SMAP Calibration Requirements and Level 1 Processing

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- Outline
  - Science requirements
  - Radar backscatter measurement accuracy
  - Pointing and Ephemeris
  - Level 1 Processing and Cal/Val approach

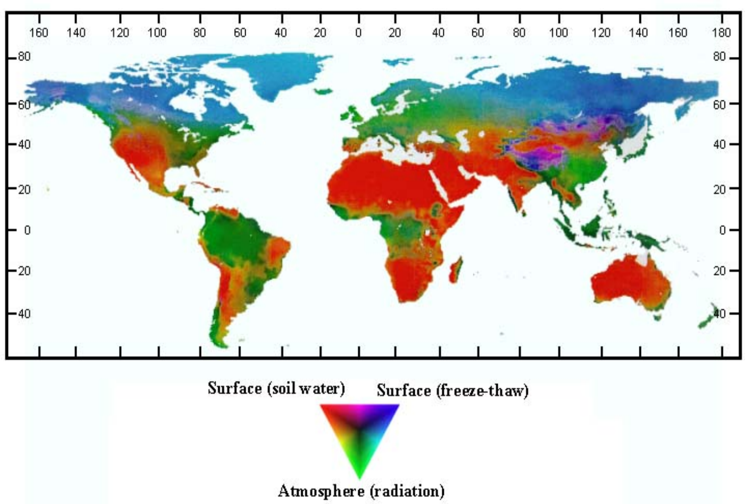
SMAP Science Objectives

- The Soil-Moisture Active/Passive (SMAP) mission will measure global soil moisture and surface freeze/thaw state from space. Launch is planned for 2014.

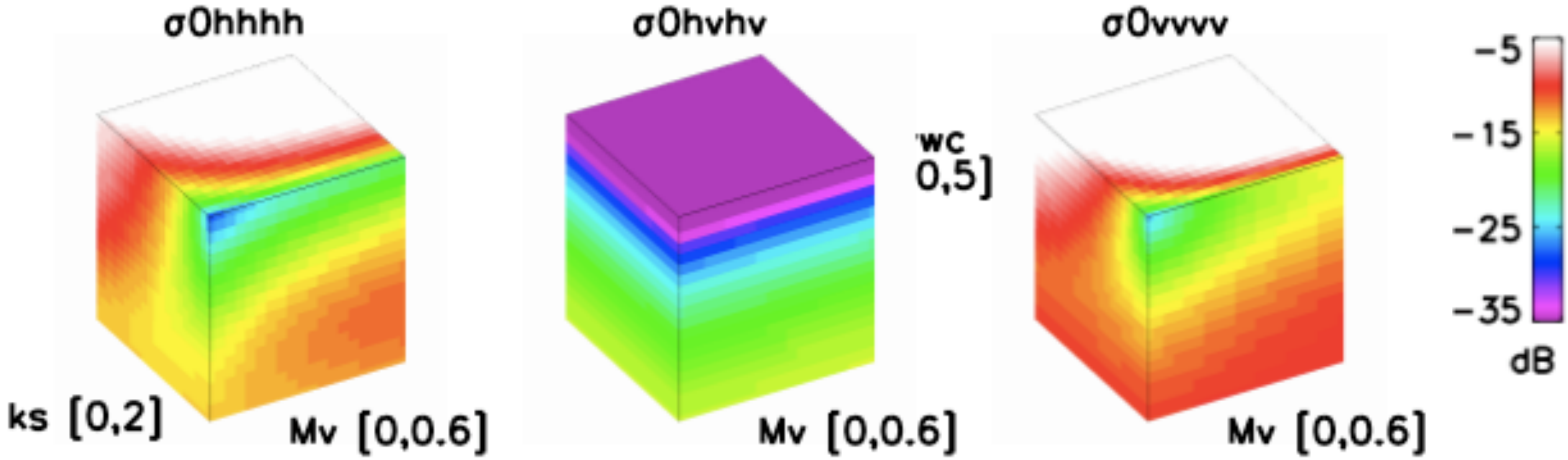
- Global, high-resolution mapping of soil moisture and freeze/thaw will quantify key parameters in the global hydrologic and carbon cycles, as well as extend weather and climate forecast skill.

- SMAP will utilize simultaneous L-Band radiometer and radar measurements.
  - Passive radiometer measurements at 40 km resolution.
  - Active radar measures at < 3 km resolution
    - Soil Moisture at 10 km, accuracy: 4% vol.
    - Freeze/thaw at 3 km
  - 3 day global revisit

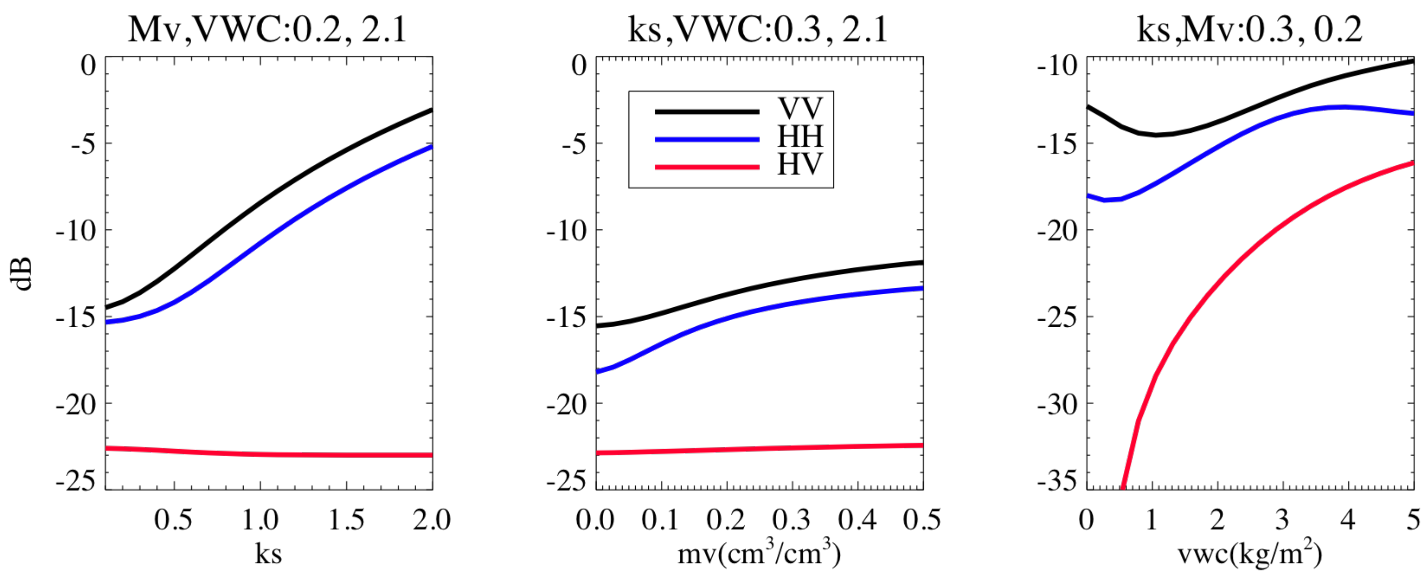
Primary Environmental Controls on NPP and Evaporation



Radar Backscatter Sensitivity to Soil Moisture



- These are the cuts of the data cubes. Typical values of soil moisture (Mv= 0.2 cm3/cm3), bare surface roughness (ks=0.3, dimensionless, k is the wave number, s is the vertical rms height), and vegetation water content (VWC=2.1 kg/m2).



Measurement Accuracy Requirement

- The radar backscatter measurements (posted at 1 km) shall have an error (that includes instrument precision, bias-removed calibration error, and RFI-induced error), defined at 3 km spatial resolution, of 1 dB or less (1-s) in the HH and VV channels, for radar cross-sections (so) of -25 dB or greater; and TBD for the HV channel.
- Soil Moisture drives the backscatter accuracy requirement. Freeze/thaw signal is about 5 dB and imposes a less stringent requirement at 3 km resolution. Pushing to 1 km resolution is more problematic.
- Radar only soil moisture retrieval needs to give 6% vol. accuracy at 3 km resolution so that combined active/passive algorithm can give 4% at 10 km resolution.

Radar Measurement Error Model

- After SAR range/azimuth processing (and thermal noise subtraction), each single-look pixel (effective resolution cell) has a "raw" magnitude D_p.
- The normalized radar backscatter cross-section (NRCS or σ^0) is calculated from this raw magnitude by applying the radar equation:

$$\sigma_p^0 = \frac{D_p}{X_p}$$

Where the parameter X_p contains the effect of all instrumental parameters relating D_p to σ_0 for that pixel (cross-pol may have more terms).

$$X_p = \frac{\lambda^2 P_t G_r G_a^2 F_{tilt} F(\phi,\theta)}{(4\pi)^3 L R^4}$$

L is the total system loss
R is the slant range to the pixel
P_t is the transmit power
G_r is the net receiver gain
G_a is the peak antenna

$F(\phi,\theta)$ is the pixel "response function" at antenna azimuth ϕ and elevation θ.
F_{tilt} is the correction to σ_0 applied for the effect of local surface slope.

- Error in σ^0 are consequently caused by
  1. Errors in estimating the mean value of D_p, or *measurement precision*.
  2. Errors in X_p, or *calibration error*.

Radar Precision

- Due to radar speckle and thermal noise effects, D_p is a random variable whose mean value is proportional to true surface σ^0.
- The resulting random error in estimating σ^0 can be reduced by averaging pixels, at the expense of spatial resolution.
- The measurement *precision*, $\Delta\sigma^0_{kp}$, is due to speckle and thermal noise and is given by

$$\Delta\sigma^0_{kp}(\mathrm{dB}) = 10\log(1 + K_{pc}) \qquad \text{where} \qquad K_p = \frac{1}{\sqrt{N}}\left(1 + \frac{2}{SNR} + \frac{1}{SNR^2}\right)^{\frac{1}{2}}$$

And where N is the total number of looks (azimuth looks × range looks) averaged.

- The radar precision $\Delta\sigma^0_{kp}$ is a value determined by the instrument design parameters (pulse bandwidth, antenna gain, transmit power, etc.) and the spatial resolution, and therefore cannot be improved with better calibration.
- The SMAP baseline design requirements are for a worst-case precision of 0.72 dB when the high resolution product is averaged to 3 km.

Radar Calibration Errors

- In general, the radar calibration error for each pixel can be expressed as:

$$X_{true} - X_{est} = B + r$$

Where X_{est} is the estimated value of X, B is a time invariant calibration bias, and r is a zero-mean random variable representing time-varying effects.

- The *absolute measurement bias* is simply B, or, for each channel B_{HH}, B_{VV}, B_{HV}.
- *Channel-to-channel relative biases* are given by $B_{HH} - B_{VV}$, $B_{HH} - B_{HV}$, etc.
- *Pixel-to-pixel relative biases* for a given channel are given by $B_i - B_j$, where i and j denote pixels at different positions in the swath.
- And the *random component of the relative calibration error*, $\Delta\sigma^0_{cal}$, is

$$\Delta\sigma^0_{cal}(\mathrm{dB}) = 10\log\left(1 + \frac{\mathrm{std}(r)}{X_{true}}\right)$$

Where r embodies all the random and/or time-varying effects associated with X such as instrument component instability, spacecraft attitude errors, etc.

- General calibration philosophy: *Whereas biases can be removed post-launch, the random component represents the ultimate limitation on calibration accuracy.*

Radar Measurement Accuracy Budget

Error Source	Allocation (dB)
Kpc	0.72
Calibration	0.35
Contamination Terms (RFI, ambiguities, etc.)	0.40
Total (RSS)	0.9
Requirement	1.0
Margin (lin)	0.1
Margin (rss)	0.43

- Radar relative accuracy budget is focused on determining *changes* in backscatter cross-section.
- Kpc is purely random term related to radar speckle and thermal noise and is driven by
  - Number of looks
  - SNR
- Radiometric calibration is determined primarily by
  - Knowledge of *changes* in transmit power and receiver gain.
  - Knowledge of *changes* in system RF losses.
  - Knowledge of pointing *changes* (primarily in elevation)
- Dominant contamination effect expected to be from RFI.

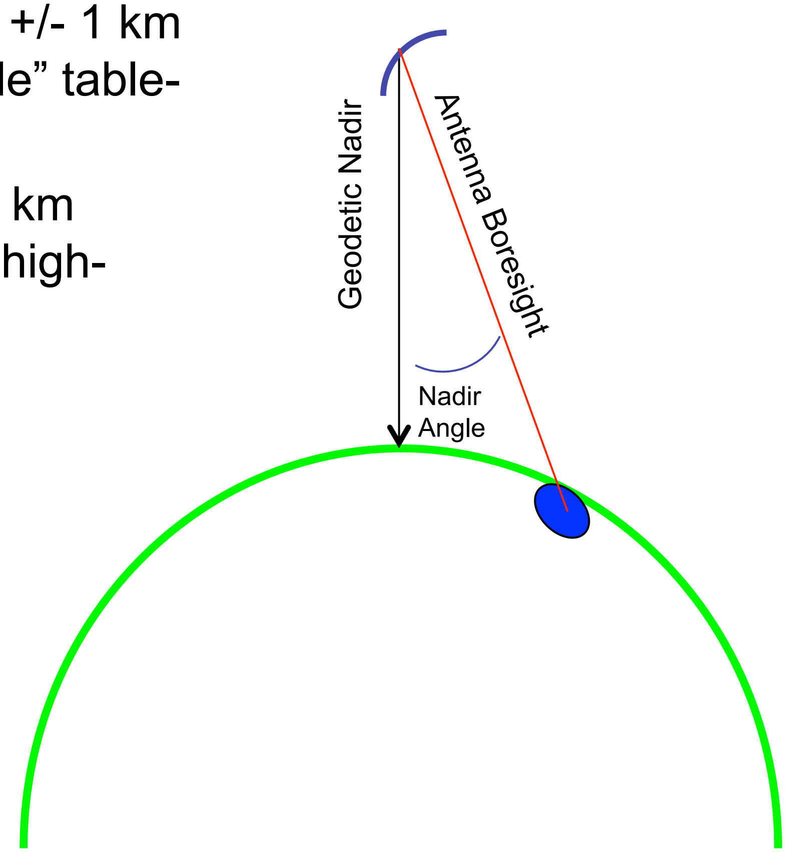
Preliminary Radar Calibration Budget

Calibration Parameter	Calibration Method	Relative Random Error/Stability	Absolute Bias
λ^2	Design	< 0.01 dB	< 0.01 dB
$P_{tx}G_{rx}$	Internal loopback	0.15 dB	0.80 dB
G_a^2	External post-launch distributed targets, pointing stability, radiometric stability	0.30 dB	1.00 dB
A_{eff}	Processing algorithm	0.10 dB	0.10 dB
R^4	GPS	< 0.01 dB	< 0.01 dB
Faraday Rotation	Minimize with morning passes	< 0.1 dB	< 0.1 dB
Ambiguity Contamination	Minimize range/Dop ambiguity levels	< 0.1 dB	< 0.1 dB
Combined $\Delta\sigma_{cal}$		**0.35 dB (RSS)**	**2.1 dB (WC)**

Key Pointing and Navigation Requirements

Observatory Navigation

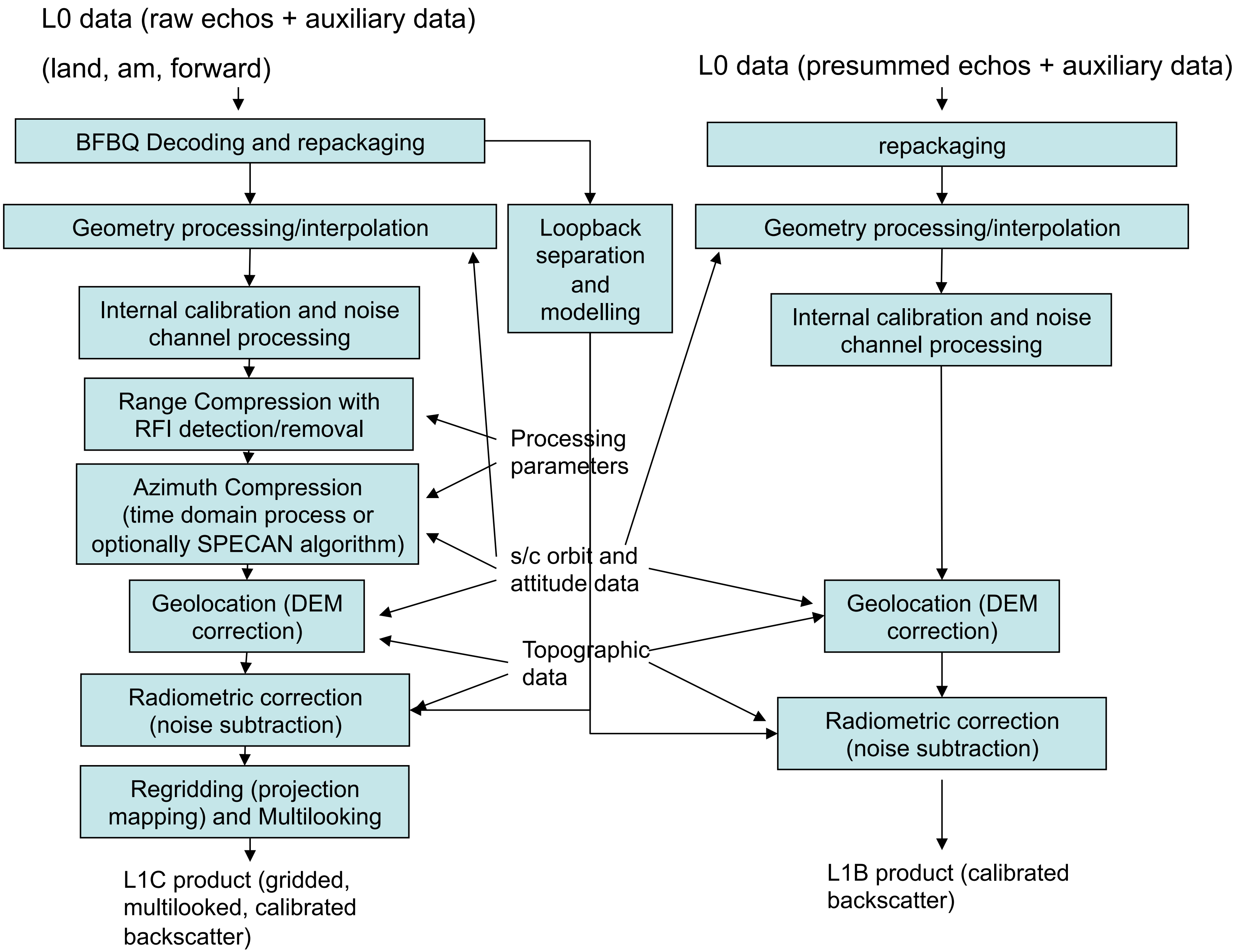
- Spacecraft orbit must be maintained to +/- 1 km at any geodetic latitude to insure “simple” table-driven radar timing scheme.
- S/C position must be known to within 1 km along/cross track in order to geolocate high-resolution radar measurements.



Observatory Pointing

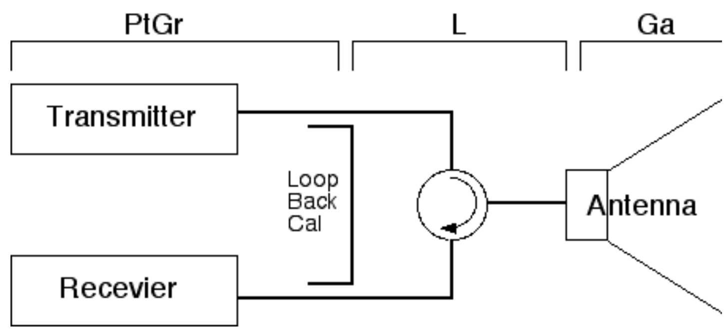
- Spin axis aligned with geodetic nadir direction.
- Antenna boresight elevation pointing stability to 0.3 deg 3-sigma for radar timing.
- Antenna boresight elevation pointing known to 0.1 deg 3-sigma for radar calibration.

L1 Baseline Processing Flow



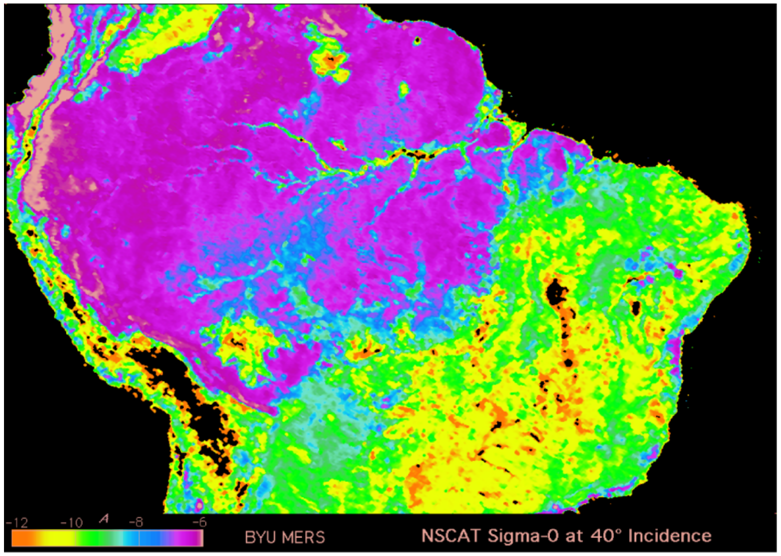
Pre-Launch, Internal Calibration Activities

- Pre-launch radar component calibration goals:
  - Primary Goal: Verify stability of electronic components and/or characterize behavior of electronic components over time/temperature, minimize $\Delta\sigma^0_{cal}$.
  - Secondary Goal: Minimize pre-launch calibration biases.
- Pre-launch radar component calibration activities:
  - Characterize loop-back path over temperature. Develop transfer function from loop-back telemetry to obtain $P_t G_r$ product on-orbit.
  - Characterize loss of all electronic elements outside the loopback path (*L*) as a function of temperature (circulators, transmission lines, feed assembly components).
  - Develop pre-launch estimate of antenna gain pattern by analysis. Perform analytical studies to verify on-orbit stability.



Post-Launch External Calibration Approach

- Post-Launch external calibration goals:
  - Remove channel-to-channel and pixel-to-pixel biases to high accuracy.
  - Remove absolute bias to best capability.
- Post-Launch external calibration approach technique:
  - No man-made targets:
    - Pixel size too large for corner reflectors. – questioned at Oxnard cal/val workshop – see later slide
    - Transponder accuracy insufficient.
  - Statistical analysis of large, uniform, isotropic, well-characterized, stable scenes (such as Amazon).
  - Verify with other contemporaneously flying radars: ALOS PALSAR, Aquarius, UAVSAR, etc.
    - Over distributed targets.
    - Over targets where comparison sensors have corner reflectors.
    - Compensate Seasonal and diurnal variation



- Natural target calibration demonstrated to be very accurate:
  - JPL Ku-Band scatterometers removed channel-to-channel and pixel-to-pixel biases to 0.2 dB.
  - JERS-1 demonstrated that Amazon is stable to < 0.2 dB at L-Band. (see later slide)

Amazon as a calibration target

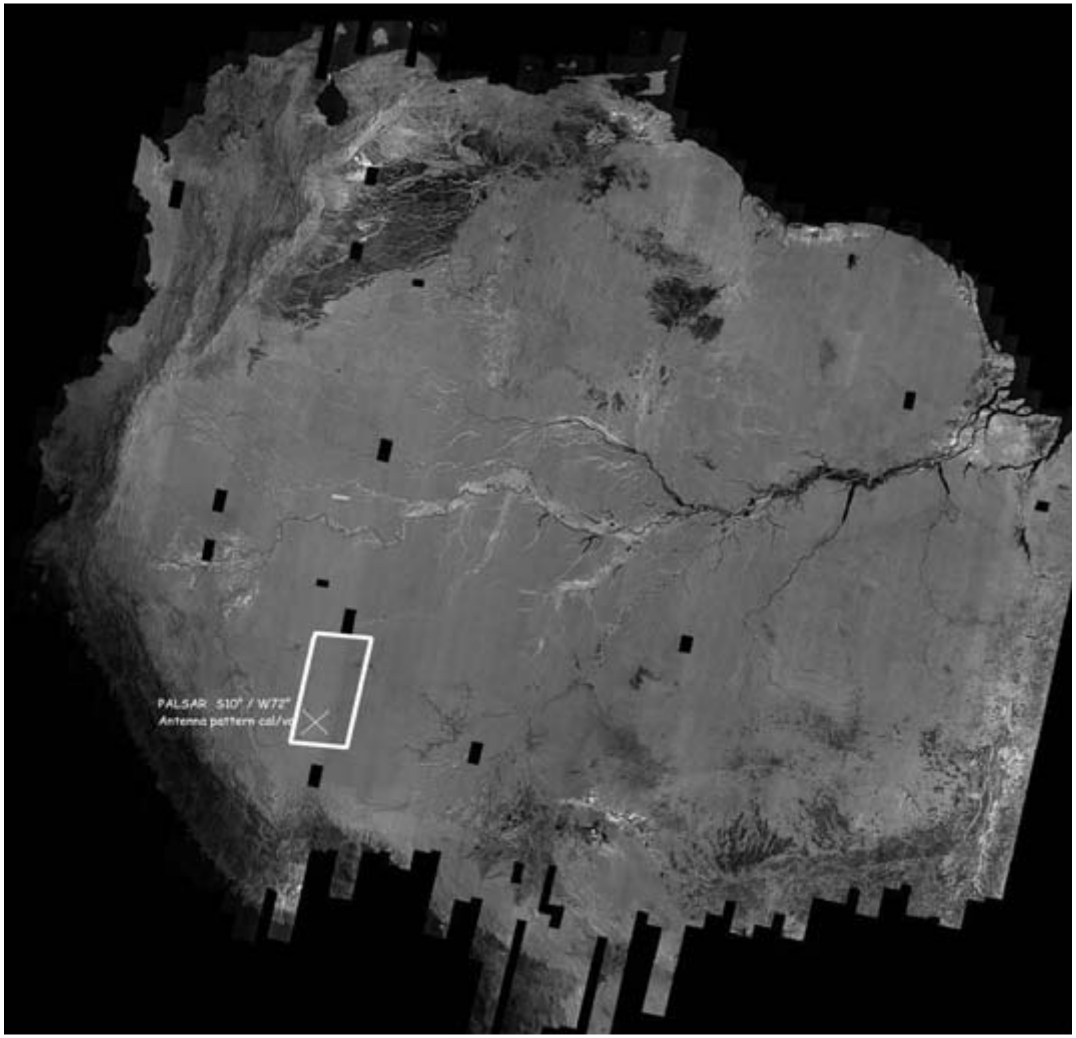


Table 3. Summary of L-band SAR normalized radar cross

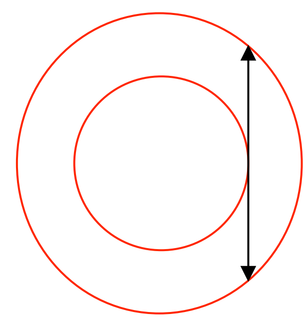
Season	Mean $\sigma0$ (dB)	SD	Mean $\gamma0$ (dB)	SD
All	6.92	0.23	-5.83	0.23
Dry	-7.08	0.18	-5.99	0.18
Wet	-6.81	0.20	-5.72	0.20

$\gamma0 = \sigma0/\cos\theta$

*From: Masanobu Shimada, "***Long-term stability of L-band normalized radar cross section of Amazon rainforest using the JERS-1 SAR,"** *Can. J. Remote Sensing*, Vol. 31, No. 1, pp. 132–137, 2005

Corner Reflectors as calibration targets

- Maximum cross-section: $\sigma 0$ = (4/3 to 12)*pi*a^4/λ^2
  - Trihedral like pic: a = 2.4 m, $\sigma 0$ = -16 dB
  - SMAP noise floor at -40 dB, need to verify scene level at L-band.
  - Note: minimum sigma0 level that meets requirements is: -25 dB
- Maximum looks available: 11/rev
  - 1 dB scatter observed in aircraft missions using corner reflectors
  - Assuming independent normal errors – average to 0.33 dB scatter/rev
- Actual use will require accurate spacecraft position and attitude data. Beam pattern fitting possible with multiple corner reflectors.
  - Mechanical imperfections can cause errors on the order of 0.2 dB
- Amazon will likely produce more looks more quickly and achieve better results earlier



Incidence Angle Correction for L1 Processing

- L. Tsang and S. Huang used SRTM data (90 m spacing) to analyze topographic variation and expected impact on L1 data
- Standard deviations of incidence angle and expected sigma0 computed for 250 m resolution elements within a 1 km grid square
  - Reveals correctable part of topographic effect
  - Most land area on Earth has low sigma0 variation due to topography with negligible contribution to sigma0 uncertainty if left uncorrected.
  - ~10% of area (mountainous areas) can produce ~0.3 – 0.5 dB of sigma0 standard deviation which could push up Kp for sigma0 a little above the 1 dB requirement.
  - Linear correction is easy to implement and could reduce these already small uncertainties.

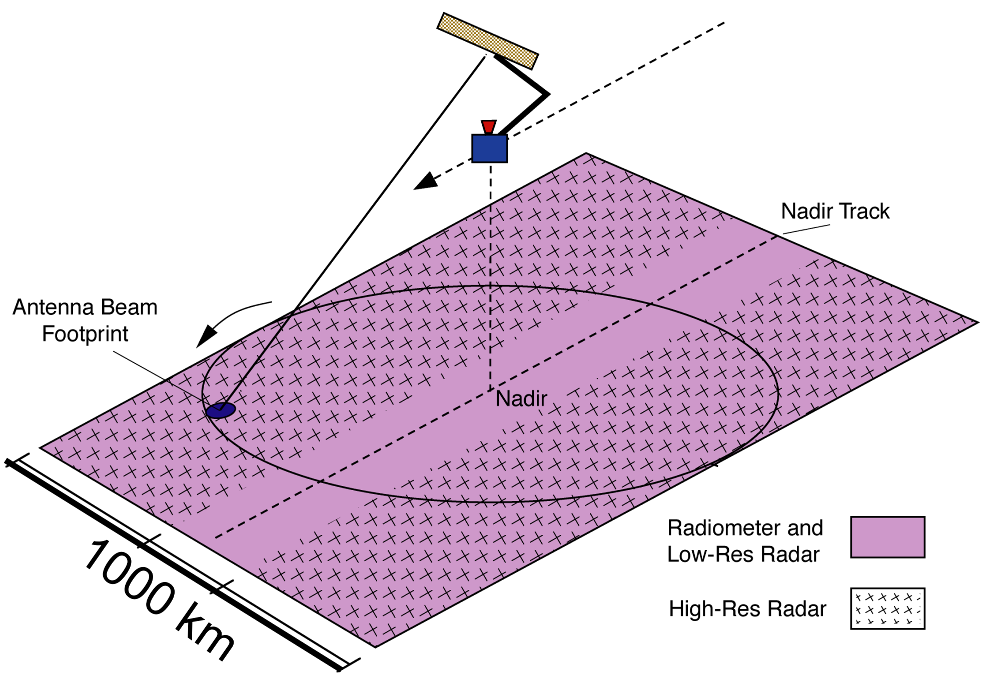
Summary

- Measurements of Amazon are primary means to constrain absolute and relative calibrations.
- Simple Linear incidence angle correction suggested for L1 processing.
- RFI contamination remains a concern. Nominal plan is to detect and exclude contaminated data. Ongoing study on how to mitigate RFI contamination in processing.
  - RFI survey measurements to be inserted in normal operational sequence
- Pre-launch measurements of transmit power, antenna gain, receiver gain, front end characterization used in calibration processing
- Post-launch cold space data will further constrain receiver calibration.
- Internal calibration measurements (rcv only and loopback) used to track relative variations and monitor RFI.
- Faraday rotation correction expected to be small for morning data and can be further corrected using rough estimates of total electron count. Afternoon data will likely require a better correction scheme

Backup

SMAP Measurement Concept

- To meet requirement for 3-day revisit time at AM local time:
  - *⇒ 1000 km swath at 670 km dawn/dusk sun-synchronous orbit.*
- For wide measurement swath of combined L-Band active and passive measurement at near constant incidence angle:
  - *⇒ Conically scanning reflector antenna.*



- To achieve L-Band passive resolution of 40 km and and active resolution of 3 km:
  - *⇒ 6 meter aperture antenna*
  - *⇒ 14.6 rpm rotation rate*
  - *⇒ Real-aperture radiometer*
  - *⇒ Synthetic-aperture radar*

Post-launch Level 1 Cal/Val cont.

- Instrument and Processing Team
  - Characterize receiver with space view maneuver and pre-launch calibration parameters (similar to radiometer cal)
  - Occasional receive only data collections to survey RFI conditions
  - Active mode data integrity checks => BFPQ statistics, spectrum check, zero range delay check, process internal loop-back measurements to look for proper chirp operation and check transmit power stability
  - SAR image formation: check for scan oriented backscatter variation (scalloping) indicating antenna, attitude, and/or ephemeris offsets => tweak processing parameters and derive attitude from radar data as needed
  - End Result is calibrated/validated sigma0 measurements (L1B,C)
- Science Team
  - Evaluation of distributed target calibration data.
  - Verify initial gridded backscatter product
  - Update high-resolution land-mask as necessary.
  - Monitor gridded products for continued fidelity.

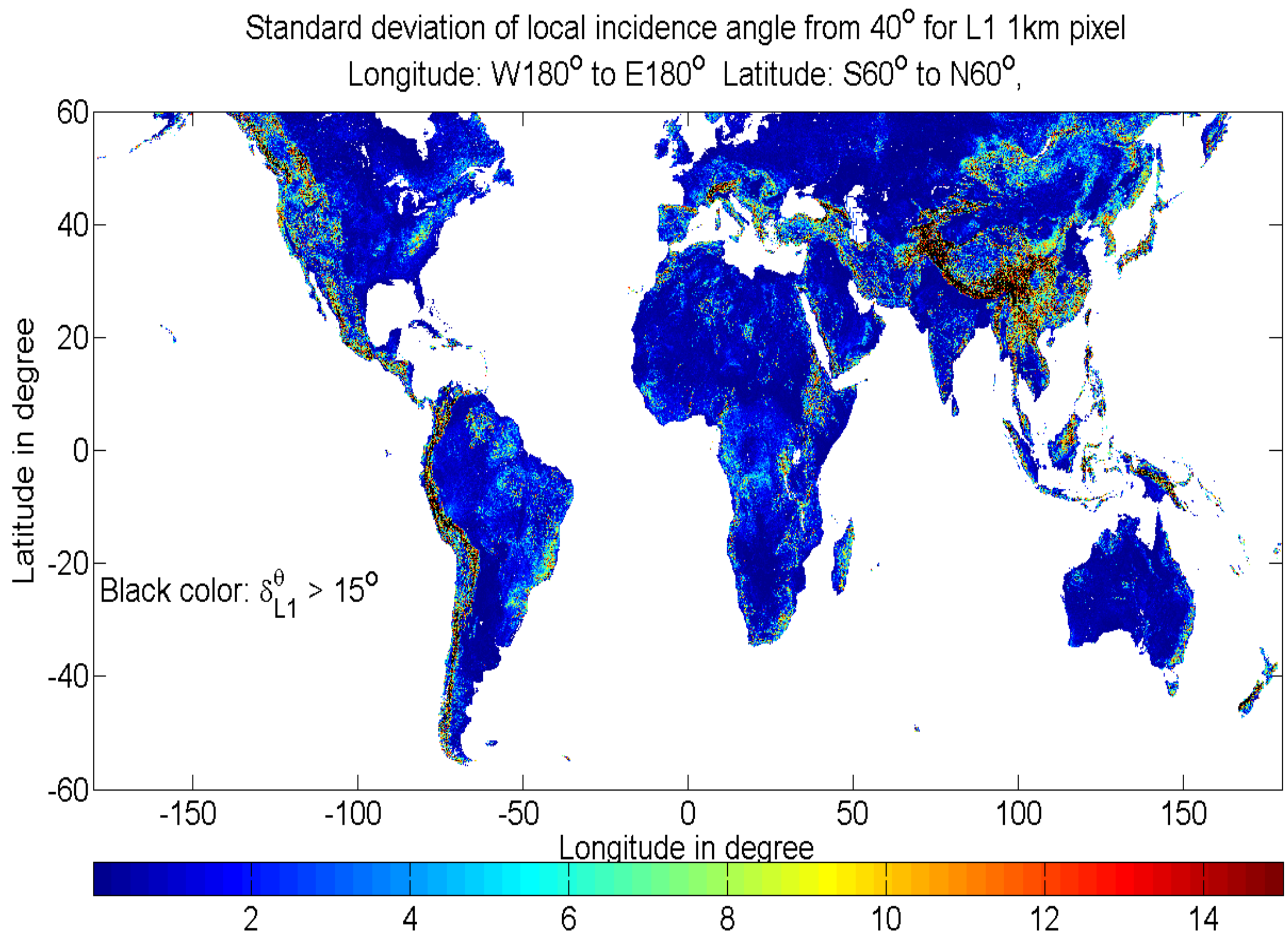
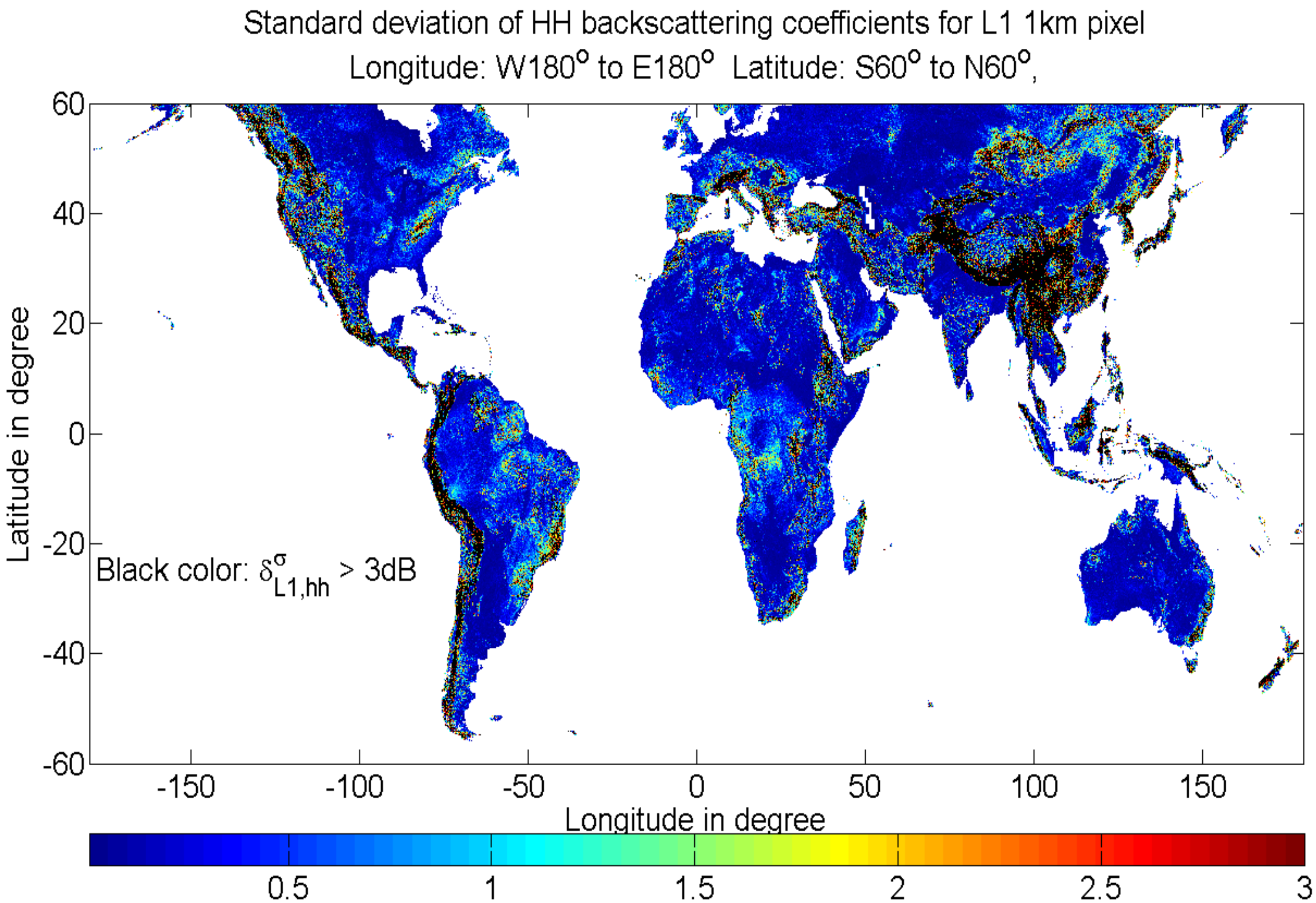
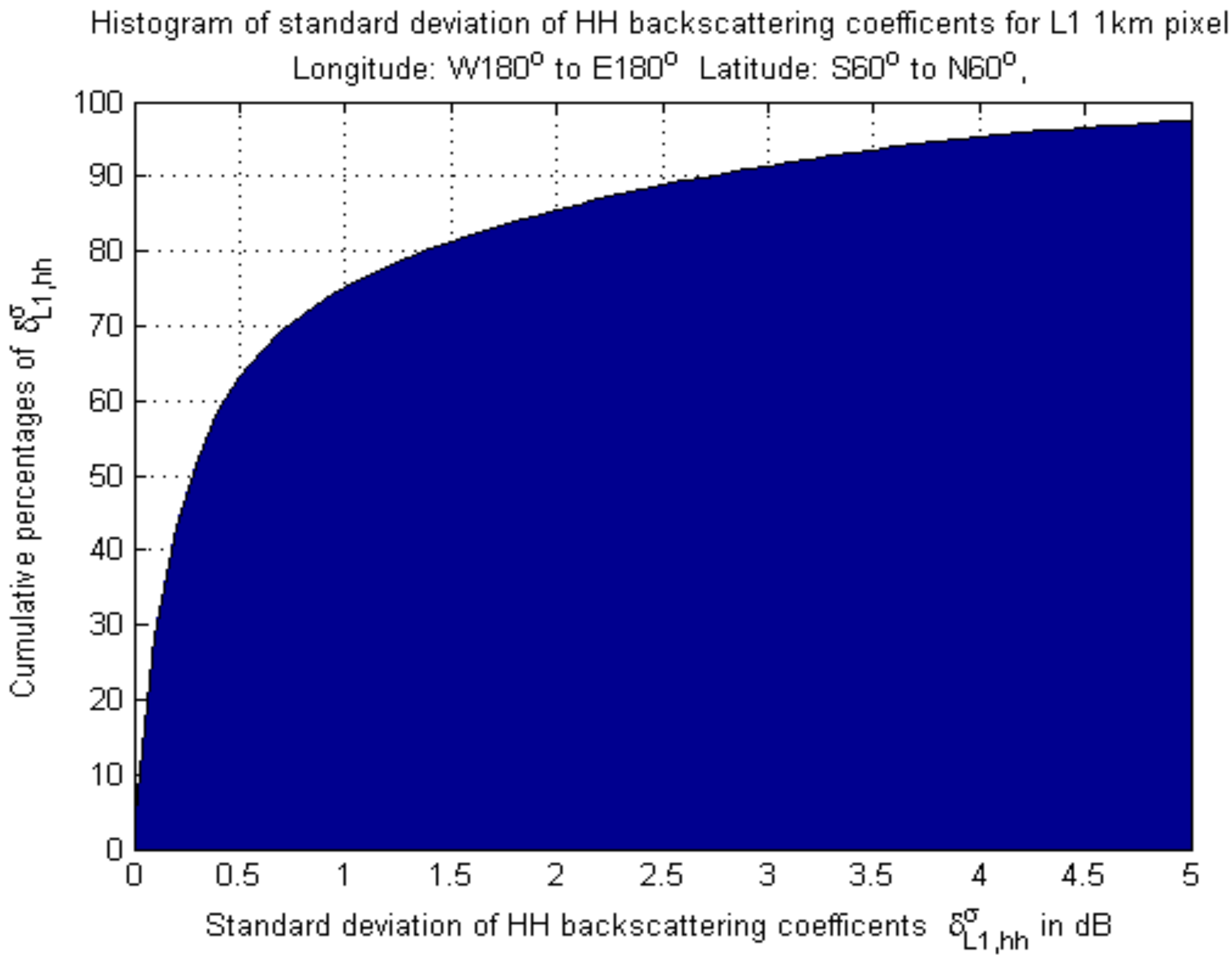


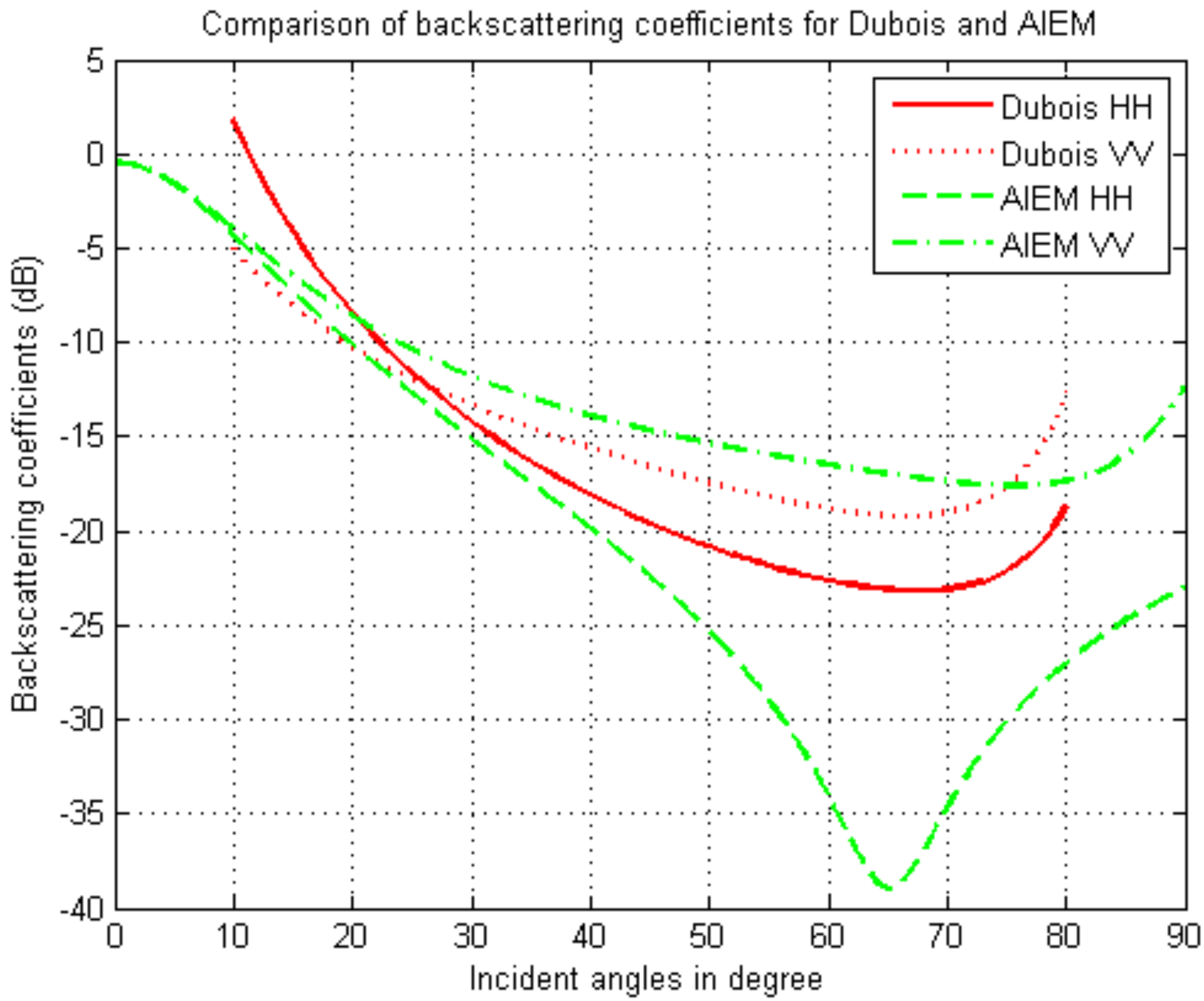
Figure 13. Distribution of standard deviation of local incidence angles from 40o over global land surfaces based on Dubois model



Distribution of standard deviation of HH backscattering coefficients over global land surfaces based on Dubois model



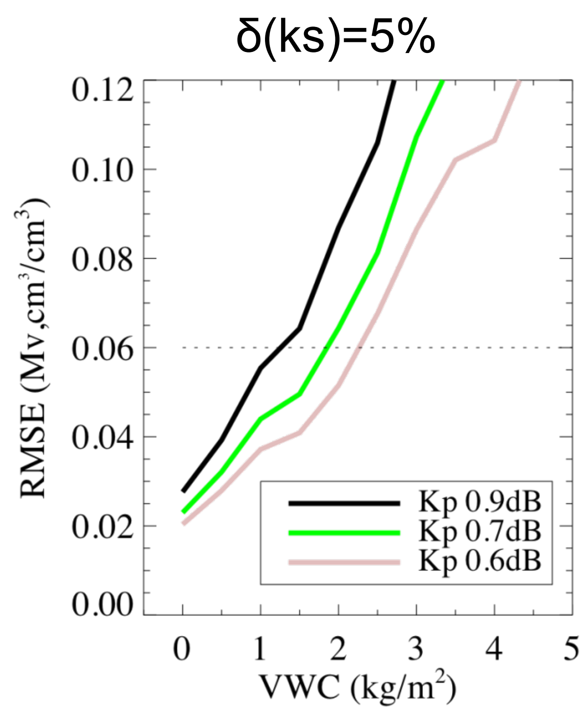
Cumulative percentages of standard deviation of HH backscattering coefficients for L1 1km pixel over global land surfaces based on Dubois



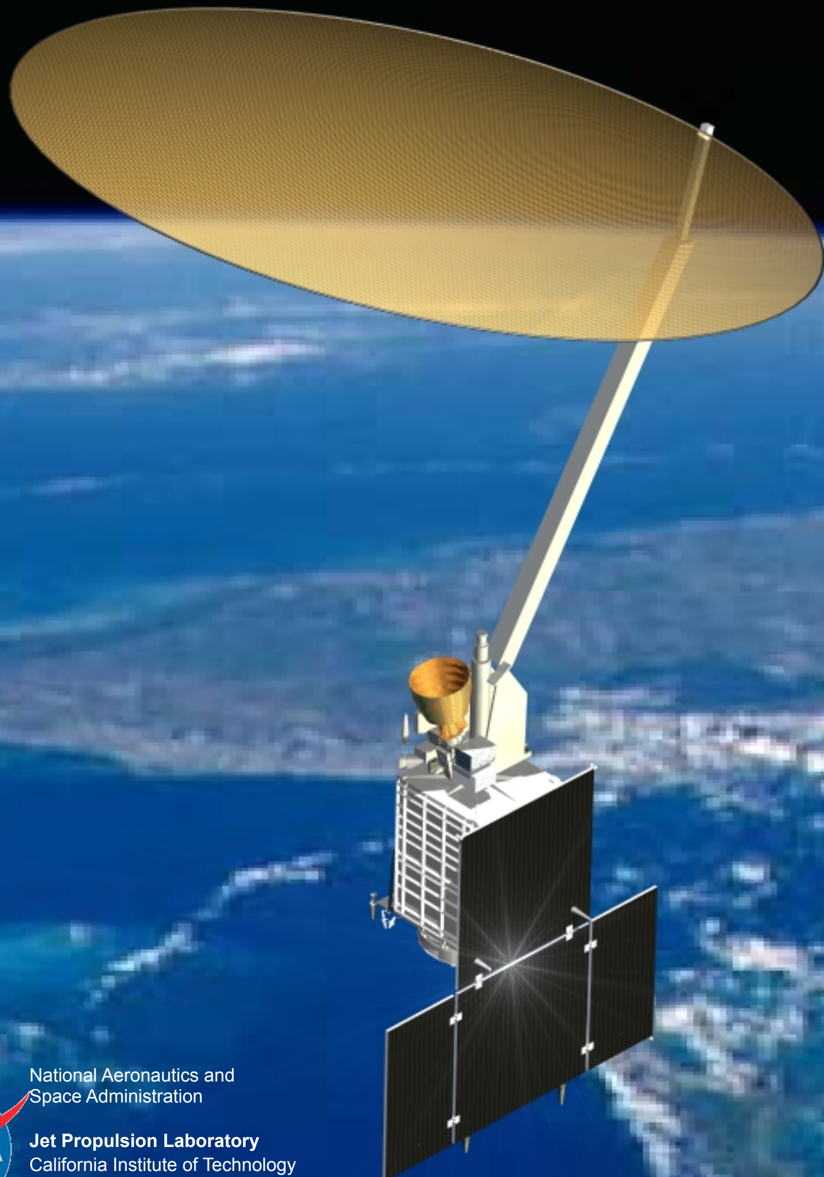
Comparison of backscattering coefficients between Dubois model and AIEM model with wavelength 24 cm, volumetric soil moisture 25%, RMS height 1 cm. For AIEM: correlation length 10 cm with exponential correlation function

Error budget

- SPM/DSM is used for forward and retrieval. The input has the 3-channel input. Mv & VWC were retrieved with roughness knowledge.
- 1500 pts were randomly selected within one orbit of the CONUS simulation. Each bin on the x-axis (0.5 kg/m2 in VWC) has at least 100 sample points.
- The three cases of Kp correspond to the case (A), (B), and (D) in the previous slide.
- The noise source includes 5% surface roughness (ks) error as well as the Kp noise.



The Soil Moisture Active and Passive (SMAP) Observing System



CEOS Workshop

Mike Spencer, Richard West

Pasadena, CA

Nov 18, 2009

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Outline

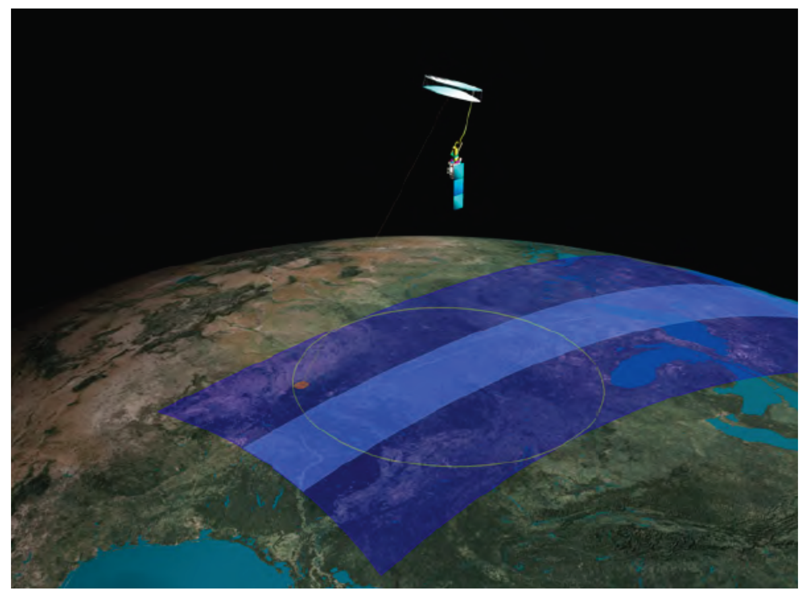
- Key driving science requirements for SMAP mission.
- SMAP observation concept.
  - Real-aperture radiometer
  - High resolution radar product
- SMAP instrument and data product key features.
- Calibration Summary
  - RFI
  - Error budget

SMAP Mission

- The SMAP mission will measure global soil moisture and surface freeze/thaw state from space.
  - Soil moisture products at 10 km resolution, 4% volumetric accuracy.
  - Freeze-thaw products at 3 km resolution.
  - 3-day global coverage.

- SMAP mission currently in Phase B, with a planned launch date in 2013.

- SMAP measurement approach:
  - Passive L-Band radiometer (provided by GSFC) with 40 km resolution
  - Active L-Band Synthetic aperture radar (provided by JPL) with 3 km resolution
  - Shared-aperture rotating mesh antenna.
  - JPL in-house developed S/C.



Level 2 Science Requirements for Instrument Measurements

Coverage/Revisit

- Average revisit time of 3 days for soil moisture globally.
- Morning observation time for soil moisture.

Incidence Angle

- Constant incidence angle for measurement between 35° - 50°.

Radiometer

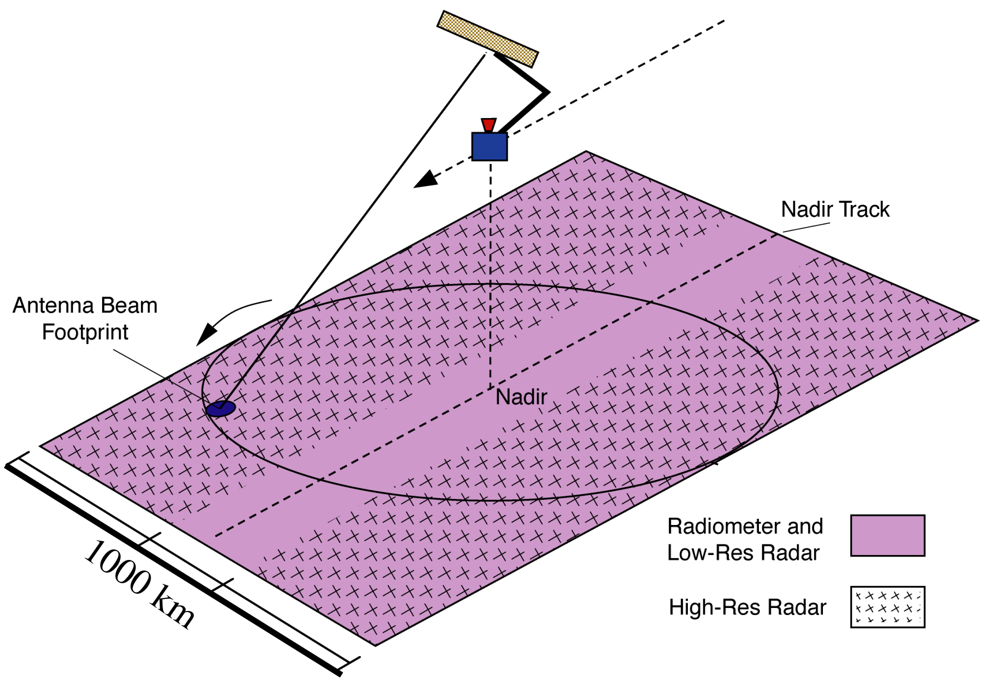
- Frequency: L-Band (1.4 GHz).
- Polarizations: V, H, U.
- Resolution: 40 km.
- Relative Accuracy: 1.3 K.

Radar

- Frequency: L-Band (1.26 GHz).
- Polarizations: VV, HH, HV (or VH).
- Resolution: 3 km
- Relative measurement accuracy < 1 dB for each channel at 3 km resolution.
- Accuracy requirements met for minimum σ_o of -25 dB.

SMAP Instrument Key Features

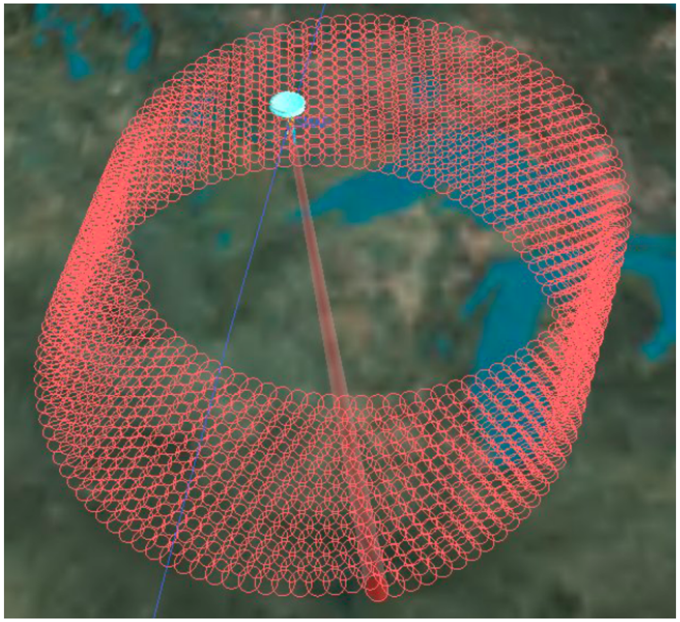
- To meet requirement for 3-day revisit time at AM local time…
  - ⇒ *1000 km swath at 670 - 680 km dawn/dusk sun-synchronous orbit.*
- For wide measurement swath of combined L-Band active and passive measurements…
  - ⇒ *Conically scanning reflector antenna.*

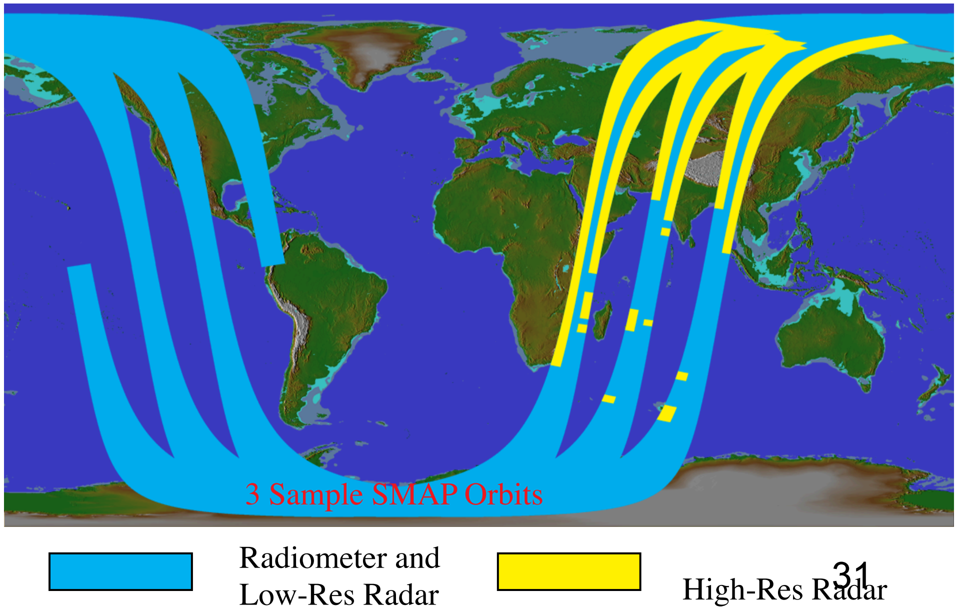


- To achieve L-Band passive resolution of 40 km and and active resolution of 3 km …
  - ⇒ *6 meter aperture antenna*
  - ⇒ *14.6 rpm rotation rate*
  - ⇒ *Real-aperture radiometer*
  - ⇒ *Synthetic-aperture radar processing*
- Incidence angle
  - ⇒ *Near-constant 40 deg incidence angle*

SMAP Mission Concept: Data Collection

- Radiometer data collected continuously:
  - Entire orbit.
  - All 360 degrees of antenna scan (both forward and aft).
  - Capability for periodic “cold sky” looks.
- High-resolution SAR data:
  - Collected only on forward arc of scan
  - Collected only on morning portion of orbit
  - Collected only over land (using built-in land mask file).
- “Bonus” radar low-resolution, real aperture data
  - Collected continuously like radiometer data; entire orbit, 360 deg

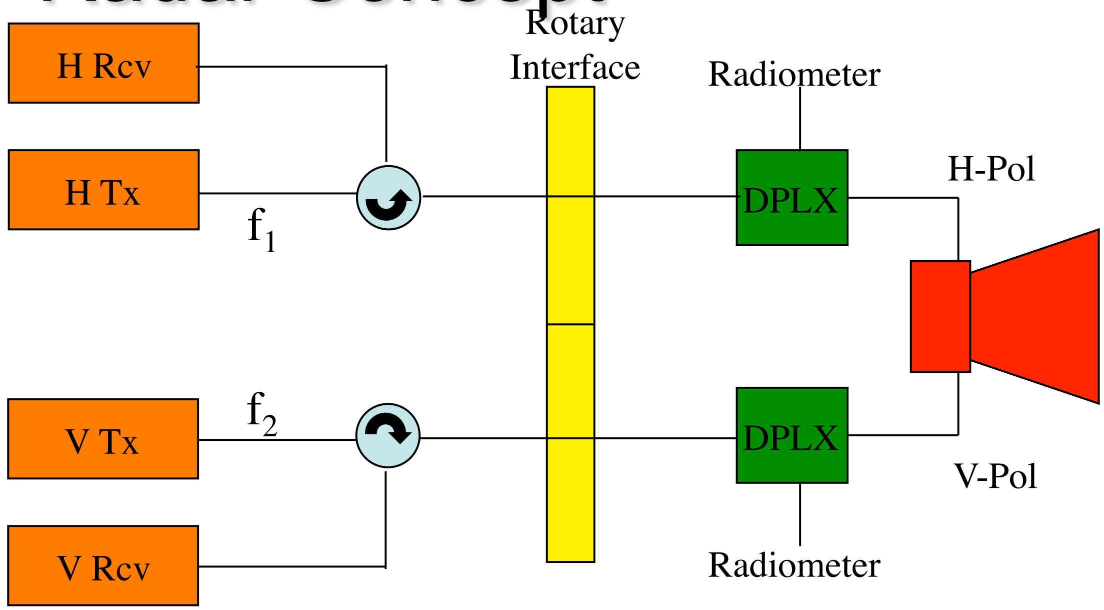


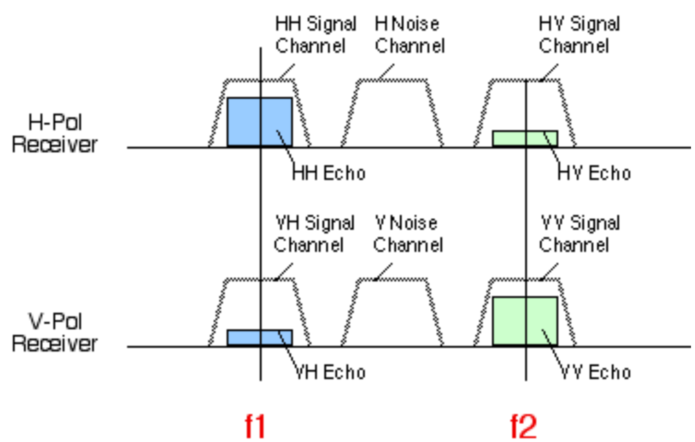


SMAP Radar Concept

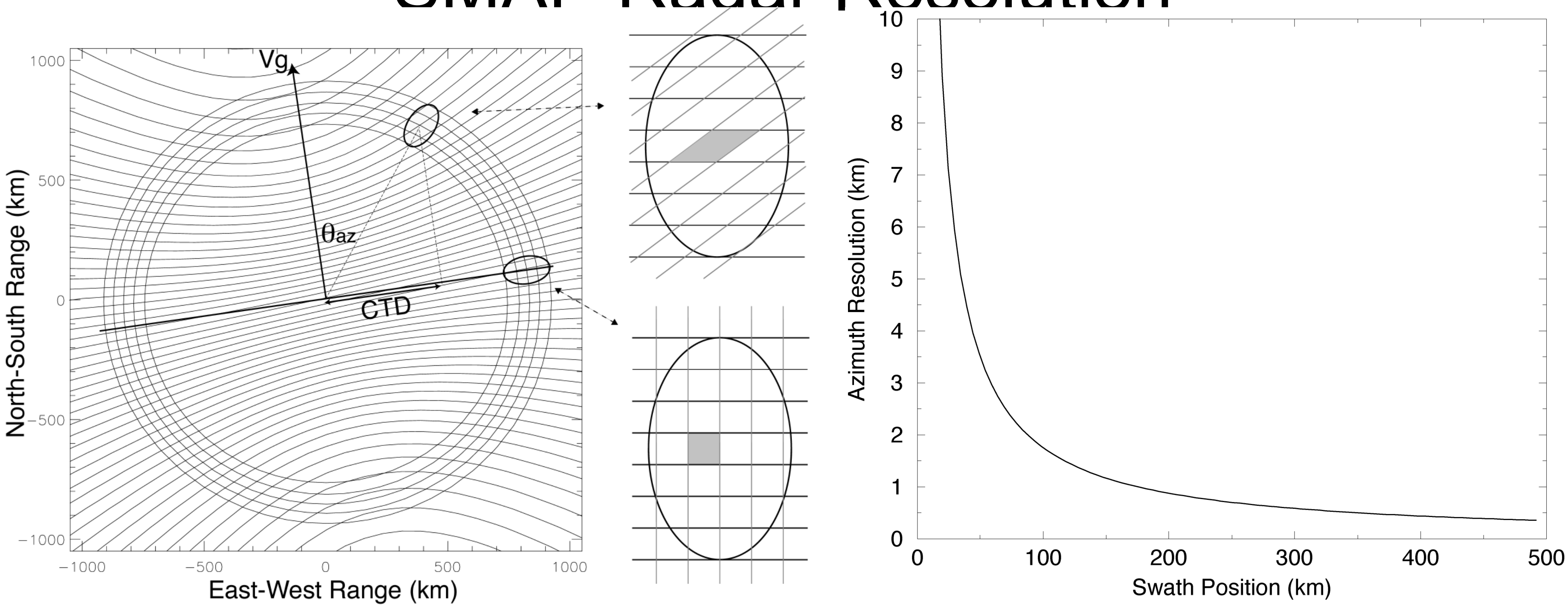
Radar Design Characteristics

- Peak transmit power (at output of SSPA unit): 200 W
- PRF: Nominally 3.5 kHz. Adjustable +/- 3% by look-up table once per antenna rotation.
- Pulse length: 40 μs
- Pulse modulation: Linear chirp at 1 MHz
- Channels (HH,VV,HV, noise-only)
- Timing: Simultaneous transmit and receive on H and V ports at two separate frequencies. Tunable over L-Band 80 MHz allocation.
- Cross-Pol Channel: Additional detection channel in HH receiver change at other frequency
- Each of three channels paired with “noise-only measurement



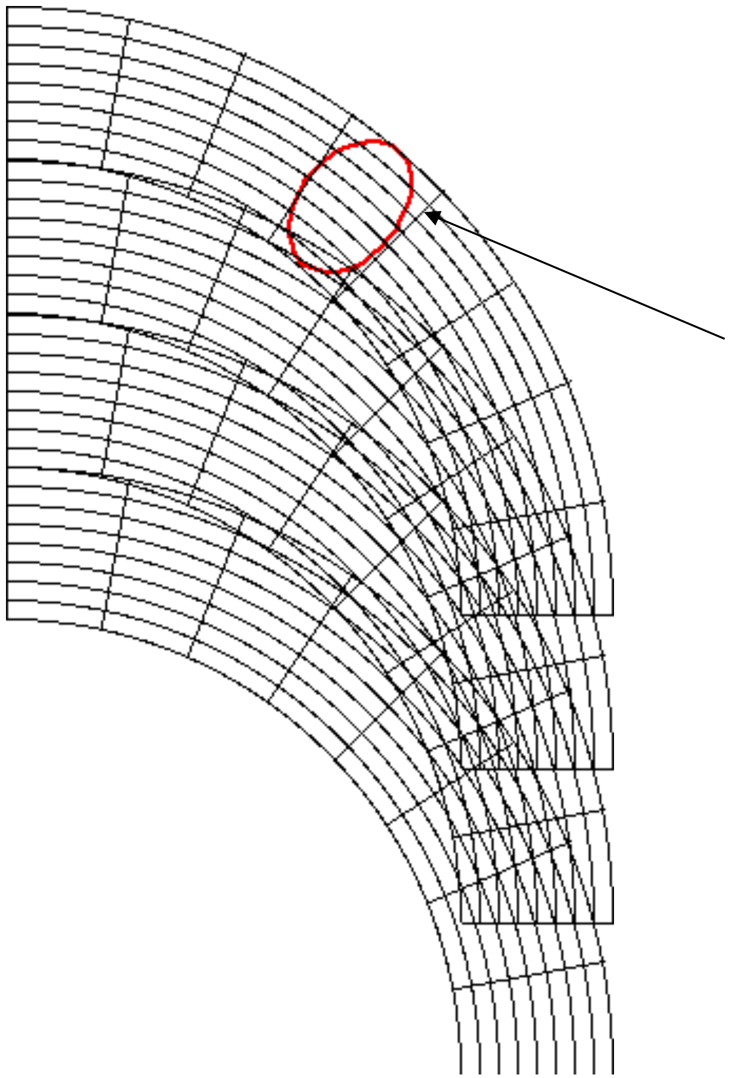


SMAP Radar Resolution



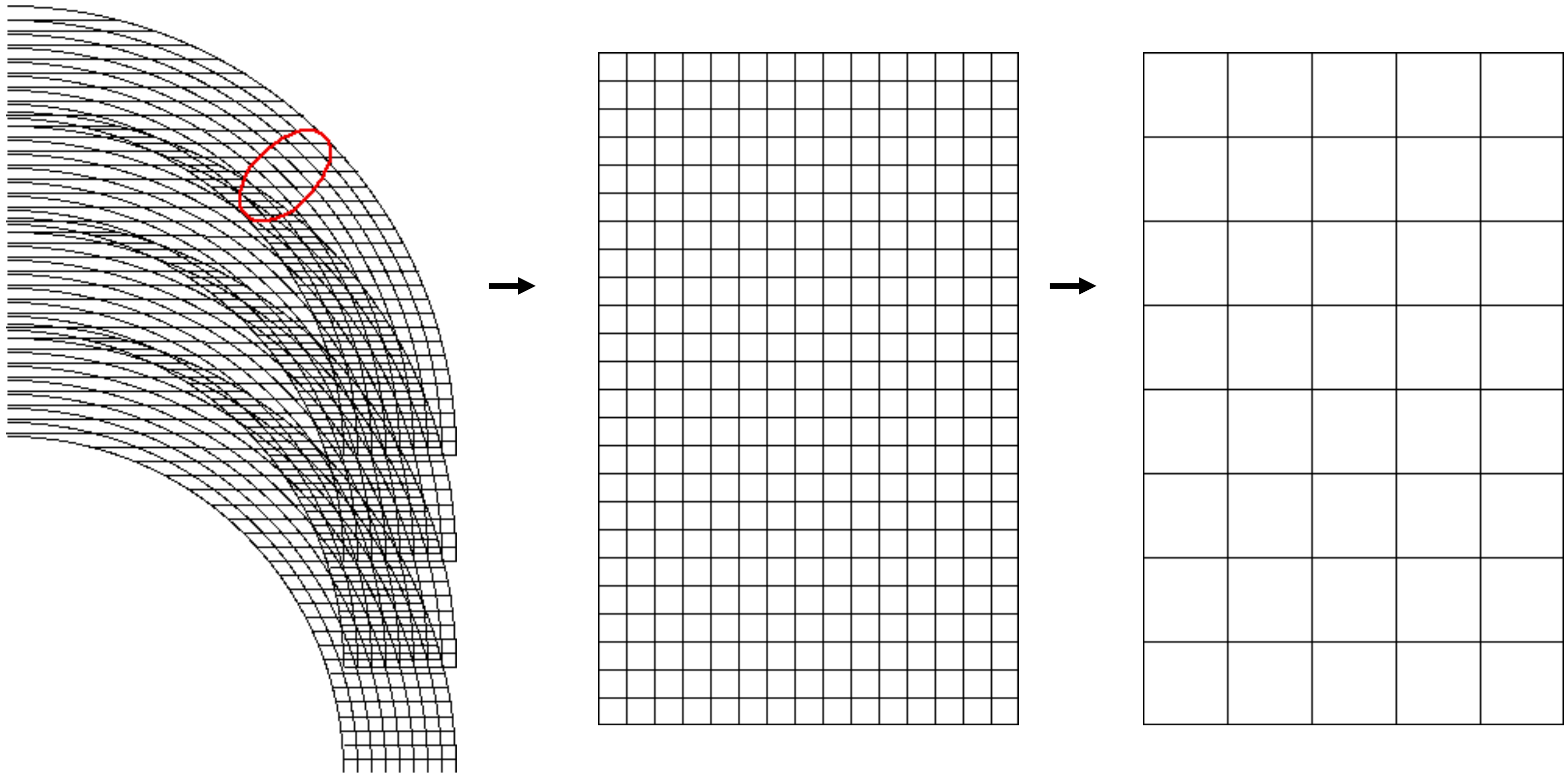
- Unfocused SAR processing.
- Azimuth resolution, and number of azimuth looks, driven by unique scanning geometry.
- High-resolution SAR data that meets science requirements for resolution and accuracy is over outer 70% of the measurement swath.

Low-Resolution (Real Aperture) Products



- Time ordered, 6 km × 30 km range "slices" through antenna footprint (resolution and grid spacing not shown to scale).
- Somewhat similar to SeaWinds Ku-Band backscatter product.

High-Resolution Radar Data Product



Single-Look, Time-Ordered Data (internal use only)

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

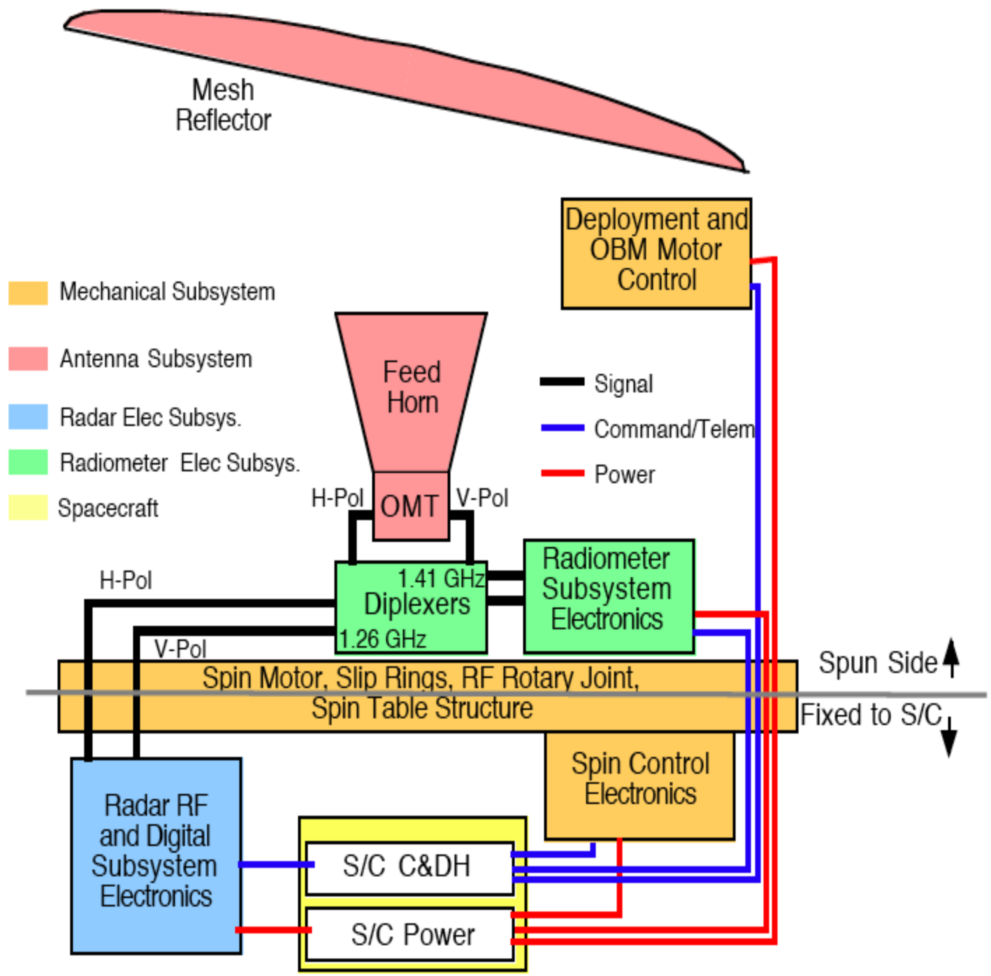
1 km Gridded, Re-Sampled Data (L1C)

- 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.

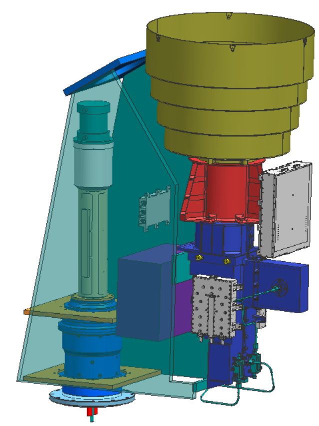
3 km (or whatever) Average Data

- 1 km posted product can be averaged up to 3 km, 10 km, etc. by investigators (using nested grids).
- Improved number of looks (and hence precision) at expense of spatial resolution.

SMAP Instrument Concept

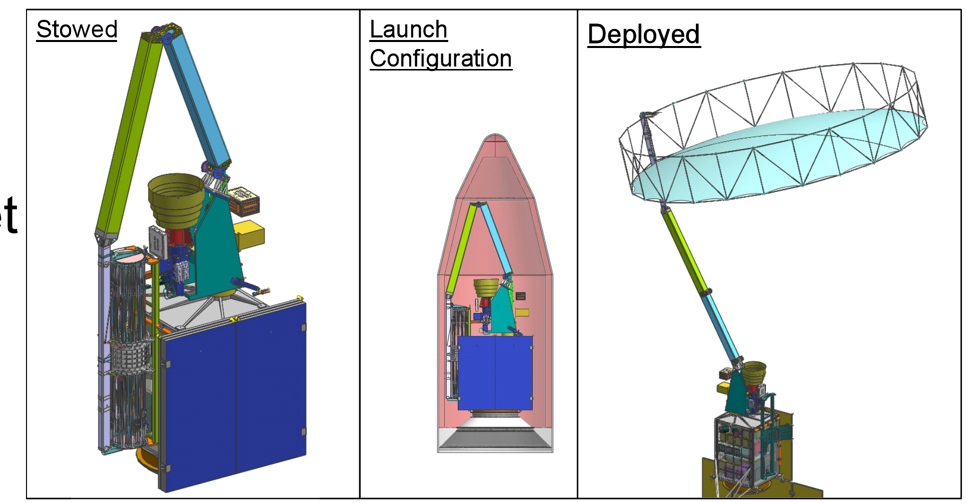


- Antenna Subsystem
  - Deployable mesh antenna, boom
  - Shared L-Band feed horn
  - Spin mechanism, slip rings
- Radar Electronics Subsystem
  - Includes RF interface from despun to spun side
- Radiometer Electronics Subsystem
  - Includes diplexers to separate radar and radiometer frequencies



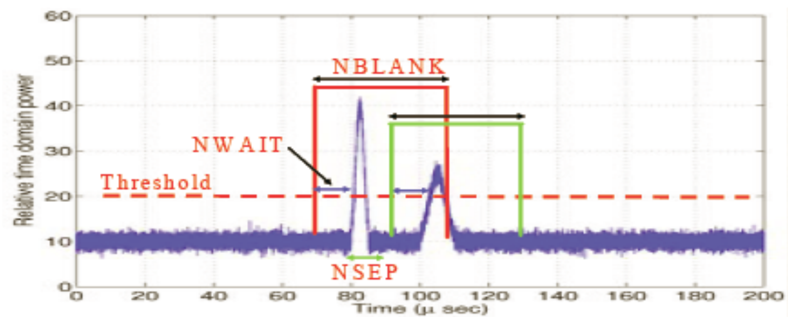
Mesh Reflector

- Key antenna requirements
  - Polarization: Dual-pol L-Band feed
  - Beamwidth: < 2.7 deg at 1.26 GHz
  - Beam Efficiency: 90% at 1.4 GHz
  - Off-nadir look angle: 35.5º
  - Mesh Emissivity: < 0.004 at L-Band
  - Pointing: 0.3º stability, 0.1º knowledge
- Antenna concept uses deployable mesh technology demonstrated in space for communications applications
- Antenna concept has been demonstrated in simulations to meet requirements while rotating.

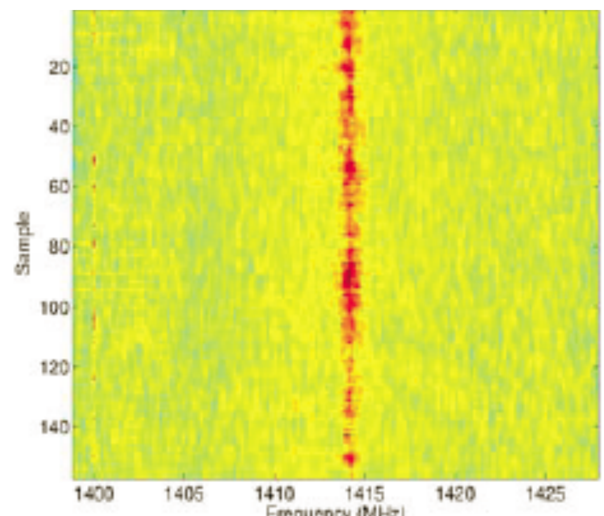


RFI: Passive Radiometer

- Radiometer operates in L-Band "protected band", but might see leakage from adjacent bands.
- Mitigation Approach: Planning on a variety of techniques with impact to HW and ground processing.
- Detection
  - Time: look for pulses
  - Frequency: look for carriers
  - Signal statistics: test for Normality
- Mitigation
  - Remove corrupted time/frequency bins
- Baseline instrument design
  - Time-domain detection and blanking
  - Digitally implemented frequency sub-banding and Kurtosis check being evaluated for inclusion in radiometer design



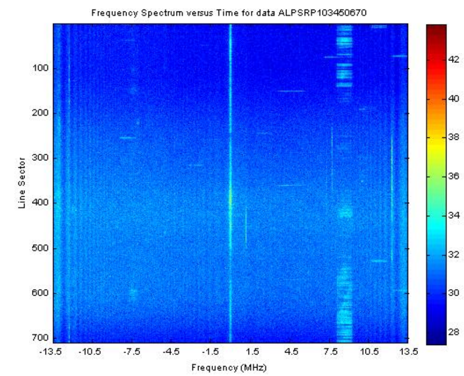
Time domain example
(pulsed RFI)



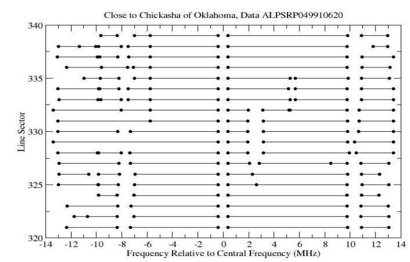
Time-frequency example
(narrow-band RFI)

RFI: Active Radar

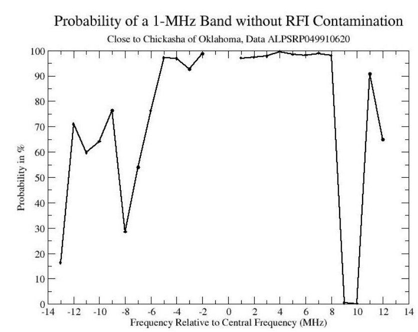
- Radar operates in "shared band" with lots of interferers.
- RFI mitigation strategy:
  1) Avoid "bad" portions of spectrum by tuning carrier according to pre-loaded table.
  2) Filter raw data in ground data processing if RFI is present.
- Characterize the L-Band RFI environment with ALOS/PALSAR data
  - Examine data close to the sites of interest in US and international for all available times.
  - Look for frequency bands which are consistently RFI free.
  - Calculate the probability of being RFI free as a function of frequency.
- Baseline Mitigation Strategy
  - Carrier frequency tunable over entire 80 MHz band
  - Large dynamic range to accommodate strong emitters
  - Residual RFI to be detected and removed in ground processing



Time of Data Take



Frequency band without RFI Contamination, sectors 320 to 340 are shown



Probability of a 1-MHz band without RFI Contamination for the whole data set

Radar Measurement Accuracy Budget

Error Source	Allocation (dB)
Kpc	0.72
Calibration	0.35
Contamination Terms (RFI, ambiguities, etc.)	0.40
Total (RSS)	0.9
Requirement	1.0
Margin (lin)	0.1
Margin (rss)	0.43

- Radar relative accuracy budget is focused on determining *changes* in backscatter cross-section.
- Kpc is purely random term related to radar speckle and thermal noise and is driven by
  - Number of looks
  - SNR
- Radiometric calibration is determined primarily by
  - Knowledge of *changes* in transmit power and receiver gain.
  - Knowledge of *changes* in system RF losses.
  - Knowledge of pointing *changes* (primarily in elevation)
- Dominant contamination effect expected to be from RFI.

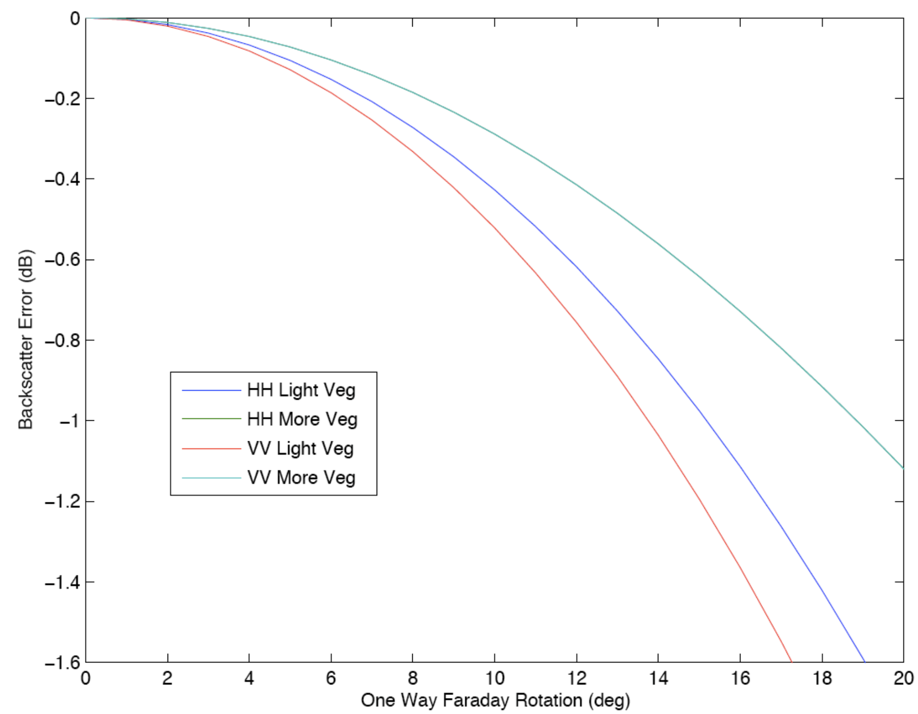
Radiometer Measurement Accuracy Budget

Error Source	**Allocation (K)**
NEΔT	0.57
Antenna pattern	0.44
Mesh emissivity	0.31
Gain, offset uncertainty	0.4
Faraday rotation	0.2
RFI	0.1
Total	1.1
Requirement	1.3
Margin (lin)	0.2
Margin (rss)	0.7

- NEΔT is set by front-end losses (3.2 dB), integration time (fore+aft), & bandwidth.
- Antenna pattern errors include instability of main beam efficiency; uncertainty in solar, sidelobe, space, and cross-pol contributions.
- Mesh emissivity is due to uncertainty in emissions and in gain.
- Gain & offset uncertainty is due to thermal fluctuation & finite time for internal calibration.
- Faraday rotation: residual remains after using 3rd Stokes to correct for it.
- RFI allocation is residual after mitigation.
- Total is found by adding mesh and gain, offset errors, then RSSing this with everything else and dividing by main beam efficiency (91%).

Faraday Rotation

- L-Band data susceptible to errors due to Faraday rotation (FR).
- FR a function of TEC and viewing geometry.
- Baseline measurement strategy is to use only 6 AM measurements to generate soil moisture.
- Radiometer: U-channel used to compute and apply FR correction
- Radar: For AM measurements, FR is relatively small (< 6 deg 90% of time) and results in small radiometric error (< 0.2 dB) which is likely correctable to better than 0.1 dB with coarse a priori knowledge of TEC.



Conclusions

- SMAP system is combined L-Band radar/radiometer for the measurement of soil moisture and surface freeze/thaw state.
- SMAP uses shared-aperture conically scanning deployable mesh antenna to achieve wide measurement swath, required spatial resolution.
- SMAP utilizes proven technologies in a unique way to meet science requirements.