# From Bursts to Back-Projection: Signal Processing Techniques for Earth and Planetary Observing Radars


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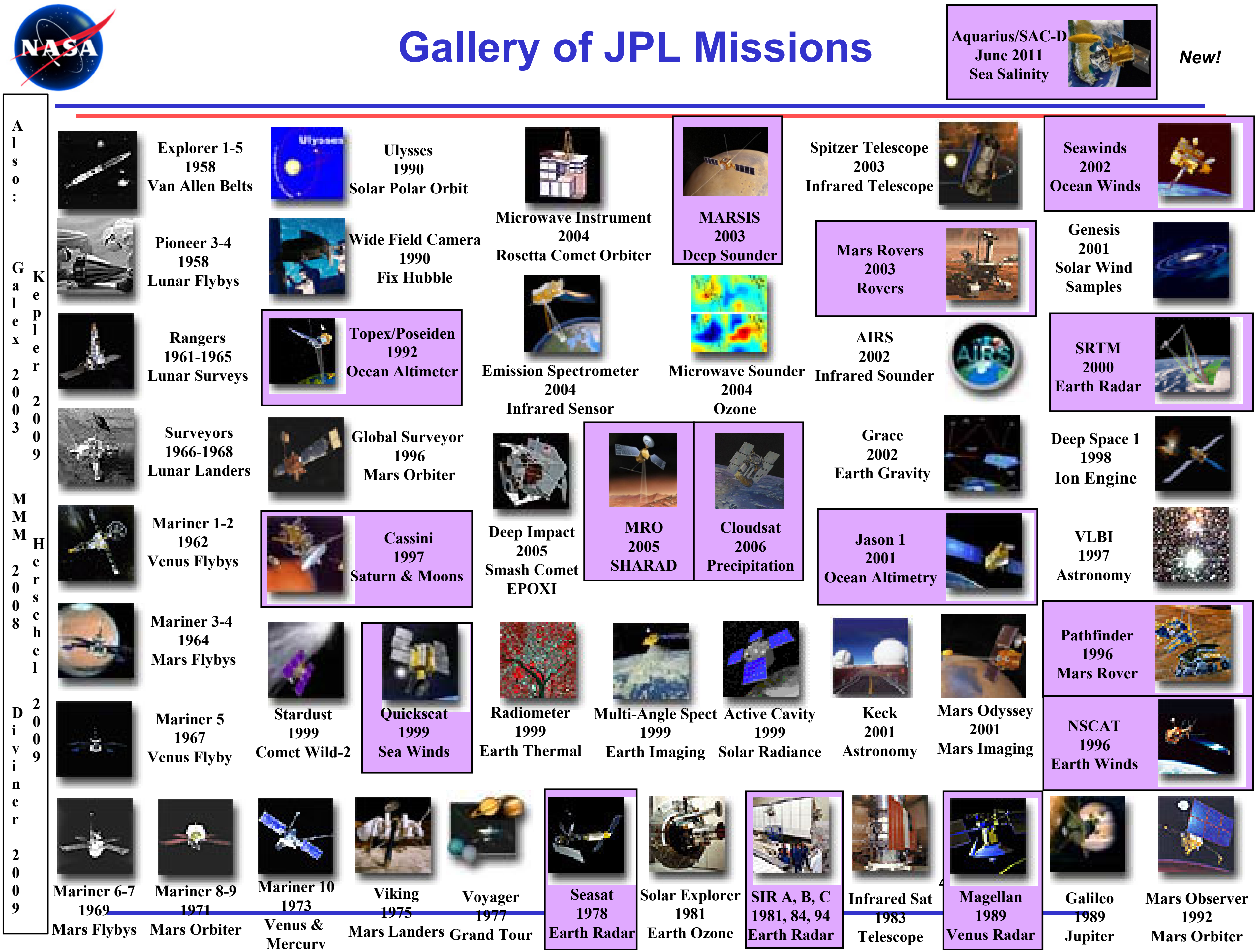
June 21, 2011

# Acknowledgment of Contributed Material

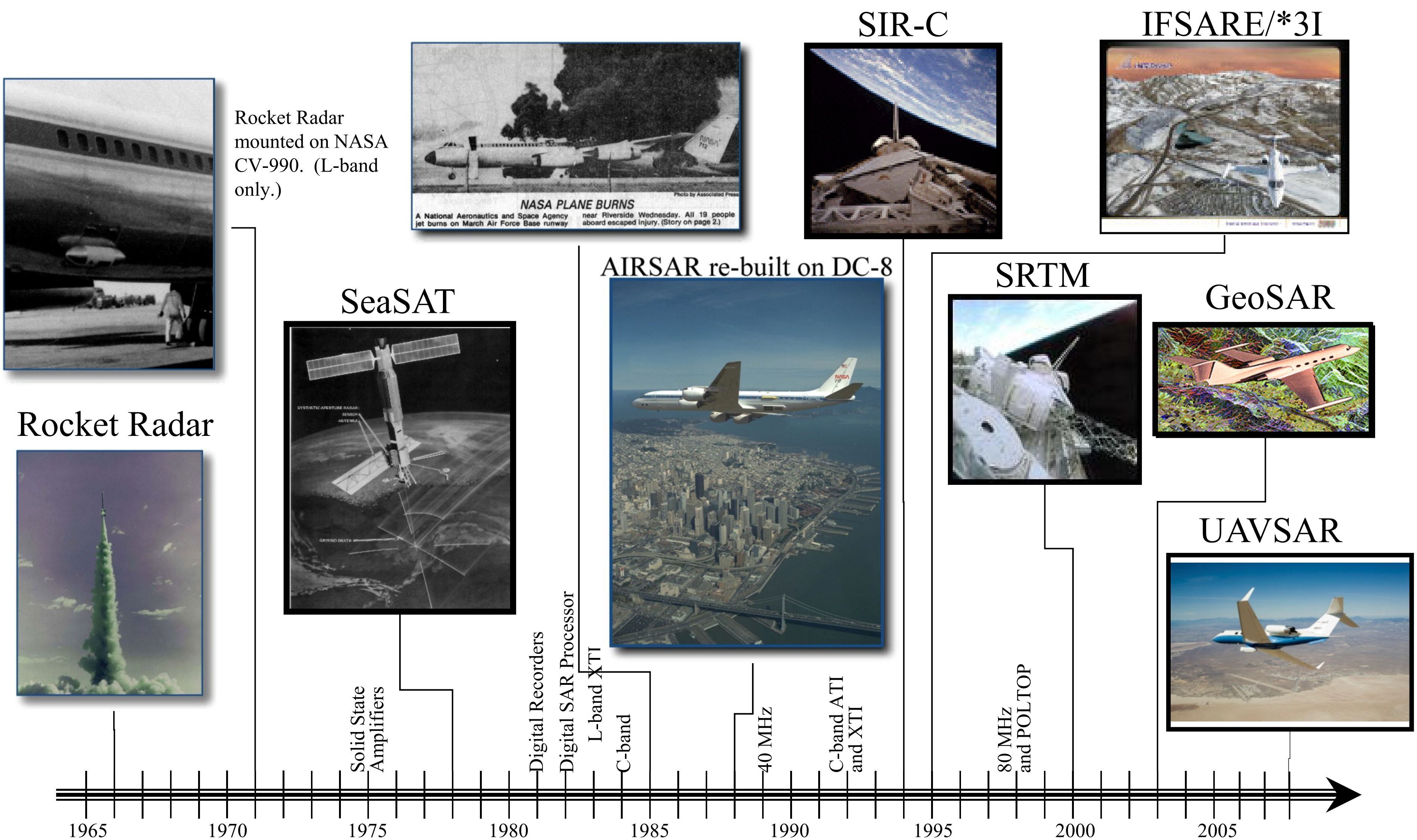

- The results presented herein are the work of many people over the years at Jet Propulsion Laboratory
- Material for this presentation were authored by by
  - Scott Hensley, Thierry Michel (UAVSAR focusing)
  - Charles Le, Duane Clark, Ron Muellerschoen (UAVSAR OBP)
  - Michael Spencer (SMAP focusing, RFI mitigation)
  - Charles Le, Duane Clark (SMAP OBP)
  - Bryan Stiles et al. (Cassini processing)
  - Greg Sadowy, Hirad Ghaemi (SweepSAR DBF)

# Outline

- JPL Radar Overview and Historical Perspective
- Signal Processing Needs in Earth and Planetary Radars
- Examples of Current Systems and techniques
- Future Perspectives in signal processing for radar missions


Gallery of JPL Missions
Aquarius/SAC-D
June 2011
Sea Salinity
New!
Also:
Galex 2003
Kepler 2009
MMM 2008
Herschel 2009
Diviner 2009
Explorer 1-5
1958
Van Allen Belts
Ulysses
Ulysses
1990
Solar Polar Orbit
Microwave Instrument
2004
Rosetta Comet Orbiter
MARSIS
2003
Deep Sounder
Spitzer Telescope
2003
Infrared Telescope
Seawinds
2002
Ocean Winds
Pioneer 3-4
1958
Lunar Flybys
Wide Field Camera
1990
Fix Hubble
Mars Rovers
2003
Rovers
Genesis
2001
Solar Wind
Samples
Rangers
1961-1965
Lunar Surveys
Topex/Poseiden
1992
Ocean Altimeter
Emission Spectrometer
2004
Infrared Sensor
Microwave Sounder
2004
Ozone
AIRS
2002
Infrared Sounder
AIRS
SRTM
2000
Earth Radar
Surveyors
1966-1968
Lunar Landers
Global Surveyor
1996
Mars Orbiter
Deep Impact
2005
Smash Comet
EPOXI
MRO
2005
SHARAD
Cloudsat
2006
Precipitation
Grace
2002
Earth Gravity
Deep Space 1
1998
Ion Engine
Mariner 1-2
1962
Venus Flybys
Cassini
1997
Saturn & Moons
Jason 1
2001
Ocean Altimetry
VLBI
1997
Astronomy
Mariner 3-4
1964
Mars Flybys
Pathfinder
1996
Mars Rover
Mariner 5
1967
Venus Flyby
Stardust
1999
Comet Wild-2
Quickscat
1999
Sea Winds
Radiometer
1999
Earth Thermal
Multi-Angle Spect
1999
Earth Imaging
Active Cavity
1999
Solar Radiance
Keck
2001
Astronomy
Mars Odyssey
2001
Mars Imaging
NSCAT
1996
Earth Winds
Mariner 6-7
1969
Mars Flybys
Mariner 8-9
1971
Mars Orbiter
Mariner 10
1973
Venus &
Mercury
Viking
1975
Mars Landers
Voyager
1977
Grand Tour
Seasat
1978
Earth Radar
Solar Explorer
1981
Earth Ozone
SIR A, B, C
1981, 84, 94
Earth Radar
Infrared Sat
1983
Telescope
Magellan
1989
Venus Radar
Galileo
1989
Jupiter
Mars Observer
1992
Mars Orbiter

# JPL Coupled Airborne and Spaceborne Radar Programs



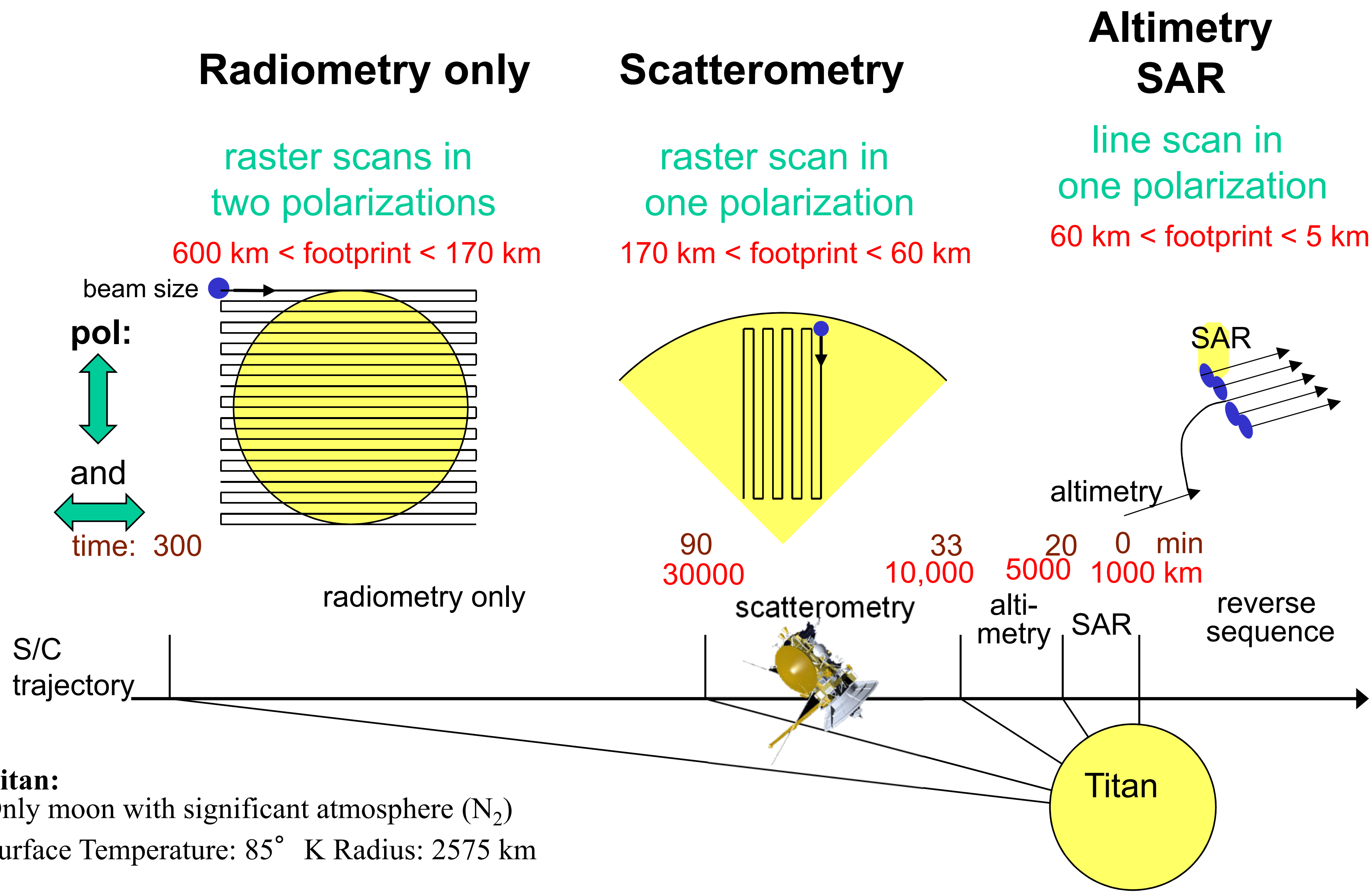
# SAR Signal Processing Taxonomy

| | Level 1<br>Radar Processing | Level 2<br>Interferometry<br>Polarimetry | Level 3<br>Geophysical<br>Products | Level 4<br>Science<br>Products |
|---|---|---|---|---|
| Algorithms | • Range-Doppler<br>• Omega-K<br>• Back-projection<br>• Motion Compensation | • Co-registration<br>• Multi-looking<br>• Correlation & Phase Estimation<br>• Smoothing | • Geocoding<br>• Calibration<br>• Noise removal<br>• Geophysical model functions | • Time-series<br>• Geophysical model functions<br>• Mosaicking |
| Signal Processing | • Interpolation<br>• Matched Filtering<br>• Fourier Transforms<br>• Chirp-Scaling<br>• Statistical minimization methods | • Interpolation<br>• Convolution<br>• Statistical minimization methods<br>• Phase Unwrapping | • Interpolation | • Interpolation<br>• Statistical minimization methods |

# Algorithmic Classes

- Signal processing algorithms have to be tailored to meet mission and implementation constraints. Implementation varies from:
  – General purpose computers including multi-processor systems running parallelized algorithms
  – FPGA to DPS systems employing fixed point arithmetic versions of algorithms
- Metrics used to assess signal processing performance also vary with application.
  – For spaceborne implementations FLOPS/Watt and FLOPS/Kg along with memory constraints on rad hard parts often driving requirements that necessitate performance compromises.
  – Ground based processing often emphasizes high fidelity maximal performance subject to reasonable throughput constraints.
- JPL algorithm development is predicated on specific science applications and mission environments
  – Examples of both types of processing are illustrated in this talk.

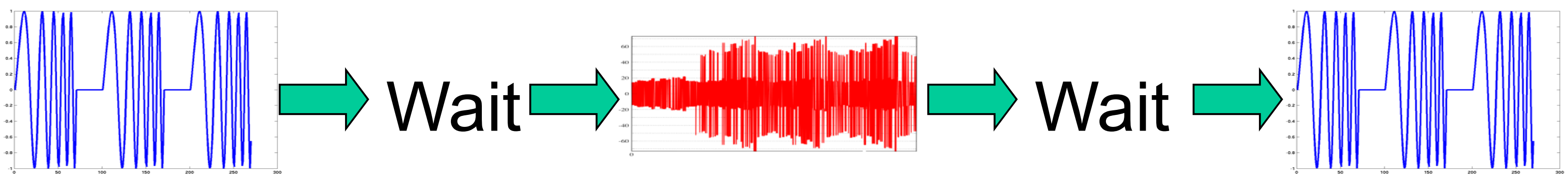
# Overview of Cassini Radar Titan Flyby




**Titan:**
Only moon with significant atmosphere ($N_2$)
Surface Temperature: 85° K Radius: 2575 km

# Cassini SAR Characteristics

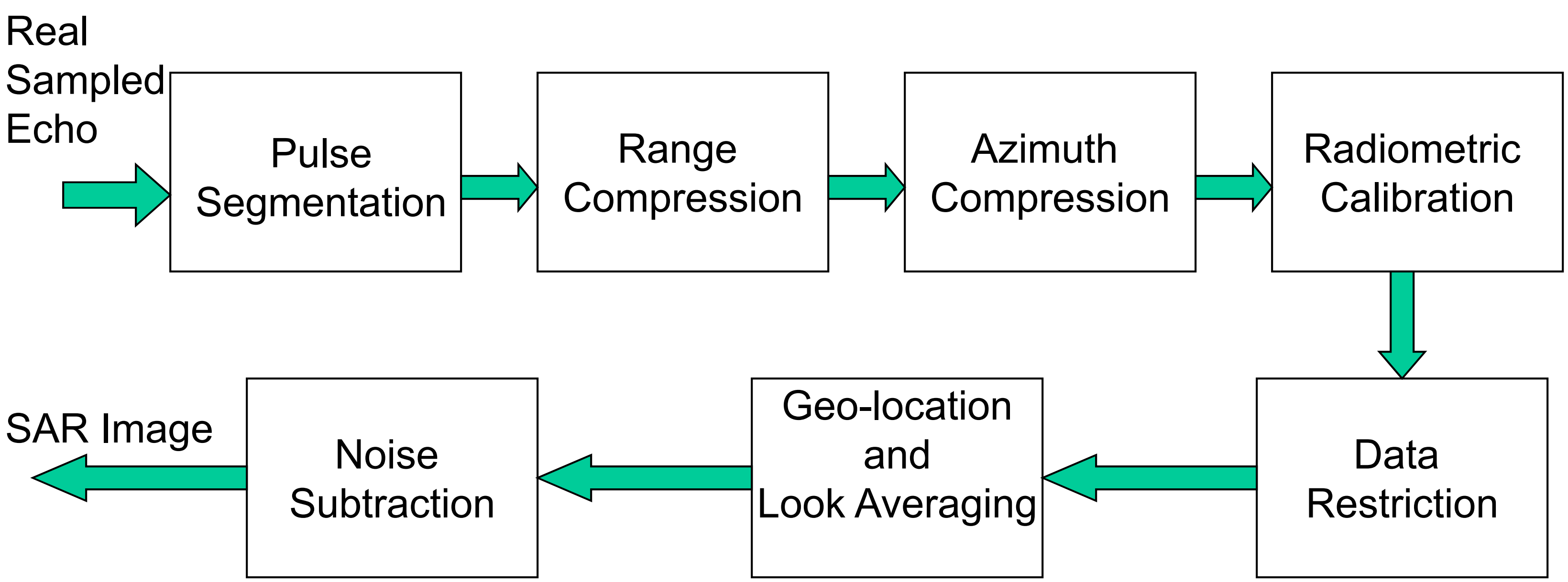
- Burst Mode SAR (7% burst duty cycle)




Transmit pulse train Receive Echo Repeat

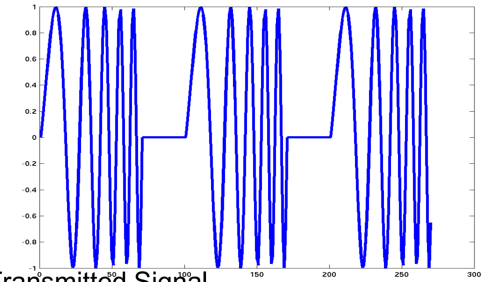
  - Multiple bursts cannot be processed coherently due to large grating lobes.
- Data is compressed using 8 to 2 bit BAQ compression.
- Highly variable viewing geometry
  - Resolution varies from 300 m to 2 km along swath.
  - Noise Floor varies from -30 dB to -6 dB.
  - Number of looks varies from 3 to 20.

# SAR Processing Block Diagram

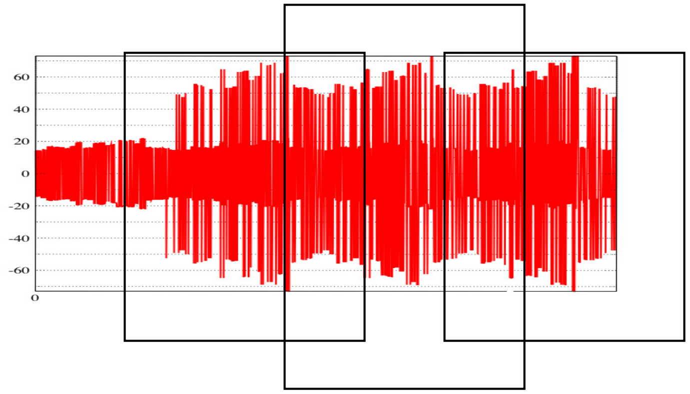


# Pulse Segmentation

- Real-Valued samples of video offset data
- Segmented into constant duration *overlapping* temporal windows
  - Separately range compress each returning pulse.
  - Preserve energy returned simultaneously from consecutive pulses.



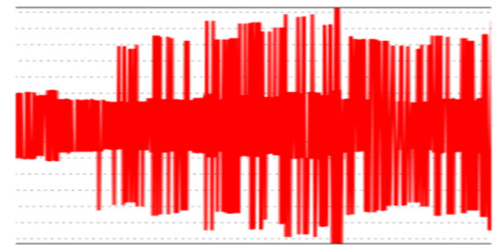
Transmitted Signal



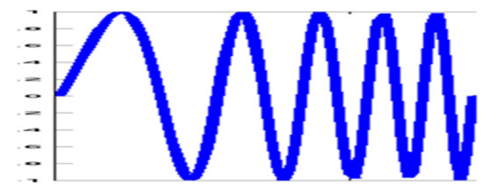
Returned echo with overlapping pulse segmentation

# Range Compression

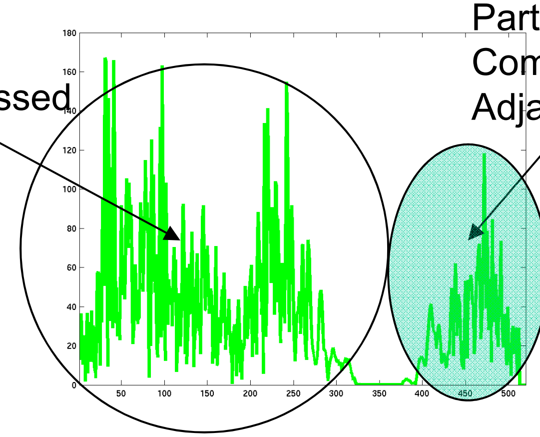
- Each segment convolved with *matched filter*
  - Estimate of Doppler shifted, base-banded echo from point target at boresight.
  - DC bin zeroed out.
- Output = amplitude M and phase $\Phi$ as a function of range r and pulse number.



convolved with

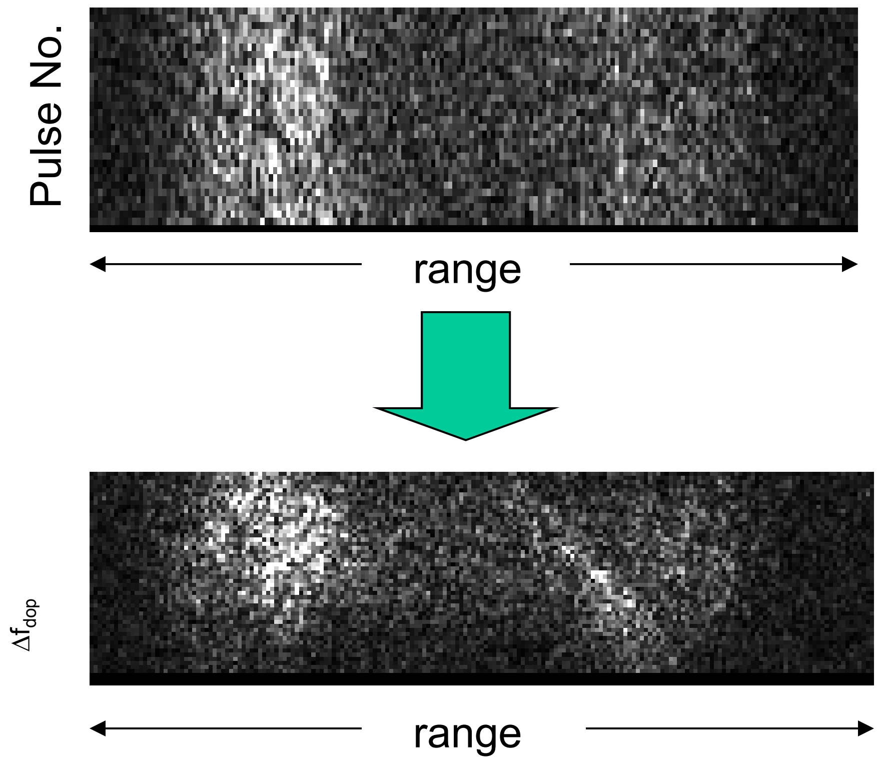


yields



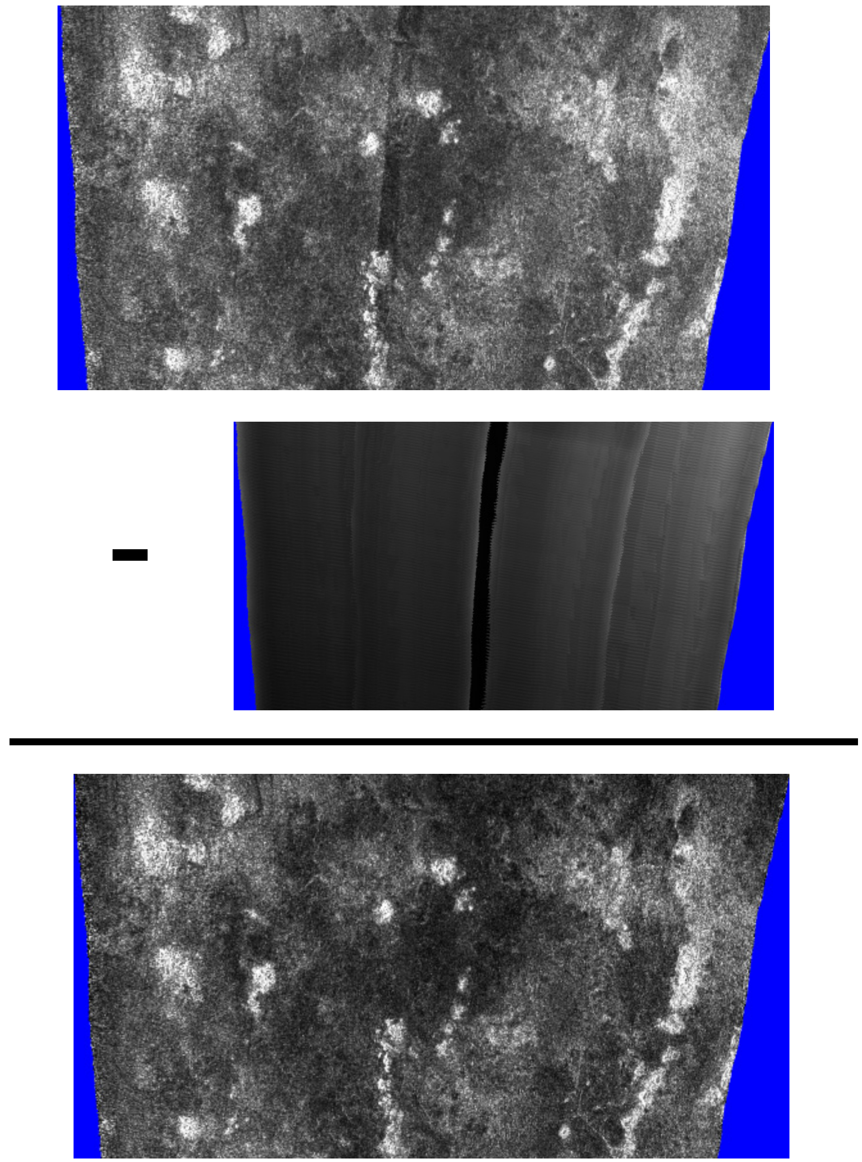
# Azimuth Compression

- Input: Each range bin sampled once per pulse
- Convolved with azimuth matched filter
  - Linear FM chirp
  - Center frequency is Doppler centroid as a function of range
  - Chirp rate is derivative of Doppler with time
- Output is $M(r,\Delta f_{dop})$ and $\Phi(r,\Delta f_{dop})$



# Noise Subtraction

- Noise subtraction performed because:
  - High altitude SAR can have SNR less than 0 dB for radar dark regions
- Simulated noise only data passed through entire SAR processor to estimate noise energy image.
  - Gaussian noise
  - Variance computed from receive only calibration
- Noise image is subtracted from standard image

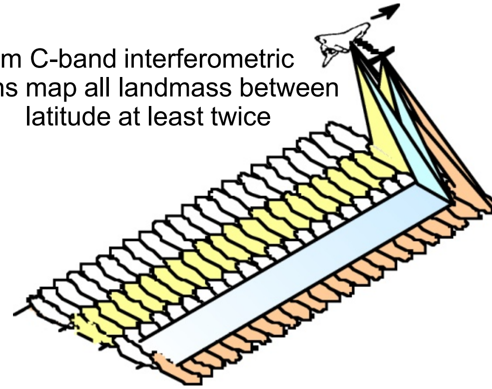


# SRTM Mission Overview

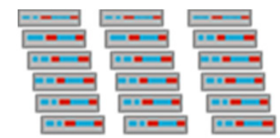
Launch

Feb 11, 2000 - STS99

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

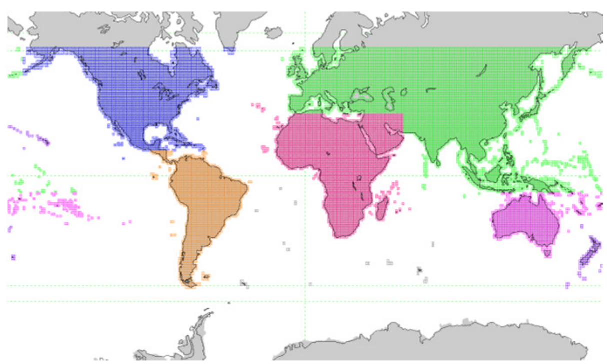


12 Tbytes data recorded on-board on 330 tape cassettes



Data returned with Shuttle to Ground Data Processing Facility

Three year processing

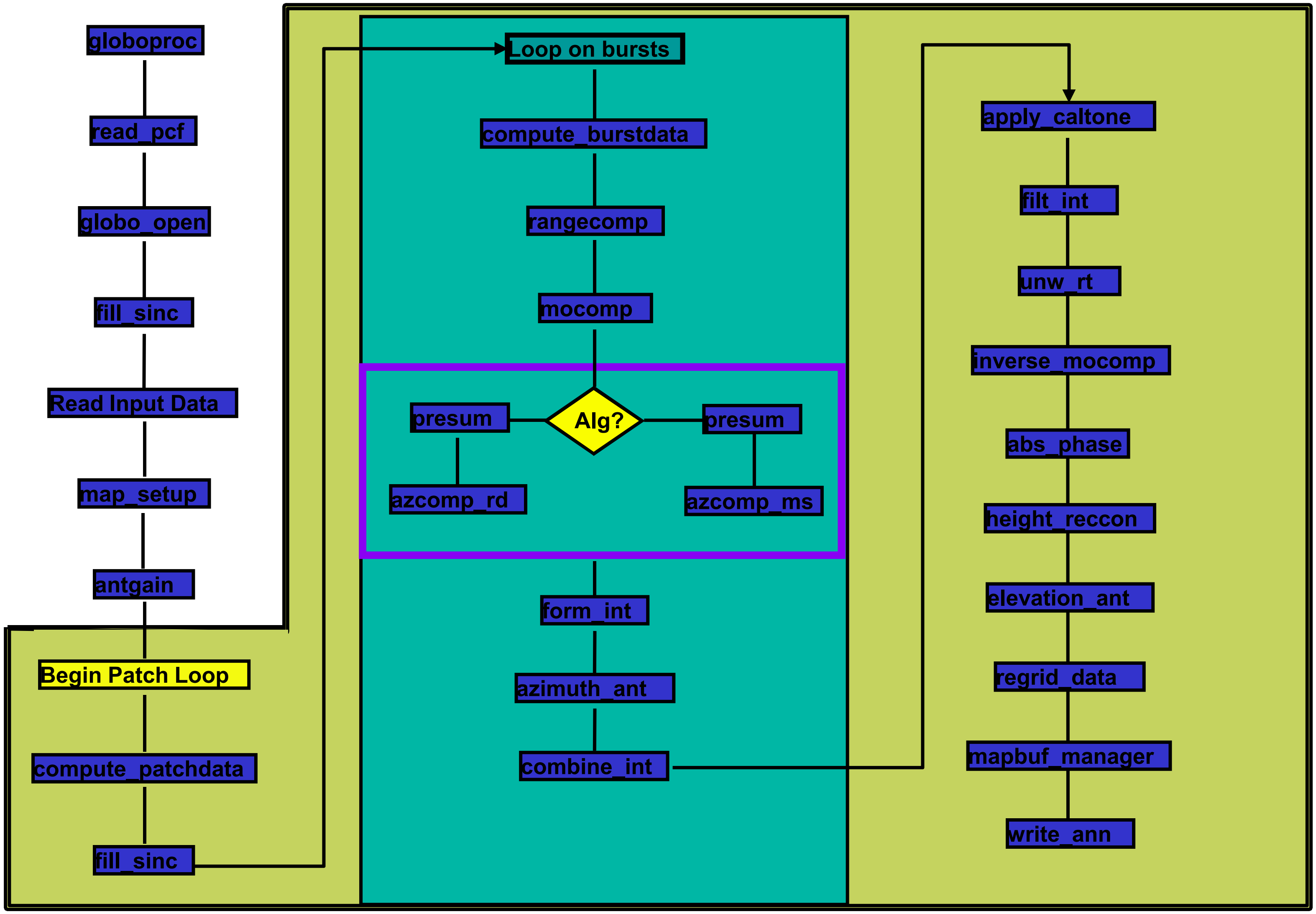


Digital elevation data delivered in 1° x1° mosaiced cells

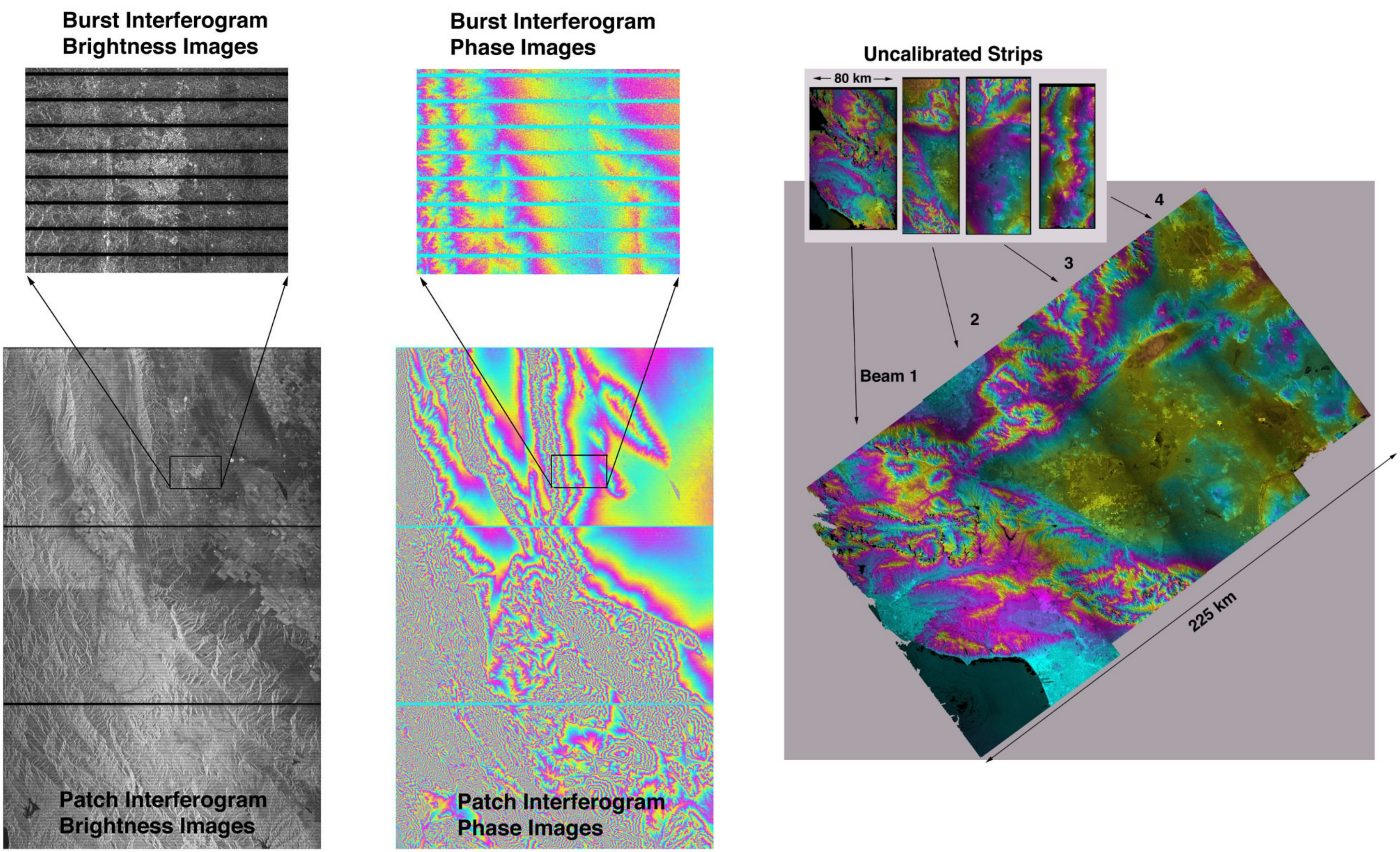
NIMA data validation, editing and distribution to military users

EDC for public distribution

# Topographic Processing System



# SRTM Patch Processing Example



# Curved ωk Processing

Thierry Michel and Scott Hensley

- Standard ωk processing algorithms require that the reference trajectory be a straight line.
- For long synthetic airborne or spaceborne apertures, a more natural reference trajectory is a curved path at a constant altitude above a curved Earth (or other planetary body).
- We have extended the standard ωk to work with curved trajectories and high squint and achieve diffraction limited focusing.
- Key algorithmic features:
  - Provide optimal batch focusing using stationary phase (SP) principle.
  - Range times frequency factorization of the SP phase in ωk domain.
  - For typical curved apertures produces Stolt map with minimal error.

# Image Formation Fundamentals

## Image

$$S(x,r) = \int dy \int dk_\omega \ \bar{D}(y,k_\omega) e^{ik_\omega \rho(x,y;r)}$$

For efficient image formation
want to express as a Fourier Transform
with phase function separable in range

$$\bar{S}(k_x,r) = \int dk_\omega \bar{\bar{D}}(k_x,k_\omega) e^{ik_\omega R(r) Q(\mu)}$$

Use stationary phase to evaluate integral
Analytic Expression Still
NOT generally separable

$$\bar{S}(k_x,r) \overset{SP}{=} \int dk_\omega \bar{\bar{D}}(k_x,k_\omega) e^{ik_\omega \phi(k_x/k_\omega, r)}$$

For sufficiently nice functions of phase
history for which analytic functions are
available can use Taylor expansions
More Complicated expressions use SVD

$$\phi(q,r) \underset{a\to\infty}{\cong} r\left(\sqrt{1-q^2} + \frac{h}{2a}\frac{q^2}{\sqrt{1-q^2}} + \frac{h^2}{8a^2}\frac{q^2(q^2-2)}{(1-q^2)^{3/2}} + \frac{r_1^2}{24a^2}\frac{q^2(5q^2-6)}{(1-q^2)^{3/2}} + O\left(\frac{h^3}{a^3}\right)\right)$$

# Algorithm Overview

- The key idea in the method is the factorization of the stationary phase point into range times frequency factorization in ωk domain.

**Linear Phase History Curved Trajectory**

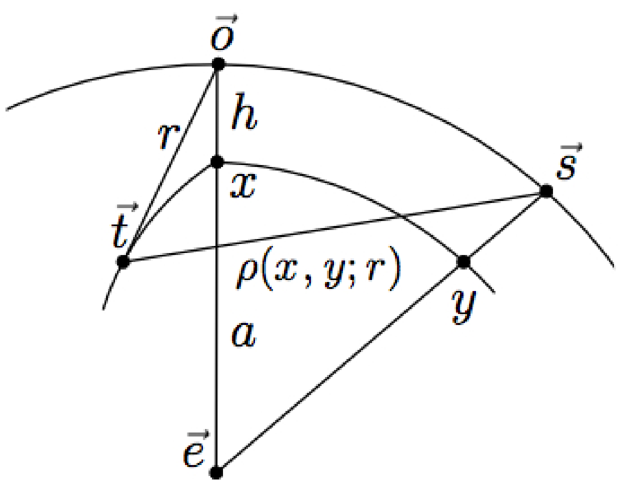
$$\rho(y-x,r) = \sqrt{r^2 + (y-x)^2}$$

**Range History Curved Trajectory**

$$\rho(y-x,r) = \sqrt{r^2 + 2\gamma(r)\sin^2(\frac{y-x}{2a})} \quad , \quad \gamma(r) = (h+a)^2 + a^2 - r^2$$

Separable $\Longleftrightarrow$ $\phi(r,\mu(k_x,k_w)) = \phi\left(r,\mu\left(\frac{k_x}{k_\omega}\right)\right) = R(r)Q(\mu)$

$$k_\omega = \sqrt{k_x^2 + k_r^2}$$




*RF Data: D(y,t) and RF Image: S(x,r)*

$$S(x,r) = \int dy \int dk_\omega \;\; \bar{D}(y,k_\omega)e^{ik_\omega \rho(x,y;r)}$$

$$\bar{S}(k_x,r) \stackrel{SP}{=} \int dk_\omega \bar{\bar{D}}(k_x,k_\omega)e^{ik_\omega \phi(k_x/k_\omega,r)}$$

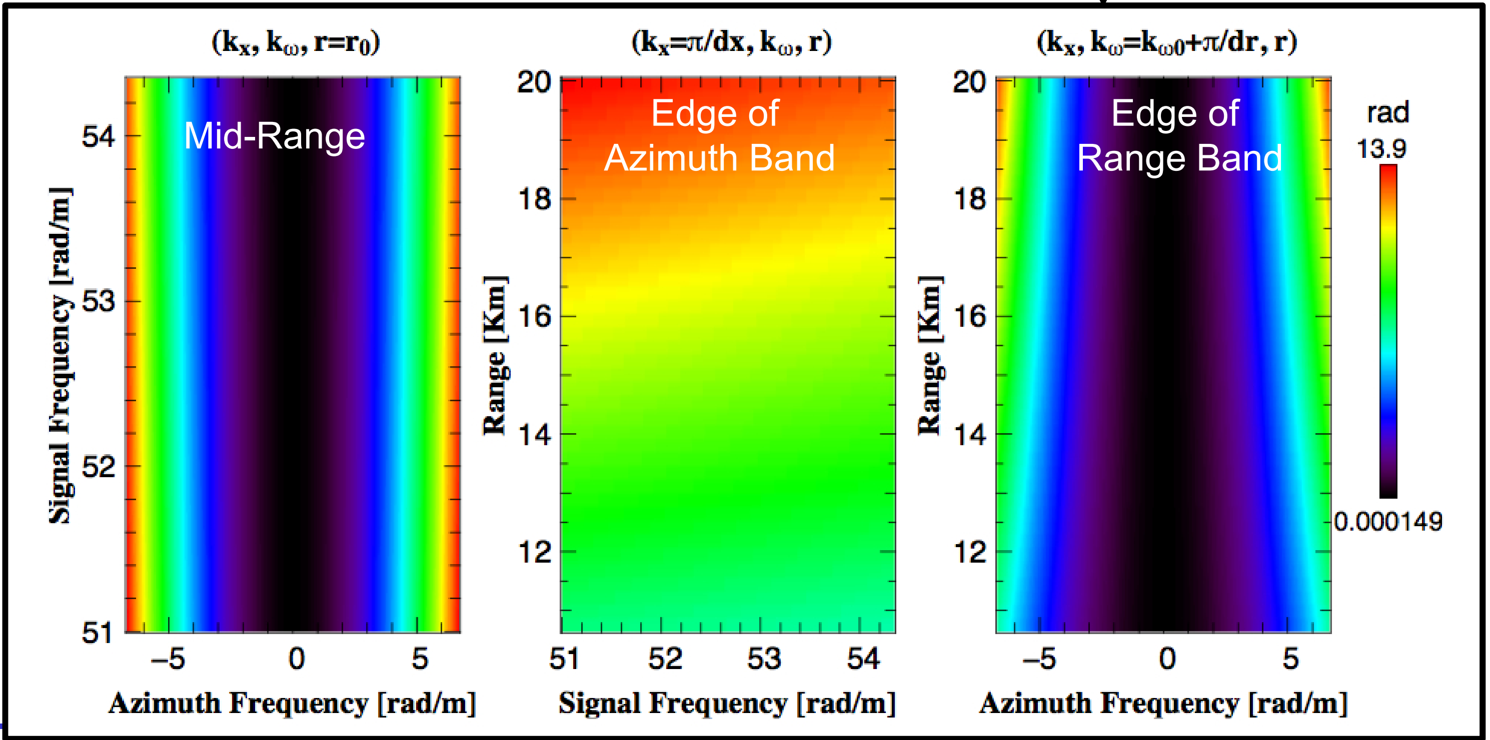
$$\phi(q,r) \cong Q(q)R(r)\,, \quad \text{factorization} \quad q = \frac{k_x}{k_\omega}$$

$$\bar{\bar{S}}(k_x,k_r) = \bar{\bar{D}}(k_x,k_\omega^\circ) \quad , \quad \text{Stolt}: \quad k_\omega^\circ(k_x,k_r)$$

# Curved Phase Approximation – Separable Terms

- Approximation to separable portion of phase history
  - This represents the difference of linear portion of the phase history compared to the curved trajectory.

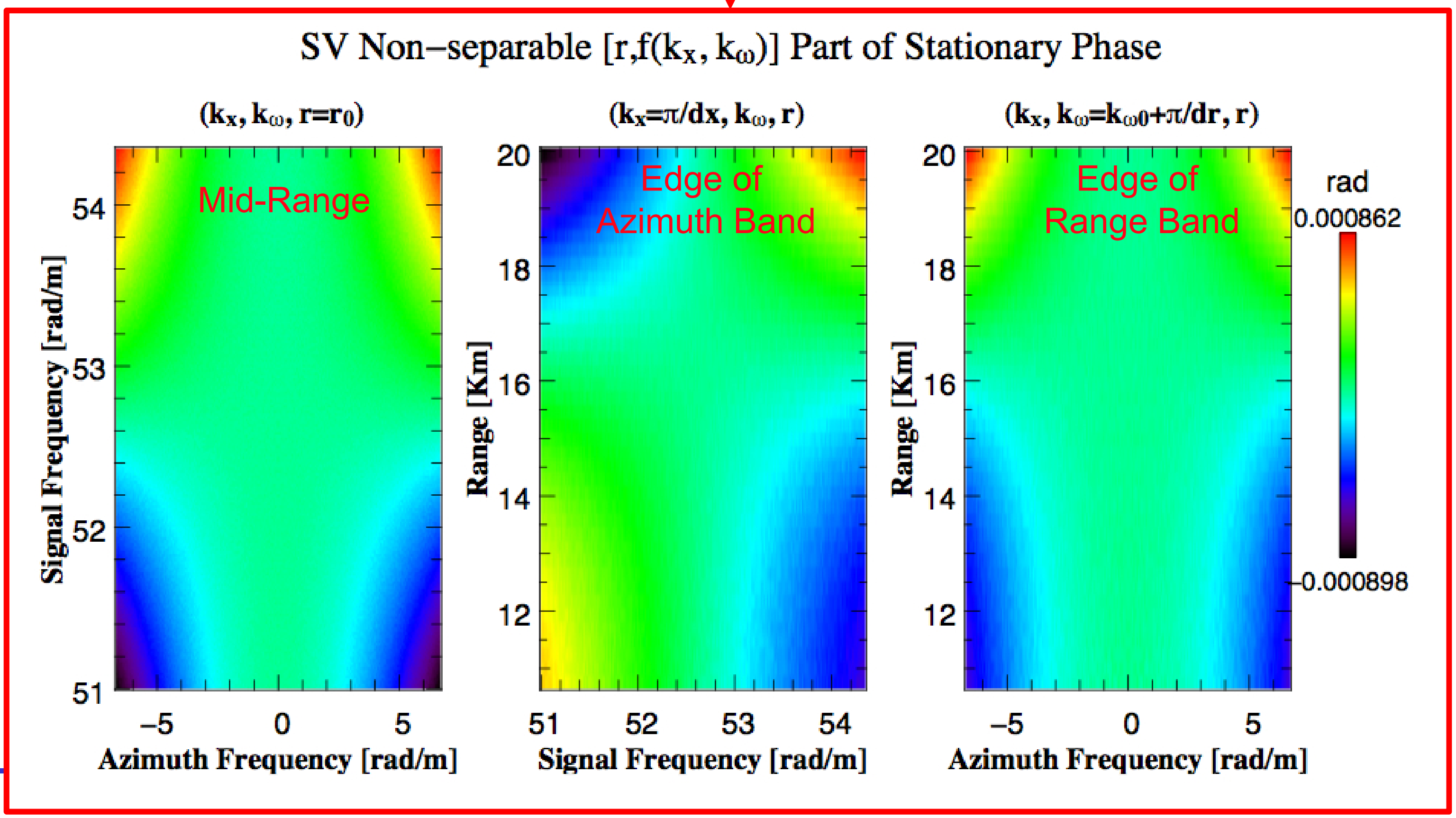
$$\phi(q,r) \underset{a\to\infty}{\cong} r\Big(\underbrace{\sqrt{1-q^2}}_{\text{Linear Trajectory Part}} + \underbrace{\frac{h}{2a}\frac{q^2}{\sqrt{1-q^2}} + \frac{h^2}{8a^2}\frac{q^2(q^2-2)}{(1-q^2)^{3/2}}}_{\text{Curved Trajectory Part}} + \frac{r_1^2}{24a^2}\frac{q^2(5q^2-6)}{(1-q^2)^{3/2}} + O\big(\frac{h^3}{a^3}\big)\Big)$$



# Stationary Phase Separability Residuals

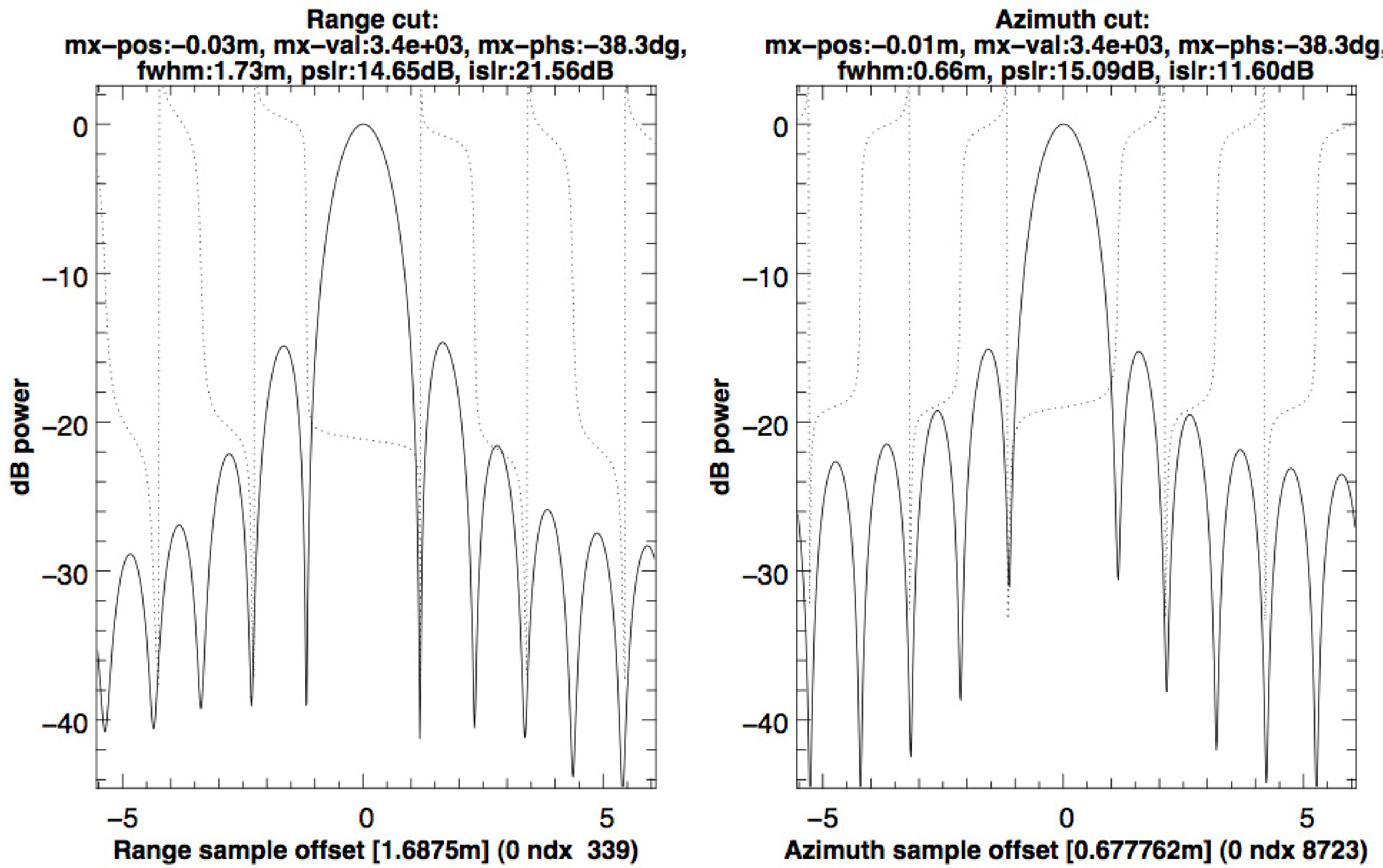
- Taylor expansion of stationary phase

$$\phi(q,r) \underset{a\to\infty}{\cong} r\left[\underbrace{\sqrt{1-q^2}+\frac{h}{2a}\frac{q^2}{\sqrt{1-q^2}}+\frac{h^2}{8a^2}\frac{q^2(q^2-2)}{(1-q^2)^{3/2}}}_{\text{Separable Part}}+\underbrace{\frac{r_1^2}{24a^2}\frac{q^2(5q^2-6)}{(1-q^2)^{3/2}}}_{\text{Non-separable Part}}+O(\frac{h^3}{a^3})\right]$$



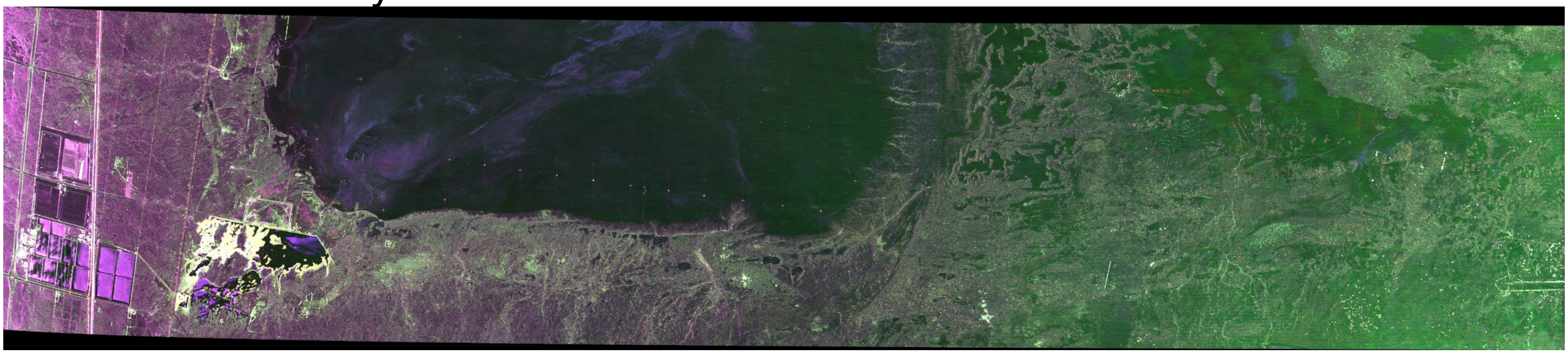
# Sample Results – Impulse Responses

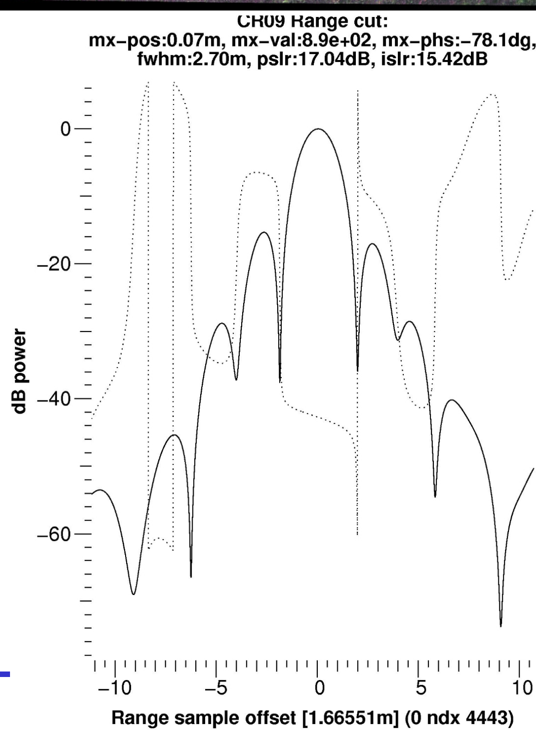
- L-band airborne example with typical UAVSAR radar parameters
  - Without curved trajectory algorithm to focusing would have 14 radians of quadratic phase error leading to severe defocusing

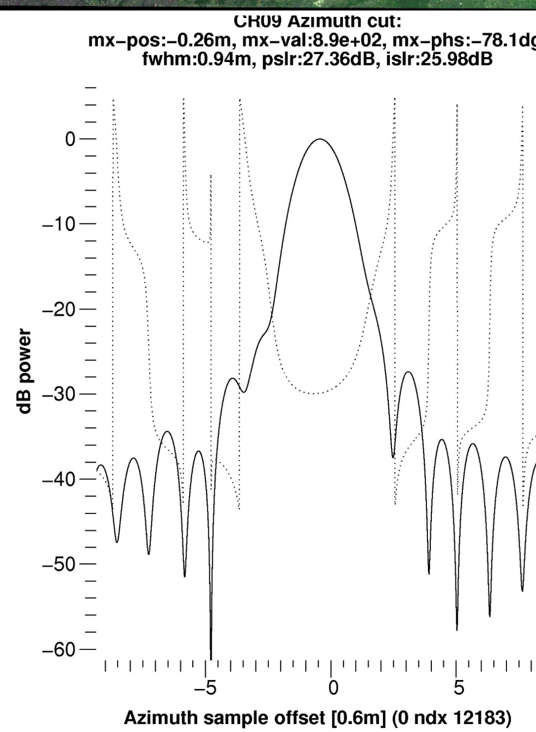


# Sample Imagery

- Measured impulse responses from Rosamond Lake Bed corner reflector array.



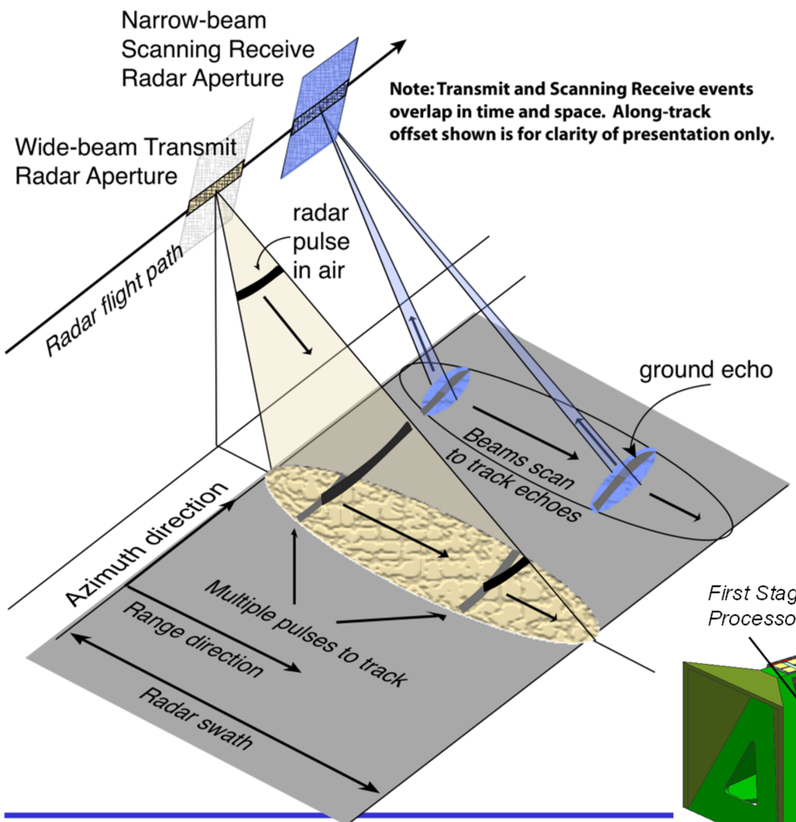


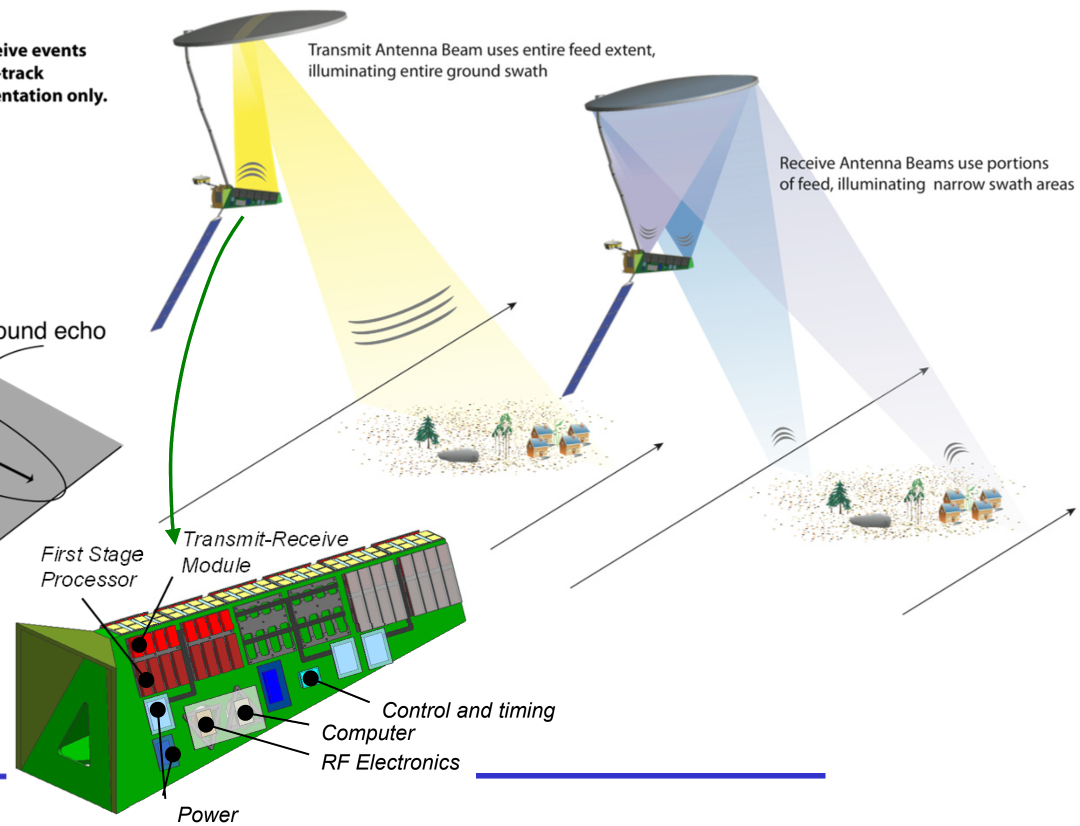



# SweepSAR – First-of-a-kind Scan-on-receive Radar using Array-Fed Reflector

- SweepSAR – Scan-on-Receive Radar
  - Transmit pulse over wide beam in elevation
  - Receive echo over narrow beam tracking echo with scanning receive beam
  - Can require multiple simultaneous receive beams to track multiple echoes

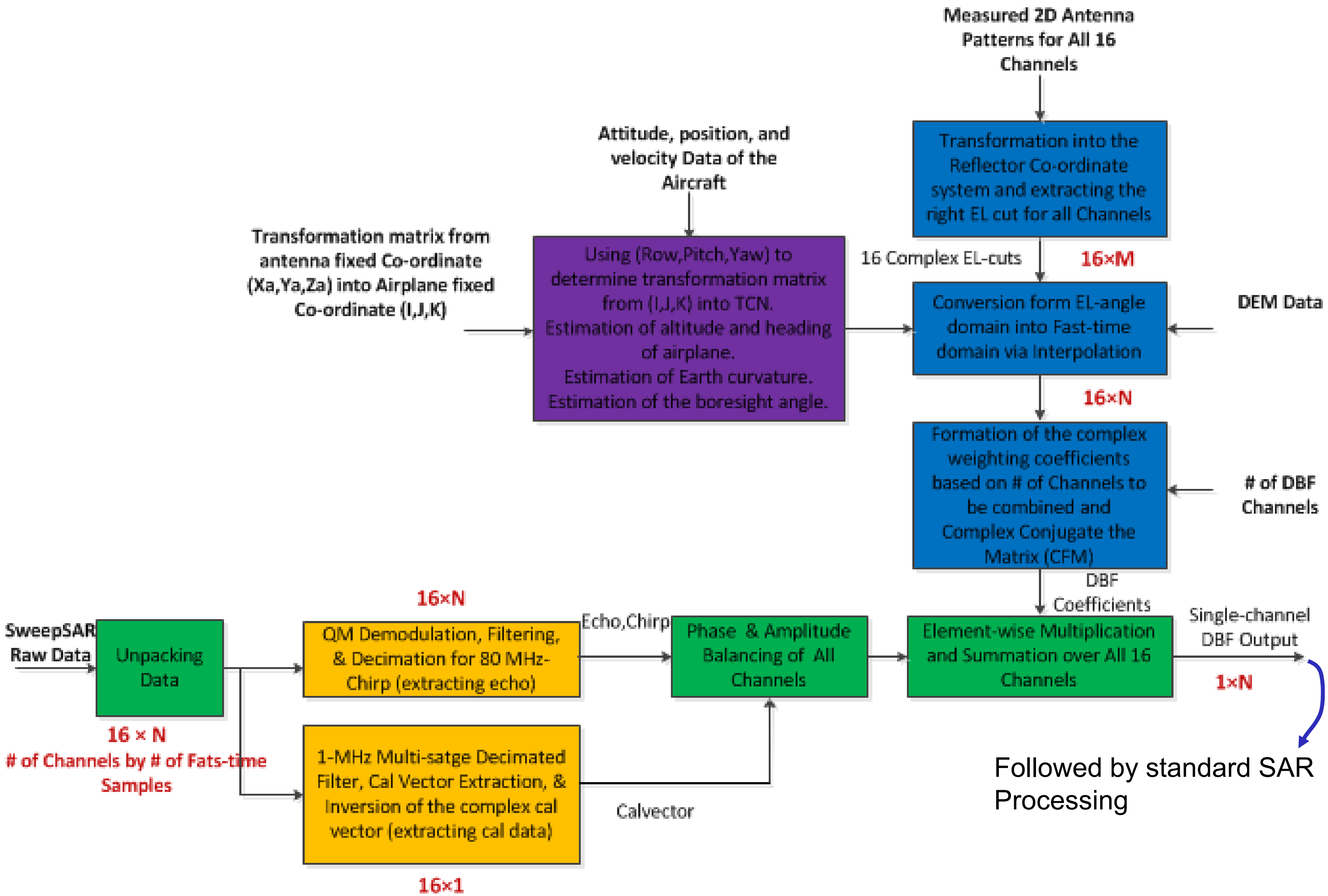
- Removes standard SAR performance limits using Digital Beamforming techniques on receive using reflector
- Achieves high area coverage at fine resolution and full polarization



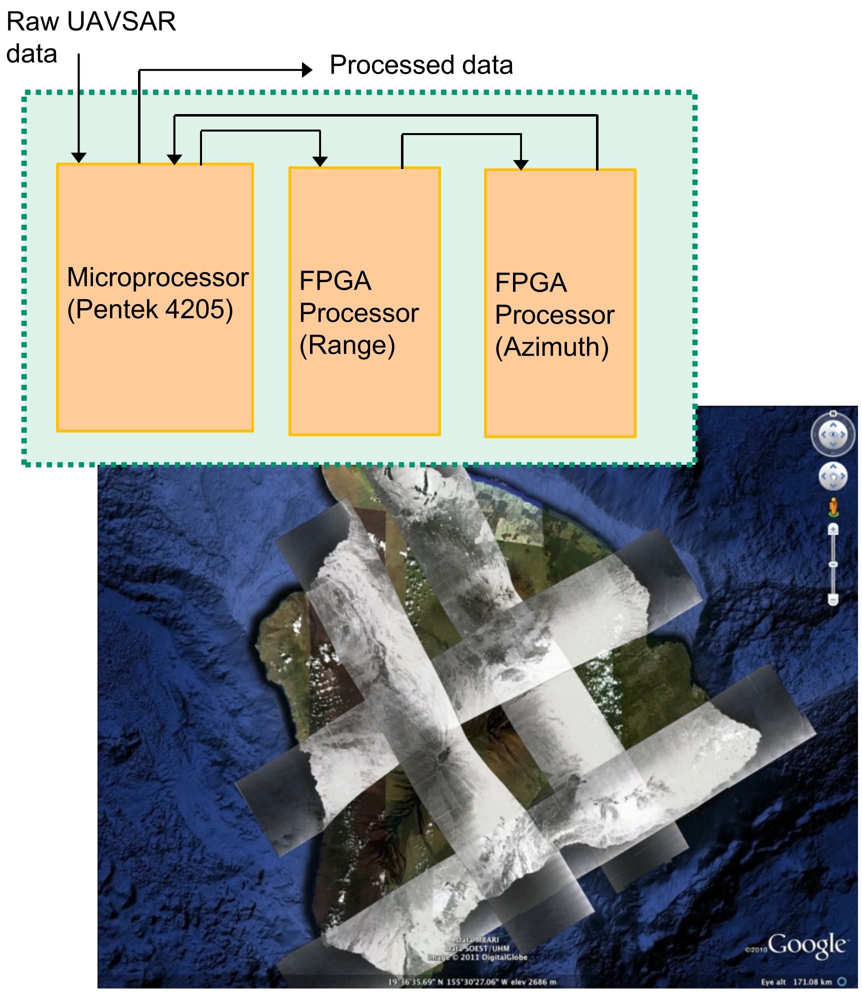



# SweepSAR Demo System on NASA DC-8 Aircraft

# SweepSAR Digital Beam Forming (DBF) Algorithm



# Real Time SAR Processing




**… and real time display into Google Earth kmz files.**

- ***Motivation:***

–Enable the observation and use of surface deformation data over rapidly evolving natural hazards, both as an aid to scientific understanding and to provide timely data to agencies responsible for the management and mitigation of natural disasters

- ***Implementation:***

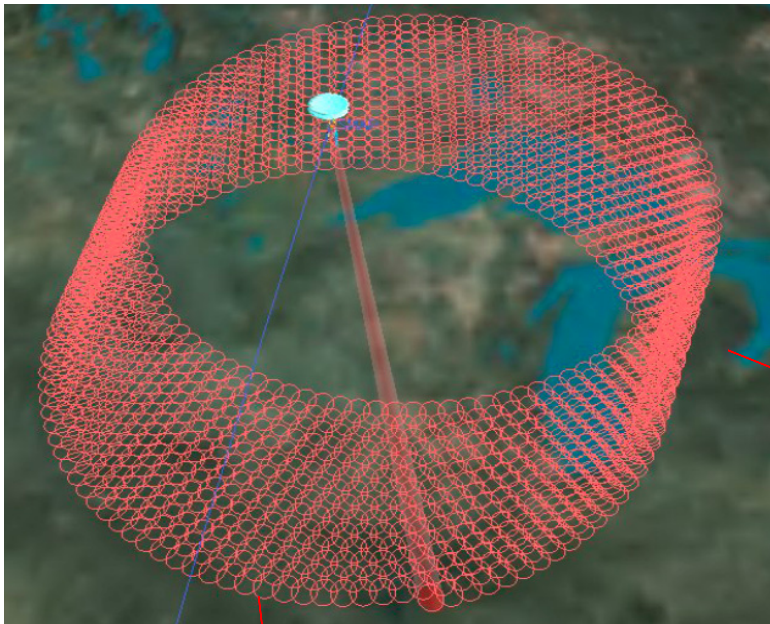
–Fully focused range doppler processing

–Processor is a hybrid design. Calculations that are needed once per range/azimuth line or less are done in a commercial microprocessor, and the rest of the calculations are done in FPGAs using processing parameters provided by the microprocessor. Reorganizing and partitioning of the processing algorithm was the major challenge of this design

–A significant challenge was the implementation of header data processing to be able to determine processing parameters in realtime

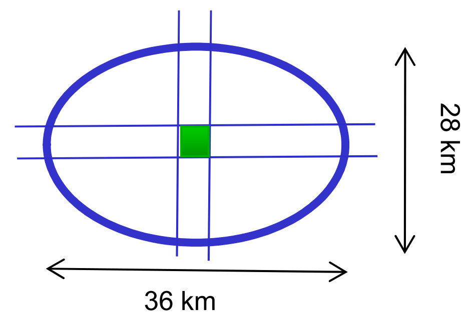
–Required implementation of many math functions in the FPGAs, including FFTs, trig functions, square roots, and division, all requiring very high throughput

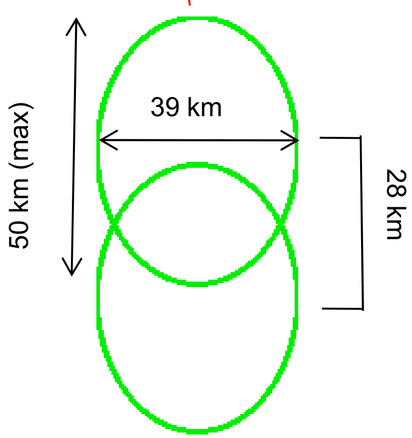
# SMAP Mission Concept: Spatial Resolution



**Radar (synthetic aperture)**

- Resolution pixel defined as intersection between range and Doppler “slices.”
- Azimuth elongation occurs for higher radar squint angles.



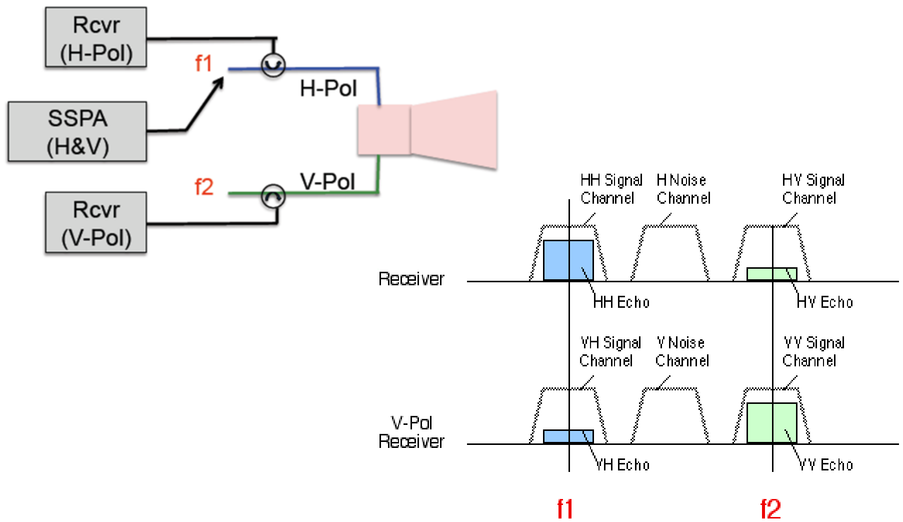

**Radiometer (real aperture)**

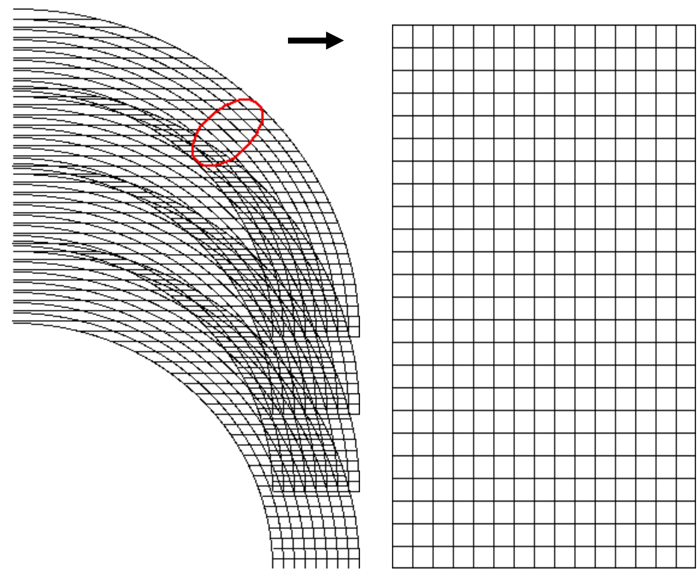
- Resolution defined as root-area of elliptical footprint on surface.
- Along-track spacing determined by rotation rate of antenna (30% required).

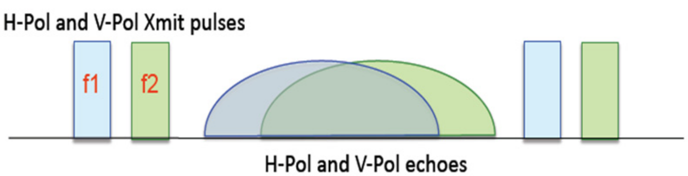
*Swath*
*+ Altitude*
*+ Resolution*

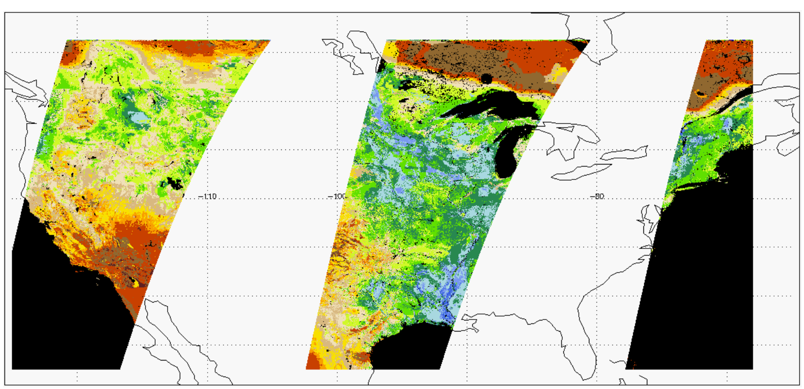
*Antenna Diameter*
*Rotation Rate*

# Proposed SMAP Radar Measurement



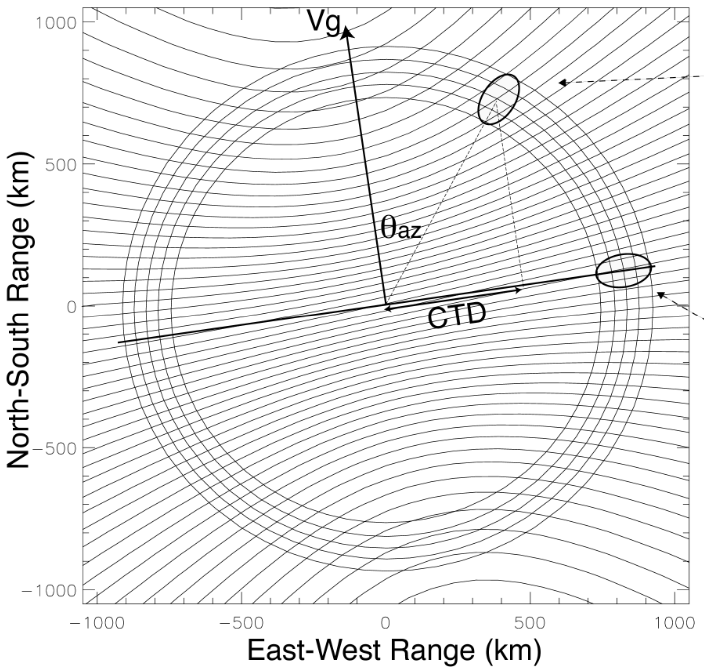



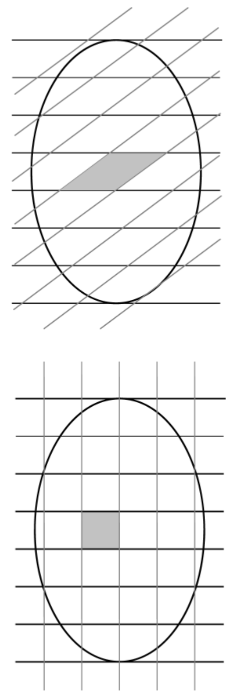


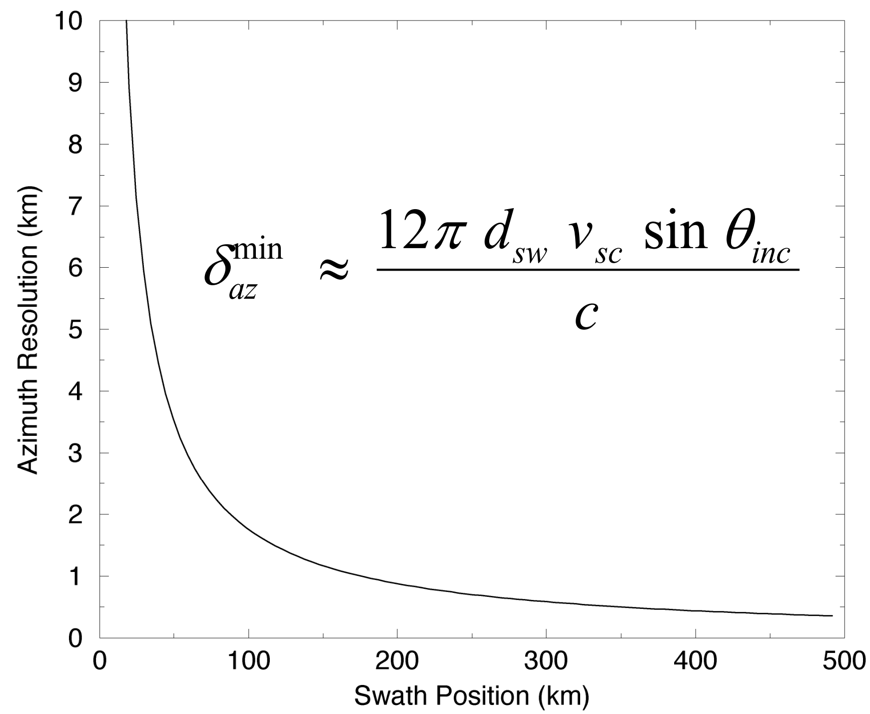



- H and V pol signals transmitted near-simultaneously at two different frequencies.
- Echoes received simultaneously in co-pol, cross-pol and noise-only channels.
- Downlinked samples processed into calibrated time-ordered single-look data.
- Single-look data resampled on 1 km grid and averaged up to 3 km resolution for more precise measurements.

# Spatial Resolution



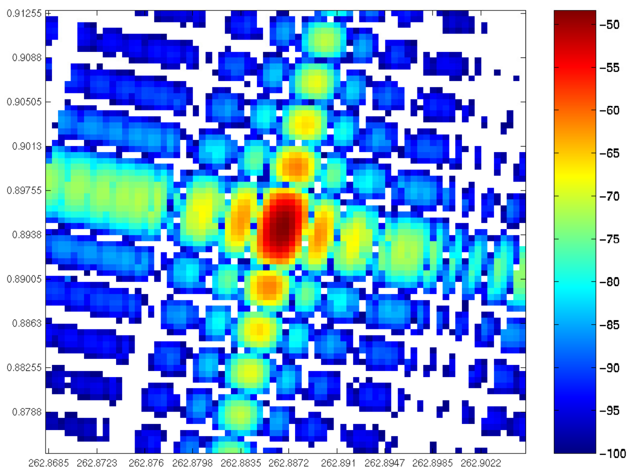



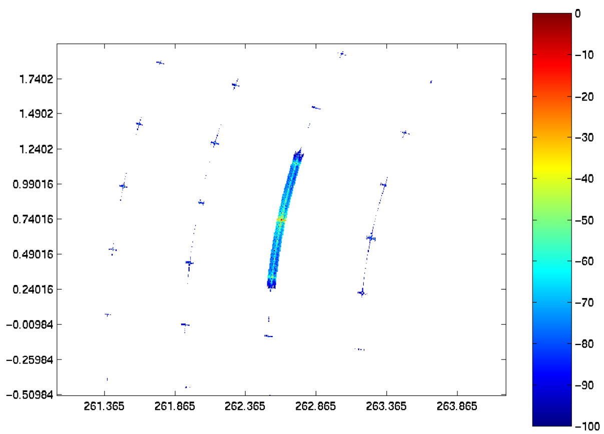



$$\delta_{az}^{\min} \approx \frac{12\pi\, d_{sw}\, v_{sc}\, \sin\theta_{inc}}{c}$$

- Azimuth resolution, and number of azimuth looks, driven by two factors unique to scanning geometry:
  - Relative short "dwell time" associated with rapidly moving antenna footprint leads to best azimuth resolution of about 400 meters.
  - Continuously varying squint angle leads to "azimuth elongation" effect at high forward and aft squints. Creates "nadir gap" region where desired resolution is not obtained.

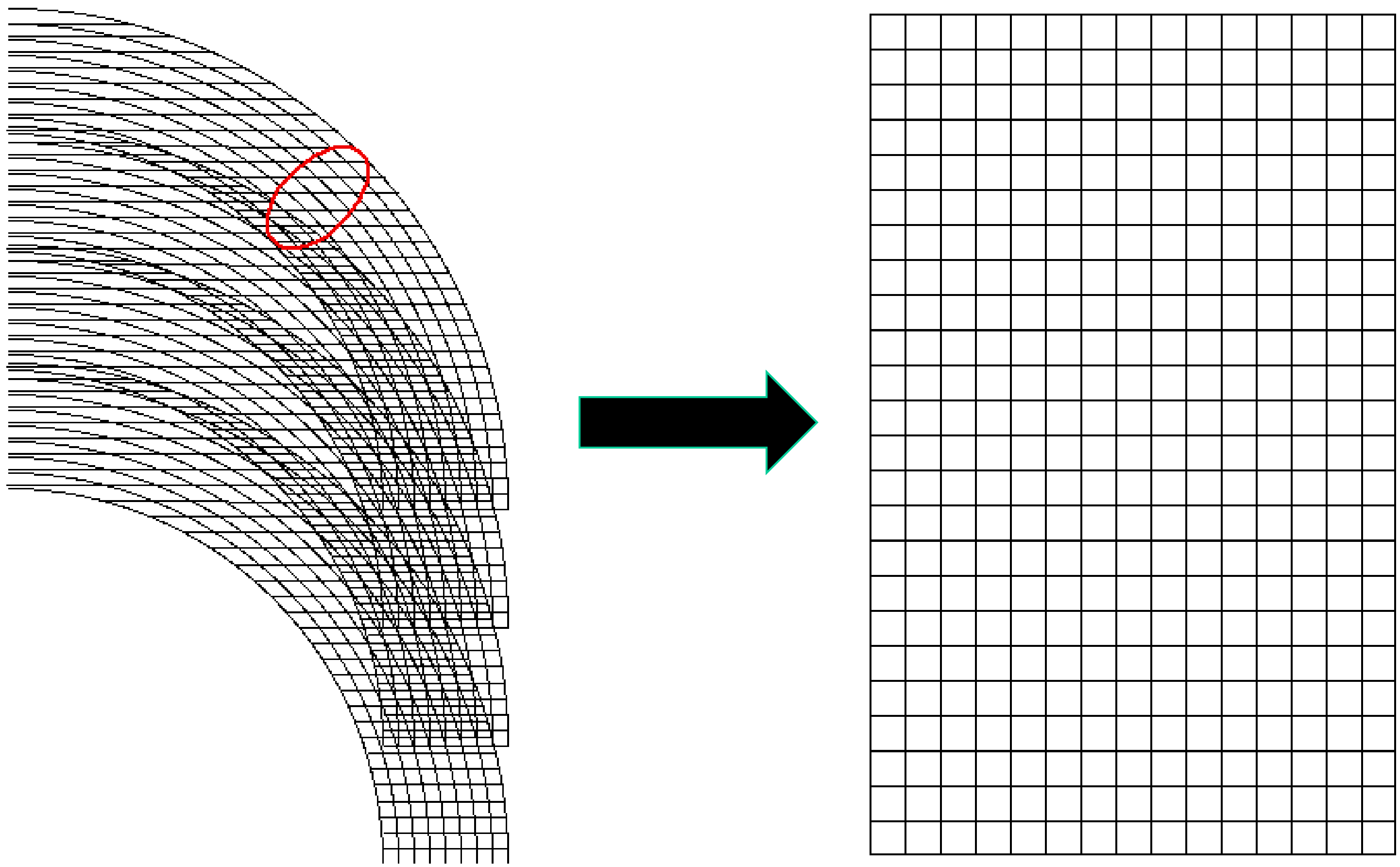
# Point Target Response Analysis





- High-rate radar data collected and telemetered. Processed using unfocused SAR in ground data processing.
- “Single-look” resolution of 250 m in range and 400-1200 m in azimuth.
- “Multi-look” gridded products of 1 km, 3 km, 10 km, etc. with sufficient accuracy for geophysical retrieval.
- Range/Doppler ambiguities < -20 dB.
- High-res radar processing approach validated with detailed modeling:
  - JPL performance simulation models S/C motion, scanning antenna, SAR processing, resolution, and ambiguities.

# Radar Product Generation



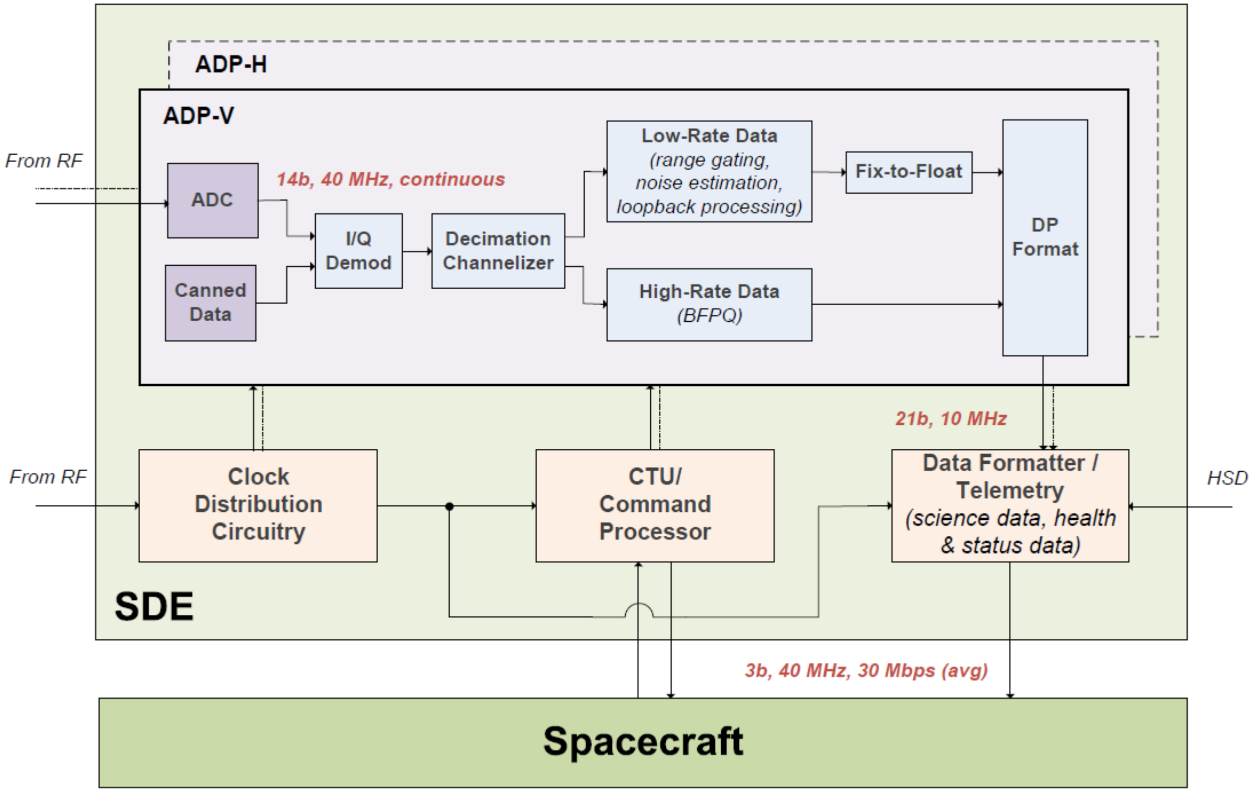
## Single-Look, Time-Ordered Data

- Native resolution: 250 m in range, 400+ m resolution in azimuth.
- Each resolution element constitutes one independent “look” at surface.

## 1 km Gridded, Re-Sampled Data

- Data resampled and posted on 1 km grid, resolution may still be > 1 km near nadir.
- Each resolution cell now has multiple “looks” at surface, decreased measurement variance.

# Proposed SMAP Onboard Signal Processing




- ***Objective:***

– to reduce the data downlink rate.

- ***Functionality:***

– I/Q demodulation;

– Decimation filtering;

– Power averaging;

– BFPQ;

– RFI detection;

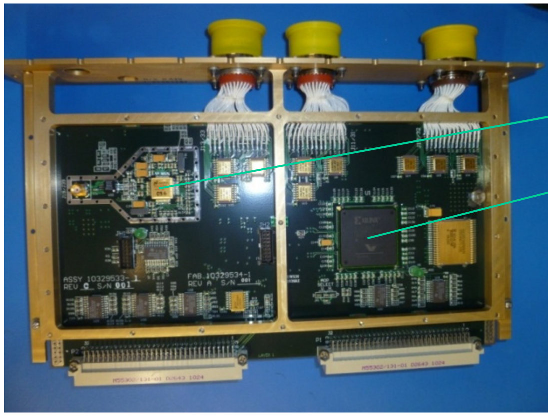
– Data conversion;

– Data formatting.

***Challenges:***

| Parameter | Stability | Sensitivity | Gain Error | Gain Linearity | Finite Precision | ISLR | Kml | Mass | Power | Data Loss |
|---|---|---|---|---|---|---|---|---|---|---|
| Allocation | 0.035 dB | 0.2 dB | 0.02 dB | 0.03 dB | 0.05 dB | -14 dB | 5% | 8.5 kg | 80 W | 0.2% |

# Proposed SMAP OBP Implementation

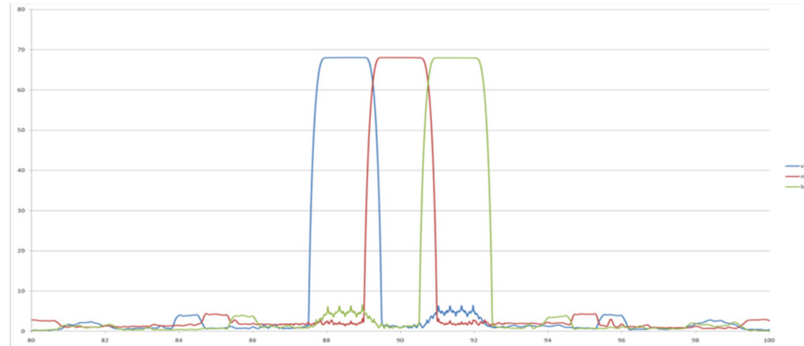


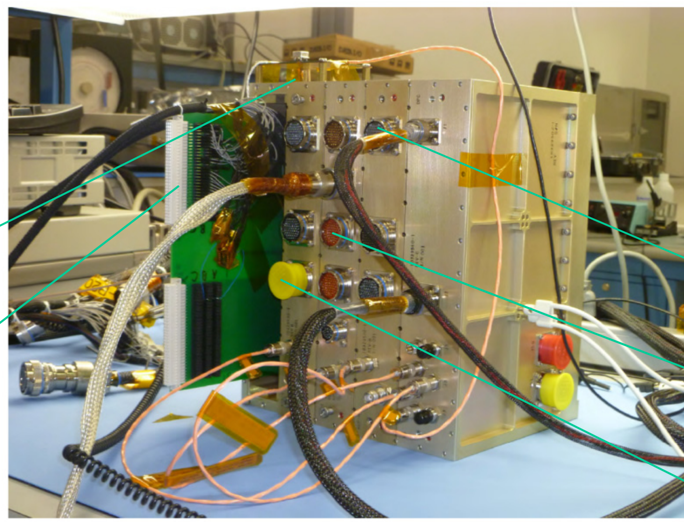
ADC

FPGA

**ADP Board**

## Decimation Channelizers





Clock Distribution

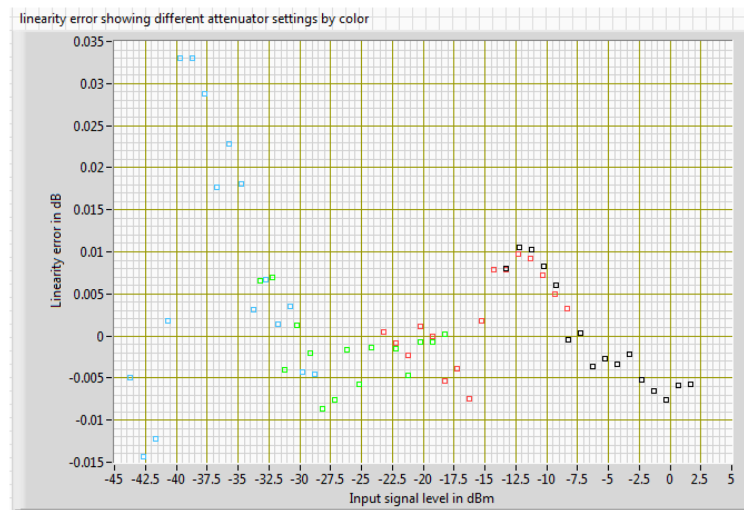
CCP Emulator

ADP-H

DFT

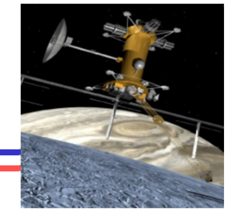
ADP-V

**Integrated SDE**

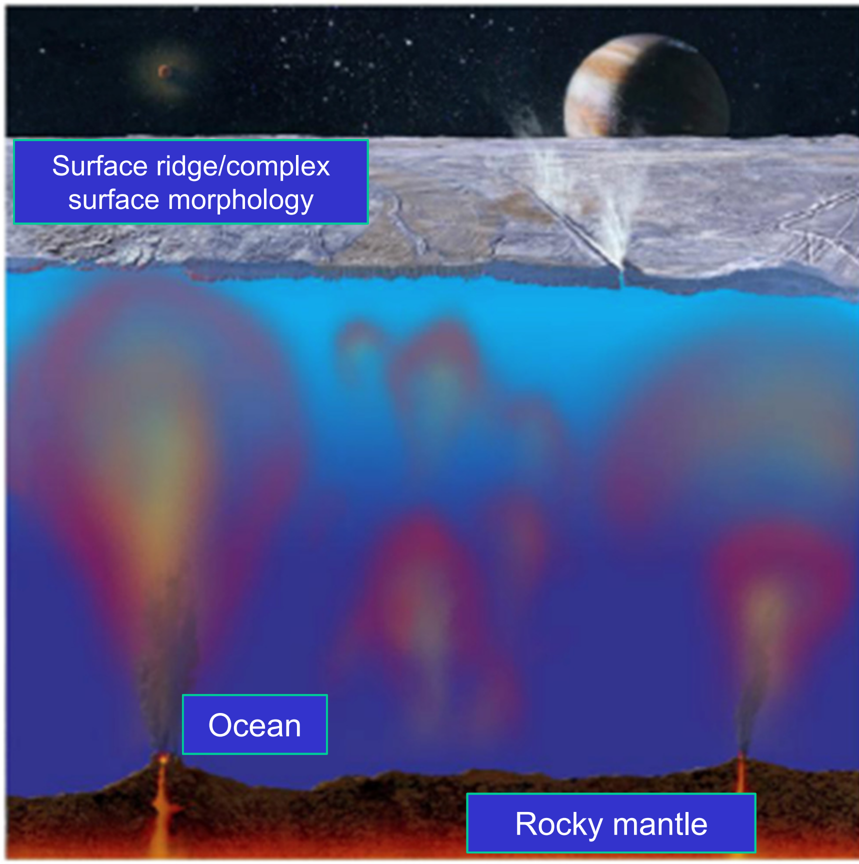



**Gain Linearity Error**

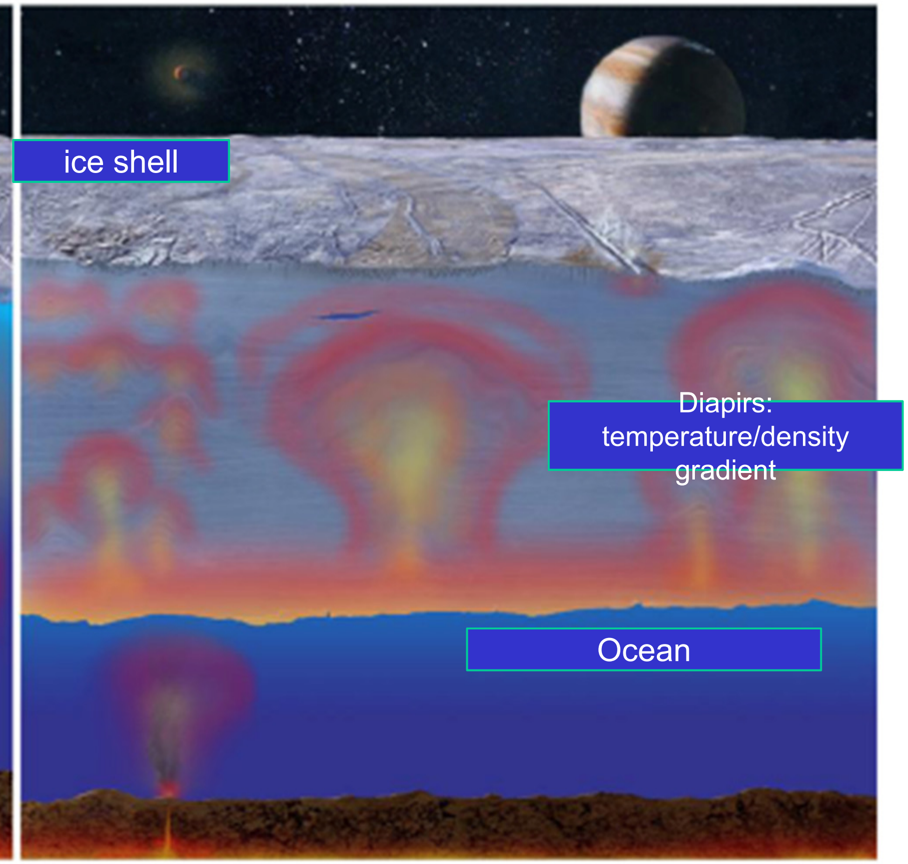
# Proposed Europa Subsurface Sounder Science Goals



3-4 km Thin ice model




30 km Thick ice model




1. Characterize shallow subsurface ice

2. Search for an ice-ocean interface

**Mission would be short and data link to Earth would be small -> Onboard Synthetic Aperture Sounder processing**

# Candidates for on-board focused processing algorithm

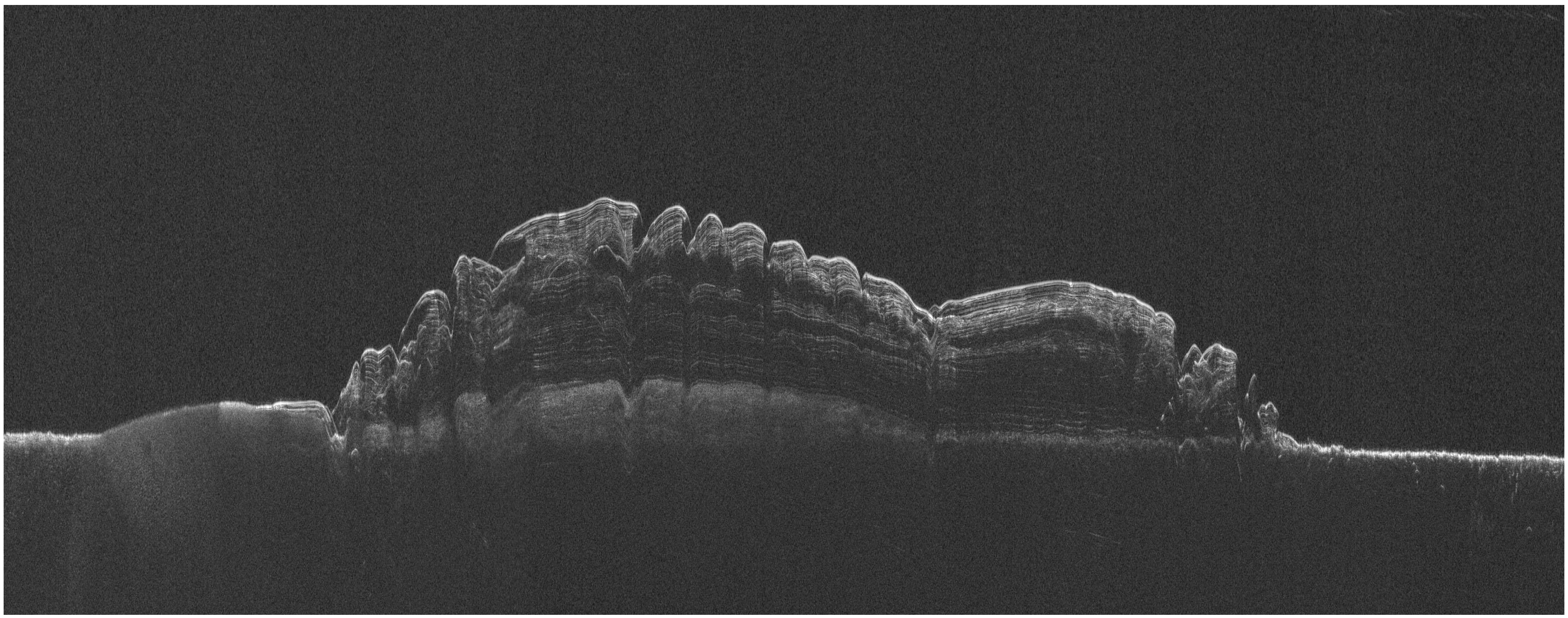
| | Omega-K | Time-domain direct back projection | Fast-back projection |
|---|---|---|---|
| Usage | 15-25 MHz SHARAD ground processor (JPL) | 150 MHz GISMO for 3D ice tomography mapping (JPL) | Wide-band airborne SAR system (developed at Lincoln lab, adopted by Swedish defense lab airborne SAR system, 20-90 MHz) |
| Flown in space | | No | |

Chirp scaling was also considered. It requires the same amount of memory as Omega-K, but its computation load is expected to be 1/3 of Omega-K.

# Omega-K

- Omega-K : 15-25 MHz SHARAD ground processor; 60 km of synthetic aperture
- Running on 2.6 GHz CPU with 8 GBytes of  memory

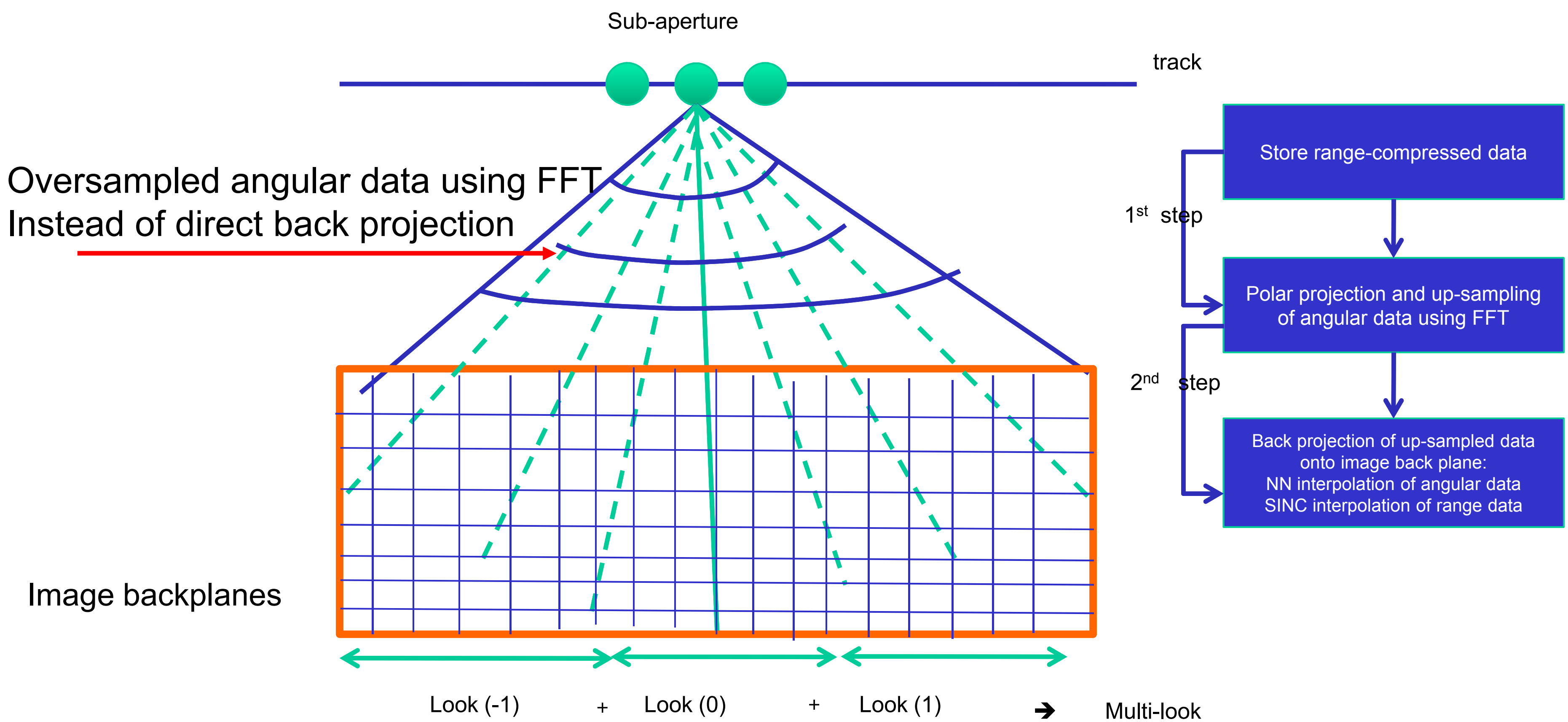
MARS North Polar Layered Deposit



# Fast Back Projection

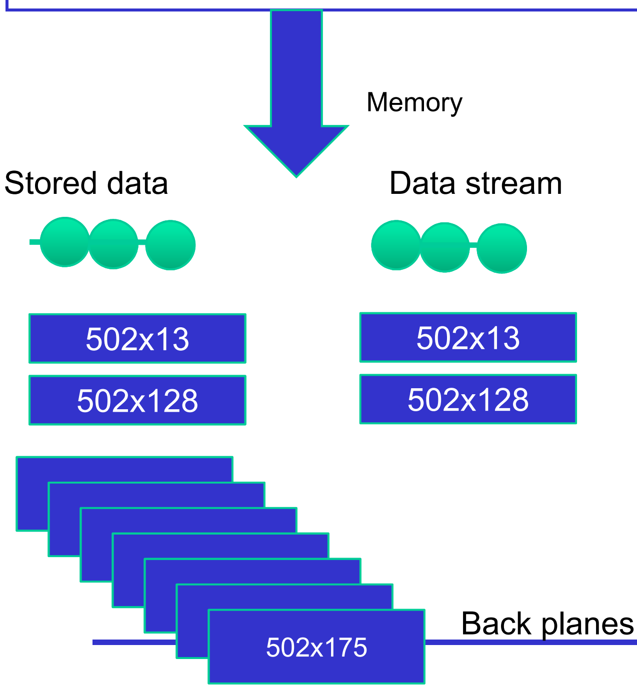
- Fast Back Projection (FBP): algorithm by Ali Yegulap at MIT Lincoln lab, adopted by a wideband airborne SAR system at a relatively low center frequency, 20-90 MHz
- Principle:
  - Instead of time-domain direct back projecting, use an FFT oversampling in the along track direction while keeping direct back projection in the range direction; a hybrid method
  - Multi-look is performed by storing projected data into separate image back planes corresponding to look direction; computational load is weakly dependent of the number of looks.
- Memory: a modest amount of on-board memory to store short track of sub-aperture data and image back planes ($=N_{looks}*N_{range}*N_{alongtrack}$)

# Schematic of Fast Back Projection



# Memory size and clock speed for 100 m along track resolution using fast-back back projection

| | Value | Unit |
|---|---|---|
| Altitude | 100 | km |
| Wavelength | 5 | m |
| Single sub-aperture length | 50 | m |
| Number of looks | 7 | |
| Range lines | 502 | |
| Along track pixels for 7 looks | 175 | |



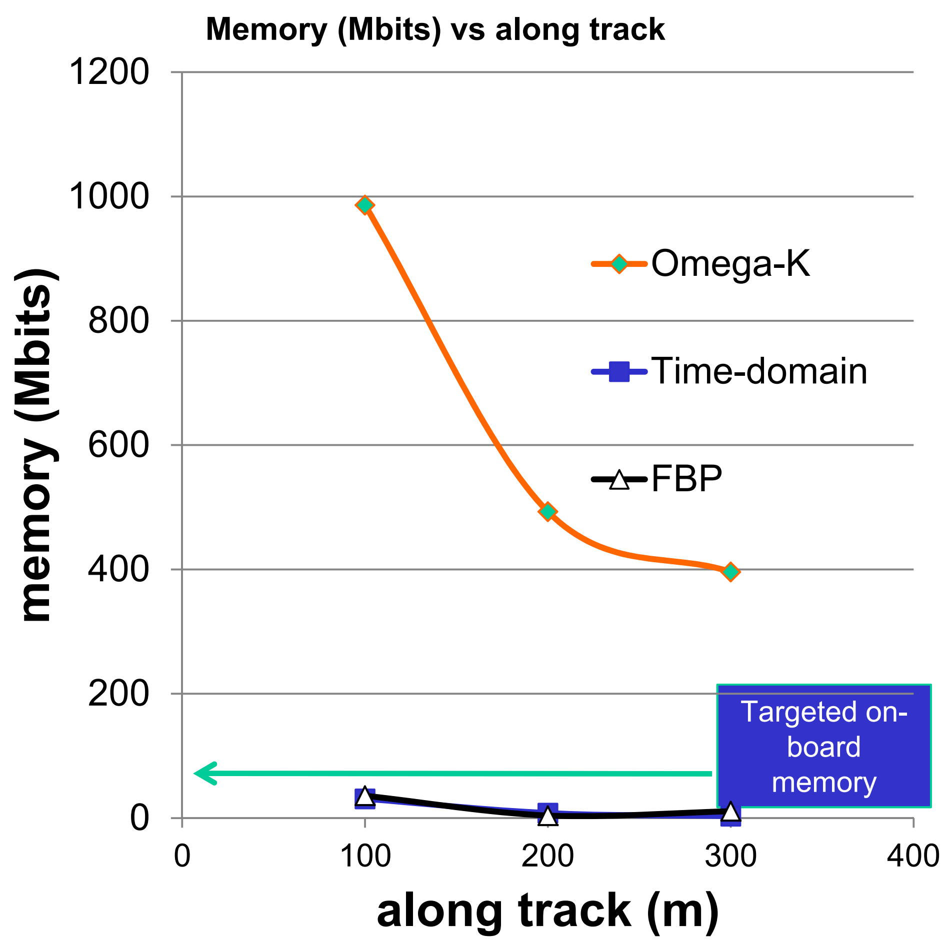

| | Value | Unit |
|---|---|---|
| Number of pre-sum | 3 | |
| Number of pre-summed echoes inside a sub-aperture corr. to s/c movement by 50 m | 13 | |
| Time to finish step1 and step2 process | 39 | ms |
| Two memory banks to store range-compressed data =2x502x13*48(bits) | 0.6 | Mbits |
| Two memory banks to store polar coordinate data =2x502*128*48 (bits) | 6 | Mbits |
| Memory for 7 back planes (502x175x7x48) | 29 | Mbits |
| FFT operation (16 FFT, 128 IFFT) | 502 x (16 FFT + 128 IFFT) | |
| Number of interpolations | 502x175 | |
| Time to back project sub-aperture data to polar coordinate | 21 | MHz |
| Time to complete 502 16-pt FFTs and 128 IFFTs | 14 | MHz |
| Time for interpolation (8 clocks/interpolation) | 21 | MHz |

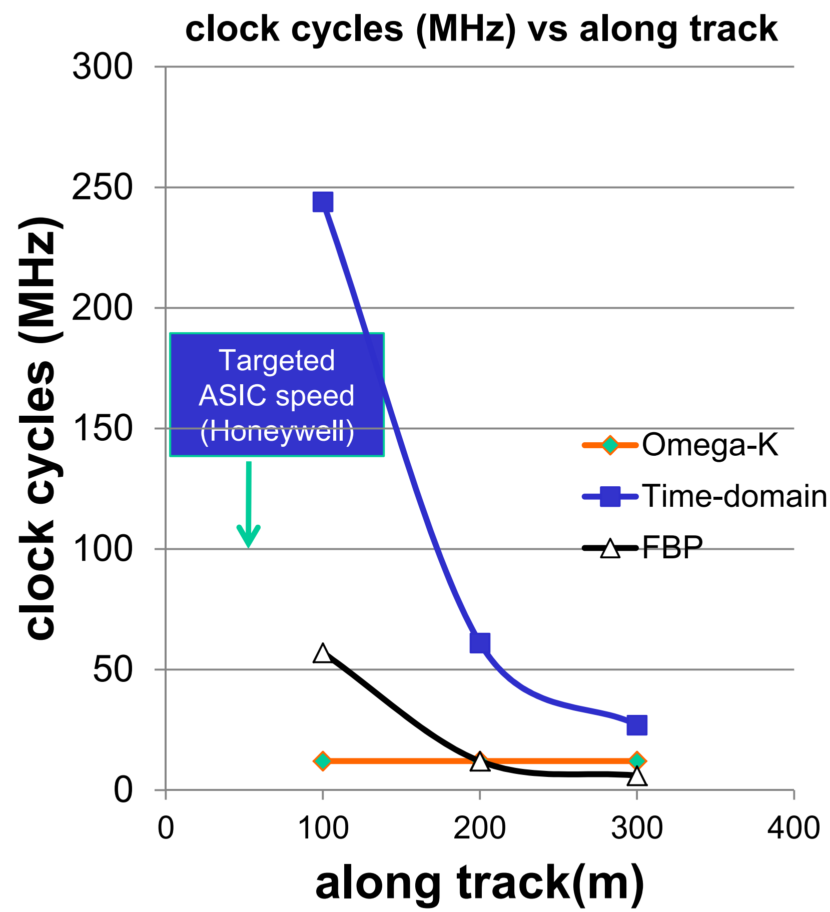
# FBP resource requirements

| Along track resolution | Memory (Mbits) | Detectable slope (deg) | Number of looks | Min. clock cycles |
|---|---|---|---|---|
| 100 m | 36 | 5 | 7 | 57 MHz |
| 200 m | 14 | 2.5 | 7 | 12 MHz |
| 300 m | 11 | 1.7 | 7 | 6 MHz |

1. A modest amount of memory is required
2. At a clock speed of 100 MHz, 75% computational margin with a single SINC interpolator and serial FFT implementations
3. Motion compensation is taken care of as part of range-computation

# Memory and Clock Speed Comparisons for Sounder On-board Processor



# Summary

- Earth and Planetary Science Radars use an array of signal processing techniques – from fairly simple to highly complex - to do powerful science
  - Each mission leads to new instrument requirements and therefore new algorithmic and processing requirements
- Imaging and flight geometries can lead to quite complex algorithms, but often the core signal processing within these algorithms reduces to some basic signal processing functions such as FFTs and accurate interpolations
- There is a strong trend to achieve more processing on orbit while minimizing downlink bandwidth
  - Digital filtering
  - Presumming
  - Beam forming
  - SAR processing