The SIR-C/X-SAR imaging radar took its first flight on the Space Shuttle Endeavour in April 1994. This multi-frequency radar has fully polarimetric capability at L- and C-band, and a single polarization at X-band (X-SAR). Calibration of polarimetric L- and C-band data for all the different modes SIR-C offers is an especially complicated problem. The solution involves extensive analysis of pre-flight test data to come up with a model of the system, analysis of in-flight test data to determine the actual antenna pattern and gains of the system during operation, and analysis of data from over ten calibration sites distributed around the SIR-C/X-SAR orbit track.

The SIR-C mission is the first time a multi-frequency polarimetric imaging radar employing phased array antenna has been flown in space. The effort put into the calibration of SIR-C data products has been considerable and is also unique in that this is the first time anyone has attempted to calibrate a spaceborne radar of this complexity.

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INTRODUCTION

During the first SIR-C mission in April 1994, a number of data-takes were downlinked to JPL and processed into full-resolution images. Several of these images were of sites containing calibration devices such as corner reflectors, transponders and ground receivers. We were able to calibrate the full-resolution data corresponding to these sites and pass some calibrated data products on to SIR-C investigators to perform real-time science during the mission.

To achieve all this within the duration of the SIR-C mission required a great deal of preparation. We put together a Calibration Workstation capable of analyzing the calibration performance of the SIR-C data and of calibrating selected products. SIR-C investigators and their teams played a part in deploying the calibration equipment at over ten of the SIR-C supersites and in sending the deployment data into JPL in a timely fashion. As a result, we were able to calibrate our first SIR-C data product 31:20 hours into the mission and to calibrate 17 other image frames during the mission.

Besides the analysis results provided by the Calibration Workstation, we were able to make use of summary raw data QA plots, showing range spectra, azimuth spectra, histograms and echo profiles generated from raw data, and histograms and amplitude/phase ratios generated from processed image data generated by the Ground Data Processor team at JPL. We were also provided with ground receiver measurements by our colleagues at DLR Oberpfaffenhofen, Raco, Michigan and from the Institute for Navigation in Stuttgart, Germany.

In this paper, we present some of the calibration results we obtained during the SIR-C mission. Further results will be presented at the conference. The SIR-C calibration team would like to express our heartfelt thanks to all those within the SIR-C project at JPL, the SIR-C investigators and their teams and our colleagues from the CEOS Sub-Group on SAR calibration who helped us to calibrate this complex radar system.

RAW DATA ANALYSIS

Our analysis of the raw data Quality Assurance (QA) plots generated from SIR-C data focused on whether the different polarization channels were behaving the same and whether the different beams for each polarization were pointing in the same direction. Doppler spectra estimated from the raw data were compared with preflight antenna model predictions, converting azimuth angles to Doppler frequency. Our initial analysis indicated that:

1. All HV and VH amplitude plots from the raw data appeared identical. We could overlay the echo profiles or raw data histograms, for example, and they were indistinguishable.

2. The Doppler Spectra indicated that all beams for a given frequency were pointing in the same directions. It was difficult to tell from the data whether L-Band and C-band are coaligned but the raw data Doppler centroids looked within 200 Hz of each other. The Doppler spectrum went from 0 to -10 dB (normalized) over a range of +/-1500Hz which was the same as predictions from the preflight SIR-C antenna model.

3. Range spectra were consistent with preflight test results, with bandwidths of around 18.8 (+/- 0.1) MHz at C-band and between 18.1 and 18.7 MHz at L-Band for a 20 MHz data-take.

4. The Calitone was where it should be (at around 5MHz at video frequency) and visible in the range spectra.

5. From the plotted image ratios of HH/VV and HV/VH amplitude and phase, we were able to infer that initially the polarization channels were not registered. Large variations in the HV/VH amplitude and phase in particular were strong indicators of this. We were able to fix this subsequently in the processor once the CAL team had determined the appropriate offsets between the polarization channels (from reflectors, PARC signatures).

GROUND RECEIVER MEASUREMENTS

Several teams of investigators were out in the field making measurements of the SIR-C/X-SAR azimuth transmit antenna patterns. Our colleagues provided us with a very impressive rapid turn-around on their results. Our principal aims in analyzing these patterns were to check whether the patterns were close to the preflight model predictions, and whether the beams corresponding to different polarizations were coaligned. The analysis of these results was given added significance since we knew from the built-in test capability of the SIR-C antenna that one of the 18 C-band panels had failed early on during the mission. Here is a summary of what was found:

1. The C-band preflight azimuth patterns had asymmetric first sidelobes, which corresponds to the measurements seen in the field. Highest sidelobe was -11.4 dB down.

2. The C-band preflight patterns had grating lobes at around 5 degrees off boresight. These were also seen in the field receiver measurements.

3. The first results from Oberpfaffenhofen indicated that the C-band and X-band beams were coaligned in elevation to within a fraction of a degree.

4. From the first results from the Chickasaw site, the CH and CV beams and the LH and LV were aligned in the azimuth direction.
IMAGE QUALITY

1. All the measurements made of the impulse response function showed that the resolution, PSLR and ISLR were well within the specifications for both 10MHz and 20MHz bandwidths. The only time we obtained bad impulse response functions was when the Signal-to-background ratio for a particular target or set of targets is low.

2. After some initial iterations between the calibration team and the processor team, the HH, HV, VH and VV channels are now registered at each frequency to within the limits of our measurement capability (which is +/- 1/8 of a pixel).

3. A data-take over the Flevoland supersite gave us an opportunity to check out our impulse response functions using the high-precision L-band and C-band transponders deployed by our colleagues from the FEL-TNO and the European Space Agency at ESTEC. The impulse response measurements from the ESA transponders (Data-take 82.5 - 10MHz Bandwidth) are summarized below:

<table>
<thead>
<tr>
<th></th>
<th>L-band</th>
<th>C-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution (m)</td>
<td>Azimuth</td>
<td>Range</td>
</tr>
<tr>
<td></td>
<td>6.47</td>
<td>16.66</td>
</tr>
<tr>
<td>PSLR (dB)</td>
<td>-29.8</td>
<td>-24.6</td>
</tr>
<tr>
<td>ISLR (dB)</td>
<td>-22.9</td>
<td>-20.7</td>
</tr>
</tbody>
</table>

There was little or no difference between the polarizations.

RADIOMETRIC CALIBRATION

The first SIR-C scene calibrated was an L-band HH image of Death Valley, California. The next scene calibrated was of Raco, Michigan, which was followed by an Amazon rain forest scene over Manaus, Brazil. All of these scenes had corner reflectors. Our objectives in trying to radiometrically calibrate these images were to see whether the preflight elevation antenna pattern matched that of the actual data and to see what the residual radiometric uncertainties were after the nominal radiometric correction had been applied. Here is a summary of our results:

1. The Death Valley scene was calibrated at MET +31:20 hours. With just the radiometric correction turned on, we were within 2.4DB of being radiometrically calibrated.

2. Residual variation in cross section (from 14 corner reflectors) was ±0.9dB before radiometric correction, ± 0.29dB afterwards.

3. We averaged image powers in the Raco image at L-band in HH, HV and VV polarizations in azimuth. Then we removed range attenuation effects, plus the sine of incidence angle term. What is left should be proportional to the 2-way antenna pattern, modulated by any backscatter variations. We anticipate that backscatter variations with incidence angle for this image (Raco 8.3) should be small, since it is mostly forest. The plots derived from the data are overlaid with the 2-way antenna patterns obtained from the preflight antenna pattern model. Any overall bias between the two sets of curves has been removed. The curves are plotted against the calculated look angle. We assume a Shuttle roll angle of 26 degrees and a mechanical offset between the Shuttle and SIR-C of 14 degrees. Electronic steering angle for this data-take is -9.75 degrees.
4. We have measured the noise-equivalent sigma-zero to be less than -38 dB for LHV and less than -35 dB at C-band for water in data-take 46.7 over the Amazon. We don’t expect those numbers to be constant.

5. Over flat areas, with no roll angle, we were able to remove the antenna pattern variation from the data, with residuals of less than 0.5 dB. The C-band and L-band beams appeared to be misaligned in elevation by about 0.35 degrees.

6. We were able to analyze two adjacent Amazon scenes processed at different times. The results indicated that both the L-band and C-band radars were indeed stable over this timeframe and the processor contribution to the calibration error was < 0.3 dB for absolute calibration.

7. For the rain forest, the residual variation in the backscatter across the swath was +/- 0.18 dB after calibration.

POLARIMETRIC CALIBRATION

Several mode 16 (quad-pol at L- and C-band) data-takes allowed us to check the polarimetric performance of the system. Here’s what we found:

1. The cross-talk is better than -35 dB at L-band and -40 dB at C-band in the main beam.

2. We are able to phase calibrate the quad-pol data fairly easily using corner reflectors or suitable distributed targets. There appears to be some stability in the channel-channel phase differences but its too early to say whether it might be possible to apply an automatic phase correction to take care of phase calibration for all data-takes.

3. As mentioned above, we analyzed two Amazon rain forest scenes from the same data-take, separated by about 12 seconds. This is a good test of the radar short-term stability as well as the impact of the processor on the calibration. After we applied the nominal radiometric correction, symmetrization and cross-talk removal, the remaining calibration parameters were:

   Absolute calibration - 1.4 and 1.7 dB
   HH-VV channel imbalance - 2.87 and 2.7 dB
   HH-VV phase imbalance - 42.67 and 44.46 degrees

   This indicates that the L-band radar is indeed stable over this timeframe and the processor contribution to the calibration error is < 0.3 dB for absolute calibration, < 0.17 dB for the HH-VV amplitude, and < 1.8 degrees for the phase difference.

   The same results for C-band were:

   Absolute calibration - -18.99 and -18.75 dB
   HH-VV channel imbalance - 1.16 and -1.25 dB
   HH-VV phase imbalance - 170.42 and 169.03 degrees

   This indicates that the C-band radar is also stable over this timeframe and the processor contribution to the calibration error is < 0.25 dB for absolute calibration, < 0.08 dB for the HH-VV amplitude, and < 0.5 degrees for the phase difference.

4. In one of the images, there was a patch of dark water on the Amazon River. This gave us an opportunity to check the correlation between HH and VV, which should be close to 1.0 and was in fact 0.9. This is OK. The high HV and VH backscatter for this data also allowed us to check the HV-VH correlation which was close to 1 (0.99) as expected.

5. The high HV and VH backscatter for the forest data allowed us to check the HV-VH correlation which was close to 1 (0.95) as expected.

LOCATION ERRORS

Location errors in the along-track and across-track directions were estimated by comparing corner reflector locations derived from GPS measurements and interpolated form the four corner coordinates of the image. Errors were as high as 5km and as low as 500m. In the across-track direction, the sign was always negative which means the Data Window Position was set too early.

DISCUSSION

There is still a great deal of work to be done on SIR-C calibration. In particular, we need to: determine the roll angle of the Shuttle from the roll-null inserted every second or so in the data; track the system gains versus temperature and time; automatically calibrate the phase between polarization channels; and demonstrate radiometric stability (over long timescales) in the system. So far, we have been able to show that: it is possible to calibrate selected SIR-C data; that the image quality is close to or better than the specified values; that the pre-flight antenna pattern is consistent with the in-flight measurements; that both the L-band and C-band radars were fully operational as polarimetric systems; that the cross-talk between polarization channels is very low; and that the processor contribution to calibration uncertainties is very small.