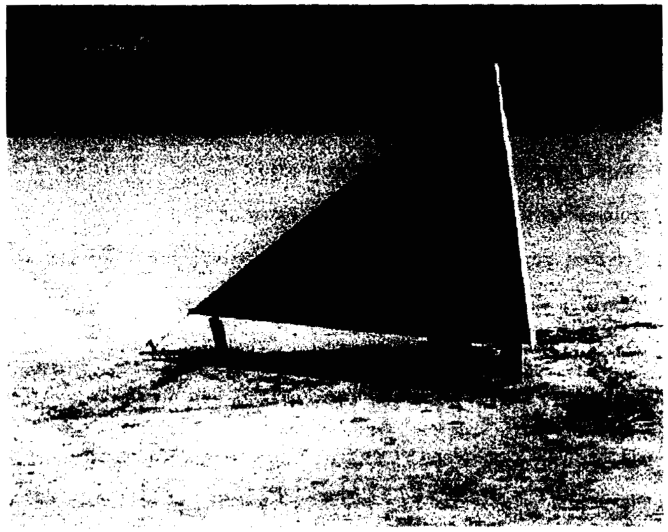

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Lessons Learned from SIR-C Calibration

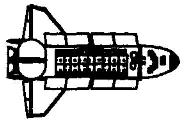
ASAR Workshop

June 25-27, 2003

Anthony Freeman

Overview

- What was SIR-C?
- How well did the radar system function?
- What was the calibration approach?
- What were the calibration results?
- Were there any valuable lessons learned?



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SHUTTLE RADAR LAB (SIR-C)

Three frequency SAR system: L-, C- and X-band (24 cm, 6 cm and 3 cm)

Multiple polarizations: Horizontal (H) and Vertical (V) transmit and receive for L- and C-bands, Vertical for X-band

Selectable illumination geometry:

- Antenna mount - fixed at 40° in elevation
- Electronic beam steering at L- and C-band, ±23° elevation, ±2° azimuth
- Mechanical steering in elevation for X-SAR
- Left or right side looking, controllable by Orbiter orientation

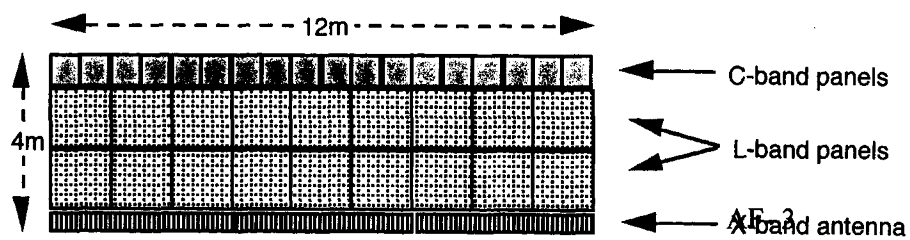
Multiple operational modes:

- Single, dual or triple frequency
- Single, dual or all polarization's in L- and C-band
- SCANSAR mode in L- and C-band for wider swath

Digital data system:

- 100% of data stored on-board in digital cassettes
- Real-time link or playback of recorder data via TDRS

The SIR-C/X-SAR antenna



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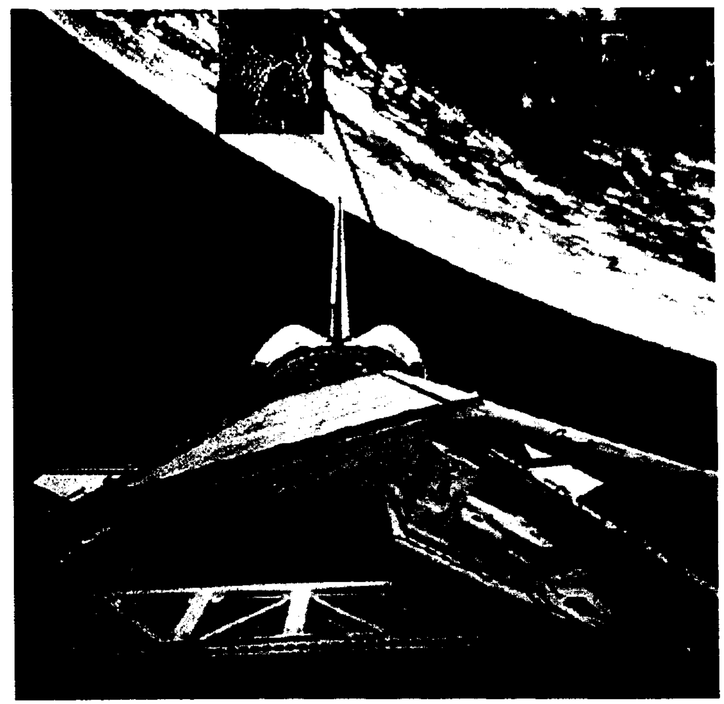
SIR-C

SYSTEM PARAMETERS:

- Orbital Altitude - 225 km
- Mission Duration - 10 days
- Resolution typically - 30 x 30 m on the surface
- Look Angle Range - 17 to 63 degrees from nadir
- Bandwidth - 10, 20 and 40 MHz
- Pulse Repetition Rate - 1395 to 1736 pulses per second
- Total Science Data - 50 hours/channel/mission
- Total Instrument Mass - 11,000 kg
- DC Power Consumption - 3000 to 9000 W
- Data Rate - 45-90 Mbits/s
- Launch Vehicle - Space Shuttle Endeavour (KSC)



- SPECIAL FEATURES:

• Digital chirp	- Flexibility in chirp length and bandwidth. Chirp can be 'up' or 'down'
• Block floating point quantizer	- 8 bit to 4 bit BFPQ doubles swath width - gives good dynamic range with slight increase in quantization noise.
• SCANSAR	- Antenna beam sequentially stepped across track (up to 4 beams) to increase swath (burst mode)
• Beam spoiling	- Phase shifters used to broaden beam in elevation
• Azimuth tracking	- Extends aperture synthesis time; improves azimuth resolution (Spotlight mode) or gives more looks
• PRF hopping	- Used to resolve Doppler ambiguities caused by pointing uncertainties
• Built-in-test	- Used for health check on active antenna elements and assess antenna performance

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SHUTTLE RADAR LAB

- FAILURES:

  1. One C-band panel failed during SRL-1
  2. Two C-band panels failed on transmit only during SRL-2
  3. Antenna pattern model broke down for electronic steering angles > 17.5° - both amplitude and phase behavior was anomalous
  4. Command S/W for changing radar set-up during a data-take had minor problems
  5. One tape recorder failed during SRL-2 (loss of some data)
  6. 3 transmit/receive (T/R) module failures

SHUTTLE RADAR LAB

- SUCCESSES

1. All radar modes worked
2. SCANSAR test was successful
3. Repeat-pass interferometry between flights and during SRL-2. Baseline 50-100m (3-frequency interferometry)
4. Along-track interferometer over Gulf Stream produced current speeds
5. Radar performance was better than specifications in most cases
6. All science targets were acquired - some targets of opportunity added during missions
7. APL on-board processor produced real-time C-VV wave spectra
8. T/R BITE test was successful

SIR-C CALIBRATION REVIEW

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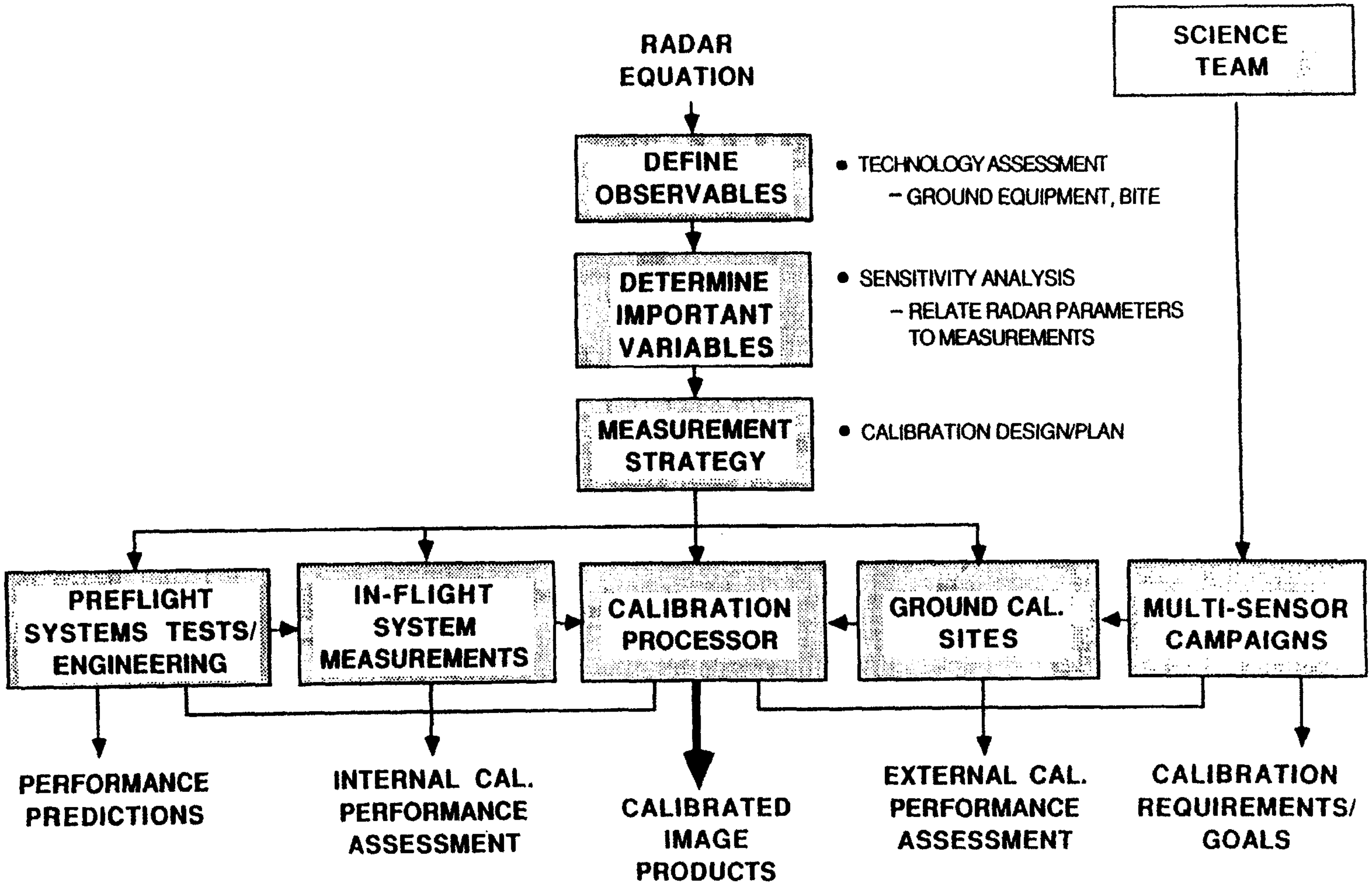
SIR-C PROJECT CALIBRATION PHILOSOPHY



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SIR-C CALIBRATION GOALS

ESTABLISHED FROM SCIENCE REQUIREMENTS VIA:

$$X = F(\sigma^o) \text{ so } \delta X = \frac{\partial F}{\partial \sigma^o} \cdot \delta \sigma^o$$

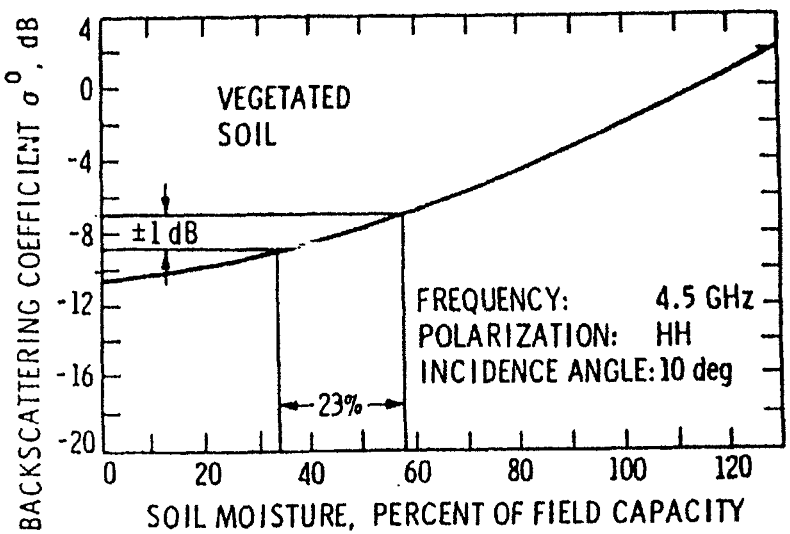
$$\text{If } \delta X \le X_o \text{ then } \delta \sigma^o \le X_o \left(\frac{\partial F}{\partial \sigma^o} \right)^{-1}$$

Short term relative calibration uncertainty	± 1 dB
Long term relative calibration uncertainty	± 1 dB
Absolute calibration uncertainty	± 3 dB
Across frequency calibration uncertainty	± 1.5 dB
Polarimetric amplitude channel imbalance	± 0.4 dB
Polarimetric phase channel imbalance	± 10 deg
Polarimetric isolation between channels	< - 30 dB

RADIOMETRIC CALIBRATION; EXAMPLE 1
TEMPORAL AND SPATIAL VARIABILITY OF SOIL MOISTURE

Objective: Discriminate soil moisture over 5 different levels from wet to saturation

Effect of Soil Moisture on Backscatter Coefficient



Reference : ULABY (85)

RELATIVE CALIBRATION: SHORT TERM ± 1 dB
LONG TERM ± 1 dB

SIR-C CALIBRATION

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- **WHAT IS THE RADIOMETRIC CORRECTION FACTOR, K_s?**

START FROM THE (THERMAL) SIGNAL-TO-NOISE RATIO (SNR)

$$SNR \approx \frac{P_t G_A^2 \lambda^2 L_s \sigma^\circ c \tau_p \lambda R G_p}{(4\pi)^3 R^4 \boxed{k_b T F B_n} 2 \sin\theta_i L}$$

THIS SAYS THAT THE POWER DUE TO THE TARGET SCATTERING IN THE IMAGE IS:

$$P_s' = \frac{P_t G_A^2 \lambda^3 L_s c \tau_p G_p \sigma^\circ}{(4\pi)^3 R^3 2 \sin\theta_i L}$$

I.E.

$$K_s = \frac{P_t G_A^2 \lambda^3 L_s c \tau_p G_p}{(4\pi)^3 R^3 2 \sin\theta_i L}$$

- **IN RADIOMETRIC CALIBRATION, WE CAN EITHER:**

- MEASURE EACH OF THE TERMS IN THE ABOVE TO GET K_s, (INTERNAL CALIBRATION)
or
ESTIMATE K_s FROM A SERIES OF POINT. TARGETS (EXTERNAL CALIBRATION)

SENSITIVITIES

Parameter	Uncertainty (dB)
P_t = peak transmit power (W)	0.2
G_A^2 = two-way antenna gain	0.8
λ = wavelength (m)	0.01
c = speed of light (m/s)	0.0
τ_p = pulse length (s)	0.01
L_s = system losses	0.3
R = slant range (m)	0.01
θ_i = incidence angle	0.2
L = antenna length (m)	0.01
G_p = Processor gain	0.4
RSS TOTAL	**0.95**
Uncertainty across images	1.30
Calibration device RCS uncertainty	1.0
Absolute Calibration uncertainty	**1.6**

Lessons Learned from SIR-C Calibration

Calibration Devices

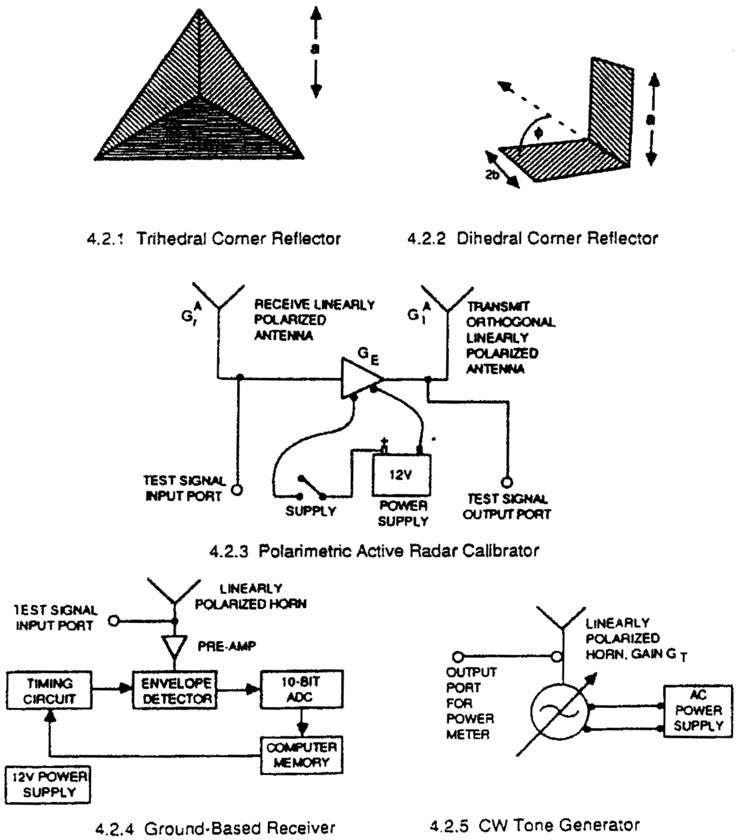
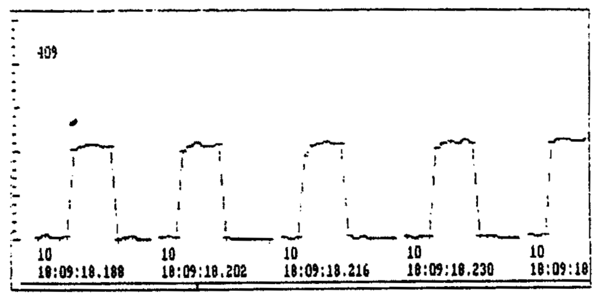
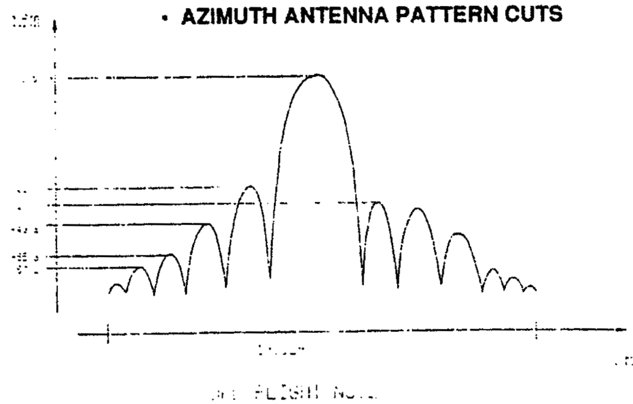


Figure 4.2 Basic Designs of SIR-C Calibration Devices

- INS RECEIVER MEASUREMENTS (C-BAND) :
  - 2μs SAMPLING (WITHIN THE PULSE)
  - CAN MEASURE BOTH H AND V PATTERNS
  - LOCKS ON TO SYSTEM PRF



- WIDE DYNAMIC RANGE - - 50 dB DUE TO 10-BIT ADC AND ADDITIONAL 30dB DUE TO STEPPED ATTENUATORS
- AZIMUTH ANTENNA PATTERN CUTS

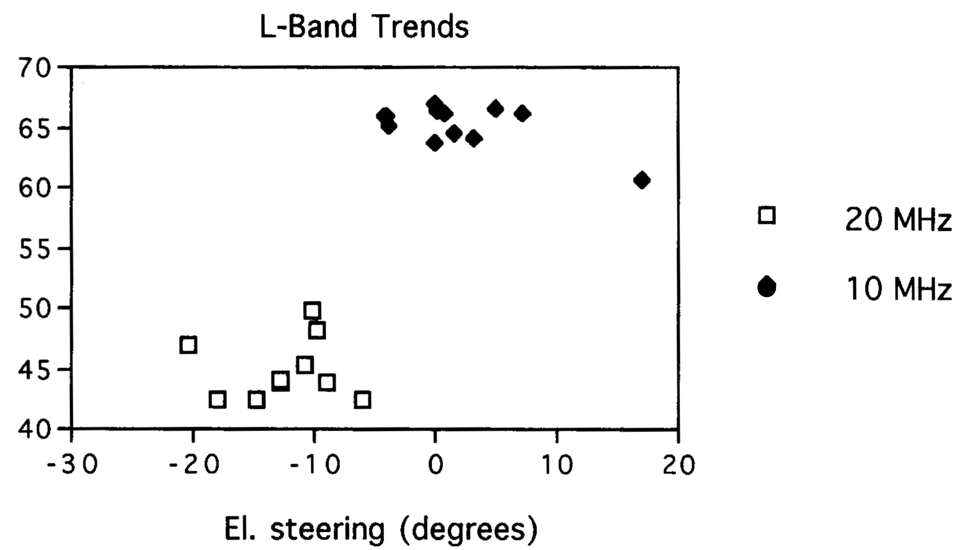


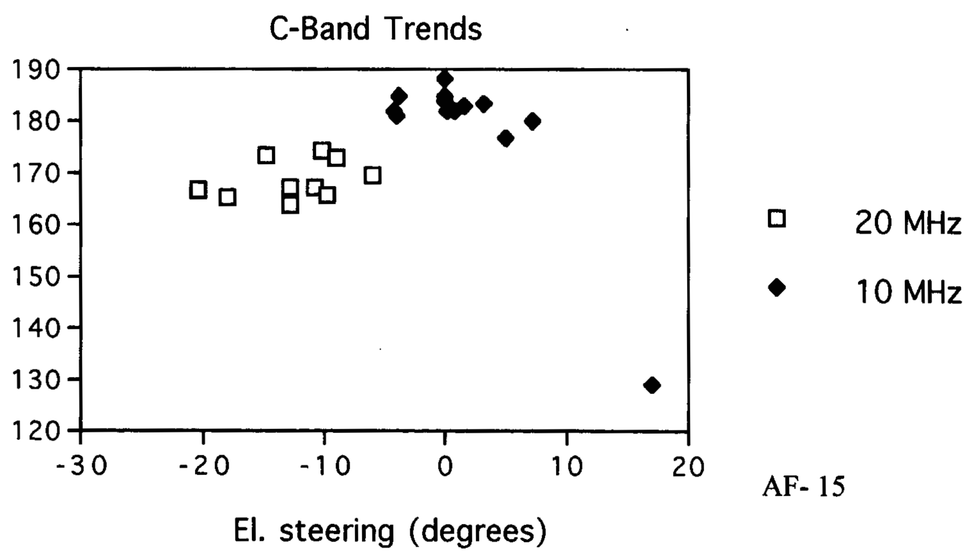
Summary of Ground Receiver Measurements

Measurement	L-Band	C-Band
3 dB Azimuth Beamwidth	1.0°	0.22°
Mainlobe width (null-null)	2.3°	0.5°
Azimuth PSLR	-12.8 dB	-10.4 dB
H-V beam alignment (Az.)	Yes	<4% of 3dB BW
H-V beam alignment (El.)	0.2°	0.3°
L,X Alignment (Az.)	<13% of X 3dB BW	-
L,X Alignment (El.)	0.5°	-
L,C Alignment (Az.)	-	<11% of C 3dB BW
L,C Alignment (El.)	-	0.6°
C,X Alignment (Az.)	-	<27% of X 3dB BW
C,X Alignment (El.)	-	0.5°
3dB El. Beamwidth	4.8°	4.7°

PHASE STABILITY

- Symmetrization results (comparing HV and VH measurements) showed remarkable phase stability





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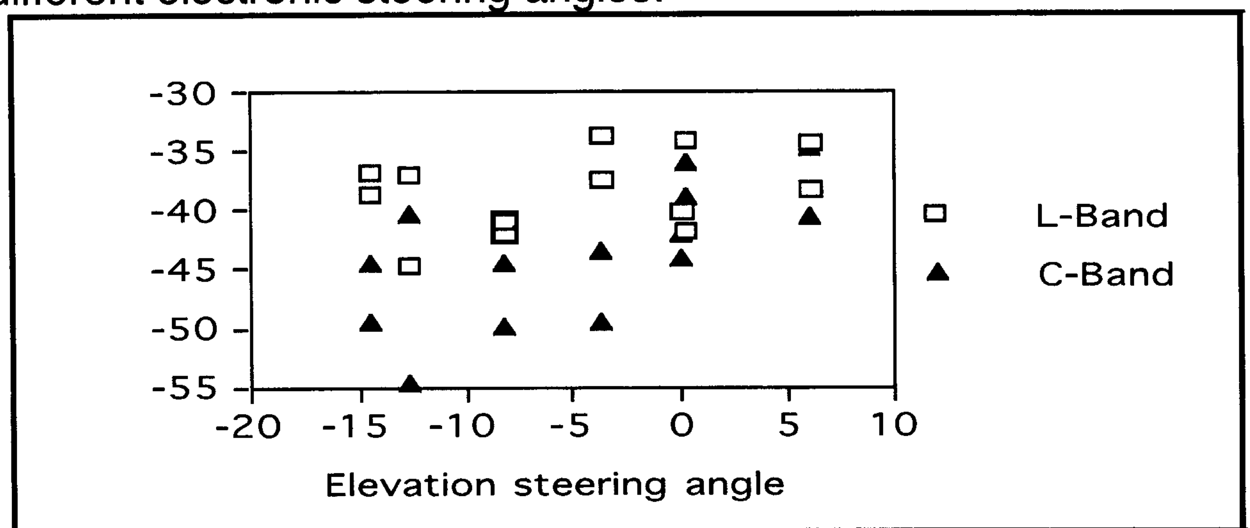
POLARIMETRIC CALIBRATION

- Cross-talk
  - Cross-talk is uniformly less than -30 db across a single image at both L- and C-Band
  - For different electronic steering angles:



Average cross-talk vs. elevation steering angle

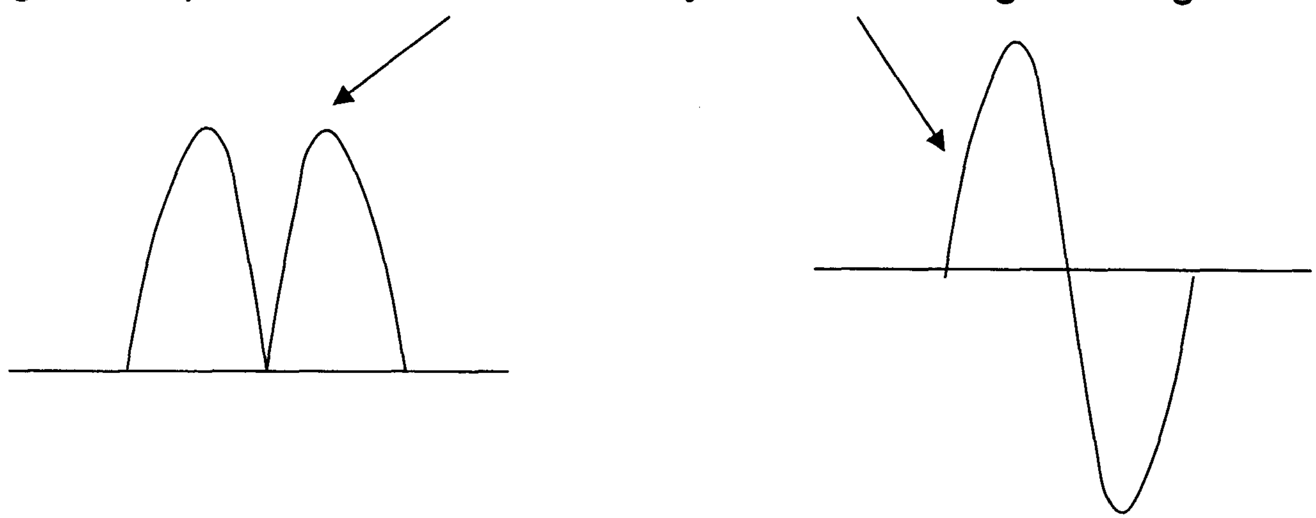
- Conclusion - no need to remove cross-talk from SIR-C data since the goal of -30dB is easily met

POLARIMETRIC CALIBRATION

How is it possible that the cross-talk is less than –30 dB? (the microstrip patch antenna is only specified to have < -25 dB)

This was achieved by arranging for the cross-talk pattern to have a null in the along-track direction

Though often plotted as a null, this really a zero-crossing in voltage



Integrating across the zero-crossing (as in azimuth compression) can result in a greater degree of cross-pol isolation as the cross-pol returns cancel

CALIBRATION UNCERTAINTIES

- Residuals after calibration is applied (SRL-1)

	L-Band	C-Band	Goal
Absolute Calibration	±2.3 dB	±2.2 dB	±3.0 dB
Cross-swath calibration	±1.0 dB	±1.0 dB	±1.0 dB
Pass-to-pass calibration	±1.3 dB	±1.2 dB	±1.5 dB
HH/VV amplitude imbalance	±0.7 dB	±0.6 dB	±0.4 dB
HV/VH amplitude imbalance	±0.2 dB	±0.2 dB	±0.4 dB
HH/VV phase imbalance	±5 deg.	±4 deg.	±10 deg.
HV/VH phase imbalance	±2 deg.	±6 deg.	±10 deg.
Cross-talk	< -33 dB	< -35 dB	< -30 dB

CALIBRATION RESULTS SUMMARY

- Image Quality goals were broadly met
- Noise equivalent sigma-naught values were very low (as low as –50 dB at L-Band and –34 dB at C-Band)
- Channel-Channel registration goals were met
- SIR-C beam patterns were as expected
- SIR-C antennas were close to being reciprocal (same on Transmit and Receive – this was not a given)
- Calibration results were separated into 10 and 20 MHz populations – had different gains and relative phases (path lengths thru' receivers)
- Calibration uncertainties were worse for large electronic steering angles (> ±17 degrees)

OTHER HIGHLIGHTS/LESSONS

- First calibrated SIR-C data was released 33 hours into Flight 1
- Residual cross-track variation after antenna pattern removal < 1.0 dB
- System was phase stable to within a few degrees
- Antenna Cross-talk < -30 dB
- Radiometric calibration goals were met
- HH/VV amplitude balance - close to goal of ±0.5dB
- All Flight 1 and Flight 2 SIR-C data were calibrated during processing (i.e. routinely)
- *Don't expect to get much sleep during a Space Shuttle Mission* ☺