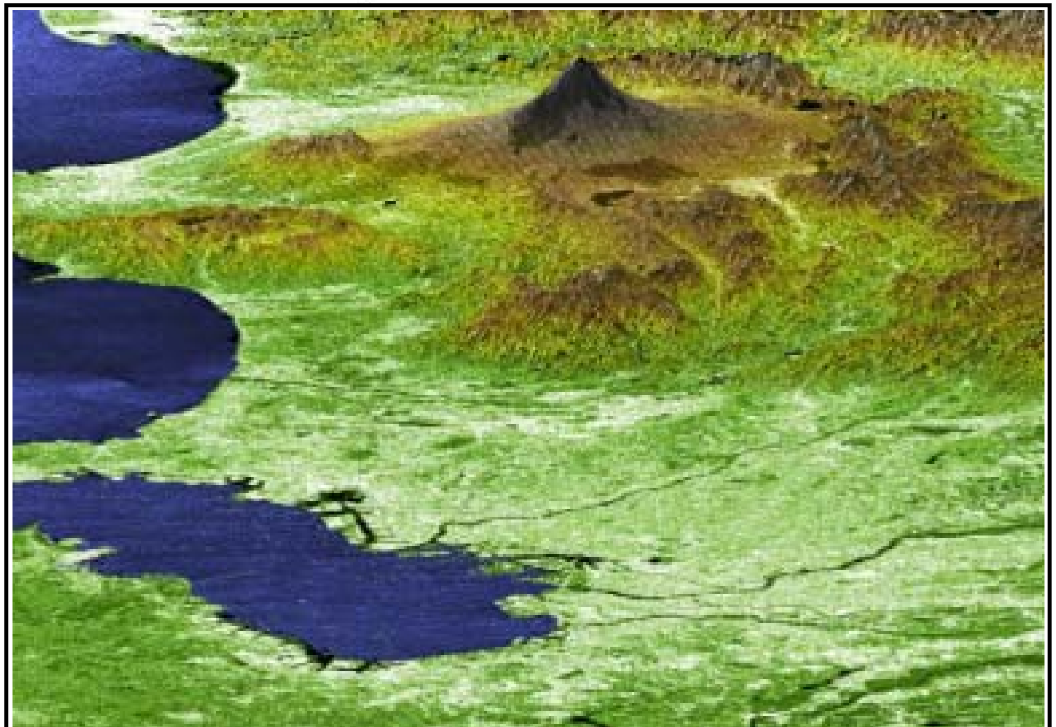
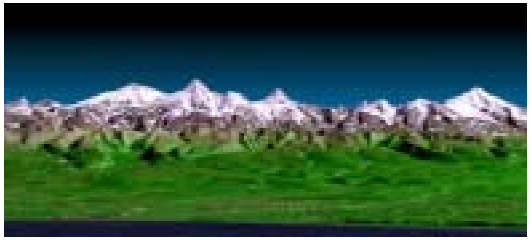
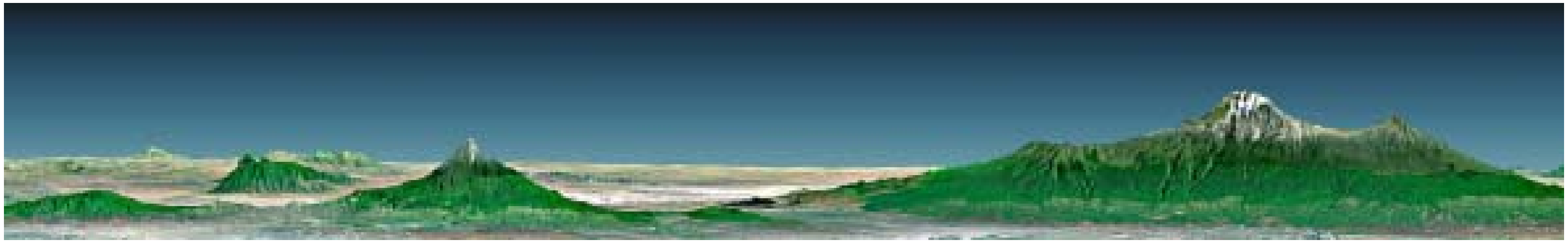




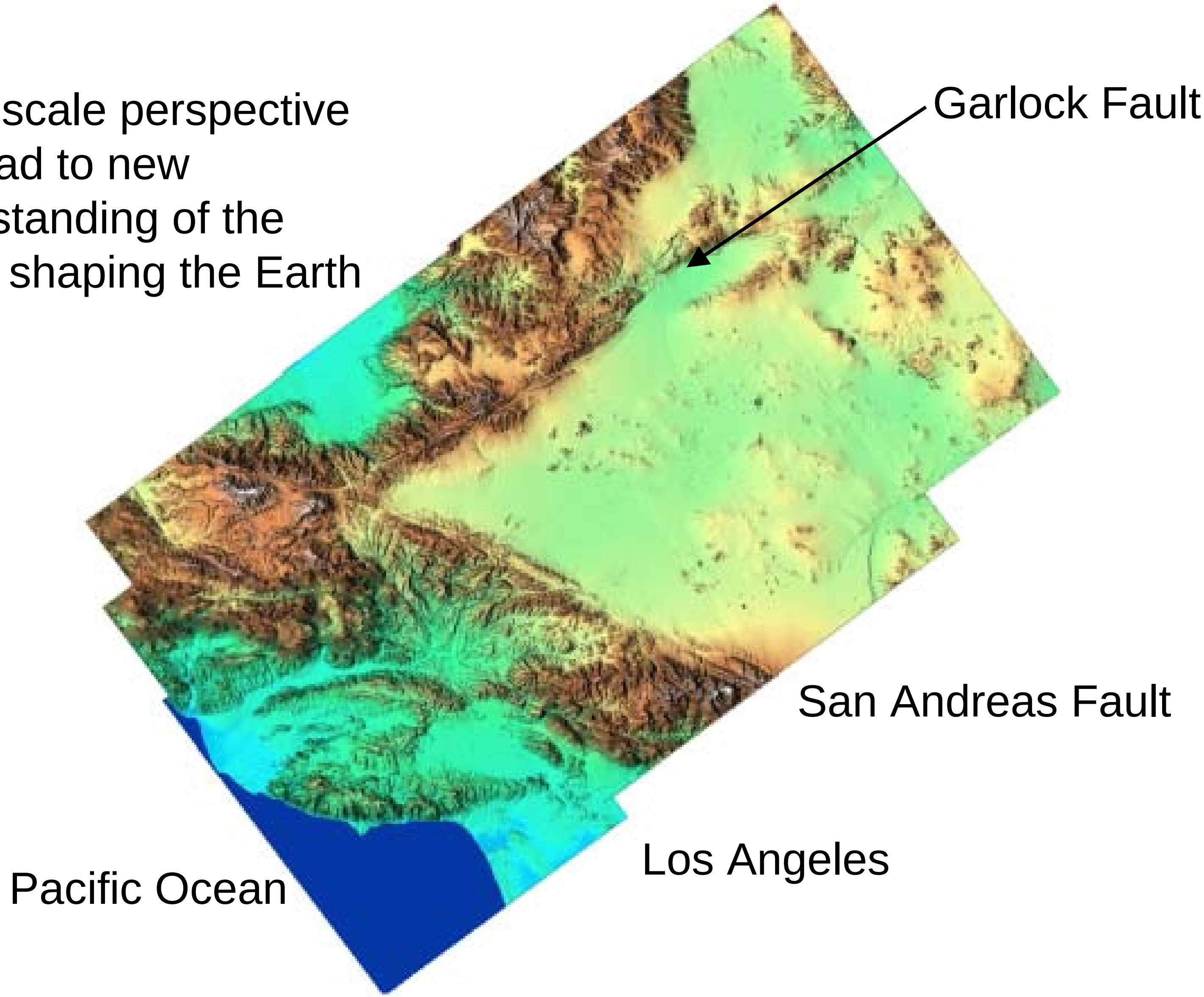
SRTM Views Global Landscapes



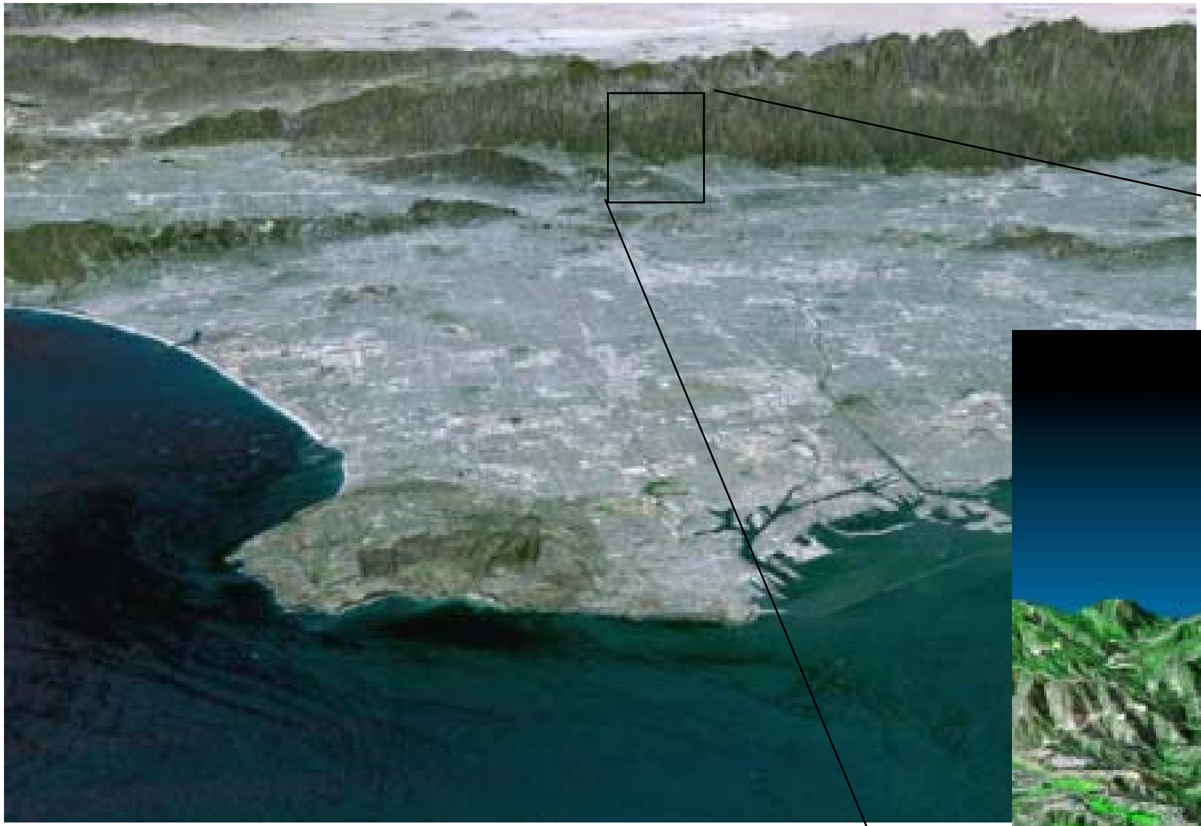


SRTM Views California

Large scale perspective can lead to new understanding of the forces shaping the Earth

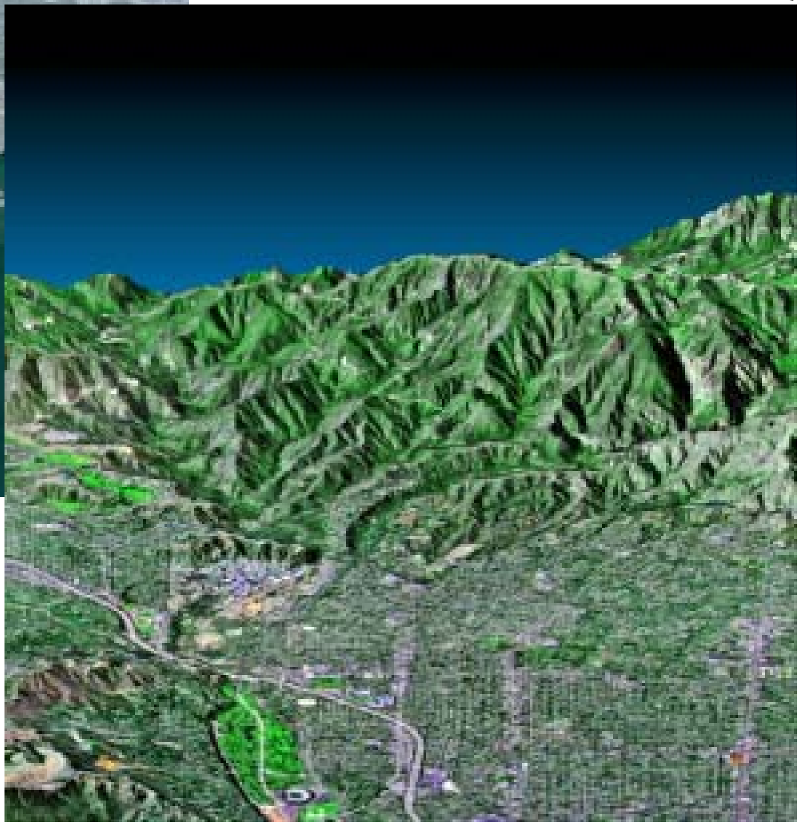


SRTM views Los Angeles



Landsat 5 overlay of SRTM Topography

Scenic JPL and Pasadena



Landsat/Aerial Photo overlay

GeoWall Presentation