The X-SAR/SRTM Project Calibration Phase

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Abstract:
After a very successful mission in February 2000, more than 3.5 terra bytes of X-SAR data are waiting to get processed to digital terrain models and radar images. The calibration or correction of the deterministic phase errors is of utmost necessity before starting the operational processing of all acquired X-SAR/SRTM SAR data. As expected, the motion variation of the Space Shuttle in orbit and the dynamic oscillation of the mast caused height errors. The basis for the motion compensation in the processor is the position and attitude data record (PADR) which has been derived from the measurements made during the mission by the different sensors of the attitude and orbit determination assembly. Furthermore there are height errors from the radar noise and also systematic height errors originating from the radar instrument itself that need compensation. Temperature instabilities are the major source for these phase variations. Telemetry data were monitored and recorded throughout the mission, they indicated periodic temperature variations along the orbit path, over the course of a data-take and over the 11 days of the mission. The major phase errors were either measured directly, as was done for the long mast cables, or were derived from the calibration tone phase by analysis. With the responses of the deployed corner reflectors at the calibration test sites, the range delay and the radiometric calibration factor has been found.
This paper summarizes and updates recent publications about the DLR X-SAR/SRTM calibration activities and shows preliminary results for the height accuracy.

1. INTRODUCTION

After a very successful mission in February 2000, more than 3.5 terra bytes of X-SAR data have been copied, screened and stored in a big robot archive at DLR in Oberpfaffenhofen and also at ASI Italy. Now the data are waiting to get processed by a new interferometric processing system to highly accurate, high-resolution digital terrain models and radar images. But before the start of the operational processing, the calibration and validation has to be finalized to produce reliable, calibrated products. [1] The mayor calibration activity in the last 12 months was to analyze the radar and PADR data and to develop appropriate algorithms to correct for the errors due to the mast motion. One problem in the SRTM case are the remaining attitude and position inaccuracies and variations contained in the PADR data which do not allow to completely remove the motion errors. The radar instrument itself caused also phase errors producing a significant height error. These are primarily the radar noise, the mast cable phase variation and the phase lock loop oscillator (PLL) instability in the down converter. The attitude errors are still predominant. Only after their removal can the slowly varying minor instrument phase errors be retrieved and reduced

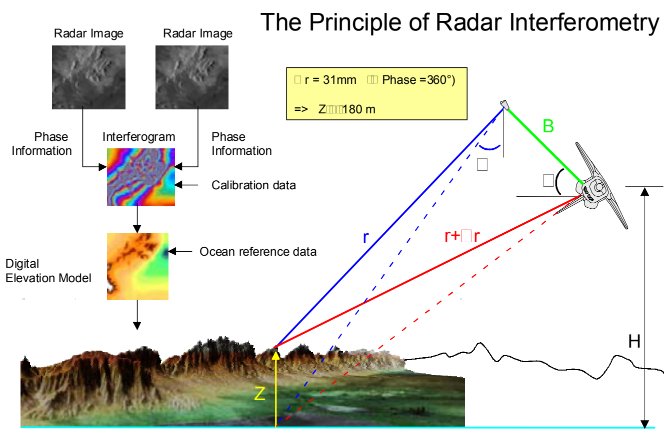


Figure 1: The SRTM single pass interferometer concept

2. TIMING CALIBRATION

SRTM requires the absolute Digital Elevation Model (DEM) pixel position to be accurate within a 20-meter circle for 90% of the data. The precision achievable in SAR image geolocation in principle depends on the knowledge of the following contributions:

Range Errors
An error of the flight path range component contributes directly to the range error in the slant range domain. The same is true for an error in the electronic range delay of the radar instrument. During the geocoding stage phase noise additionally adds on the range timing and can blur the ground range position of the DEM and the image pixels.

Azimuth Errors
Any discrepancy between the clock used for the orbit measurement and the clock in the radar system results in an azimuth shift of the image. The compensation of the mast motion components within the aperture also requires a precise relationship between radar and geometry timing. A

strong mislocalization of the image in azimuth would be caused by the use of a wrong PRF band during SAR processing.

Once per second the relative timing between the X-SAR instrument clock and the clock of the GPS system was measured with a precision of 1 microsecond. We are left with an instrument specific systematic time offset in azimuth and an electronic range delay, which can be considered constant over the 11-day mission. To determine the offset and the delay, we used corner reflectors (CRs) in California with precisely known position. We calculated where the CRs should appear in the slant range image using an a priori timing relationship. Then, we measured the true position of the CRs in the image and used the differences to determine the desired azimuth and range timing offsets.

To verify these timing offsets we used another set of 9 CRs with known position in Oberpfaffenhofen, Germany. This second set of CRs was imaged 16 hours later in the mission than the first one. For the second set our prediction of CR location in the image was only offset in azimuth by 80 cm. The standard deviation of the prediction error was only 20 cm in azimuth and 30 cm in range. From the results above, we expect no significant image location errors due to incorrect timing.

To avoid azimuth displacements caused by a wrong PRF ambiguity band we use the precision Attitude and Orbit Determination Data (AODA) for the PRF band validation. [2]

3. MOTION ANALYIS AND COMPENSATION

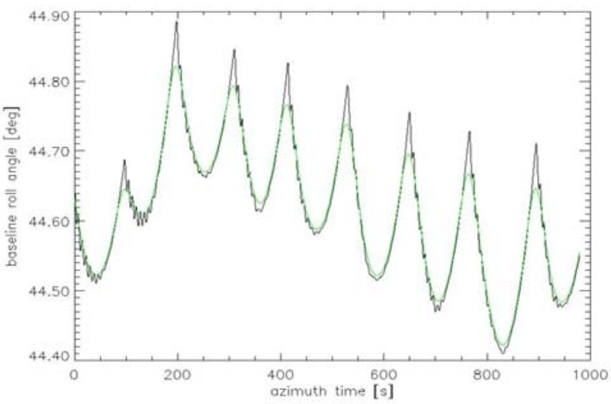


Fig. 2: Baseline roll angle along a data take. The peaks are caused by corrective thruster firings which cause a subsequent damped 50 km period oscillation on the baseline roll component

For SRTM, the platform motion has to be considered during SAR focussing as well as during DEM geocoding. Due to the high mass of the Space Shuttle we assume the primary antenna, contained in the cargo bay, to follow a smooth track, while the secondary antenna is the unstable part, because it is mounted to the end of the 60 m long mast oscillating with a period of around 7 seconds and with amplitudes of about ±4 cm. Without proper motion compensation the focussed SAR image of the secondary antenna would be shifted with respect to the primary image by an amount proportional to the momentary differential velocity of both antennas in the line of sight direction. This differential shift together with the high Doppler frequencies of typically 3 kHz would lead to intolerable phase and height errors. [3] [4]

The problem with the cold gas system, that was designed to support the attitude hold of the orbiter, caused much more frequent attitude corrections and higher velocities in the roll axis that the orbiter attitude control system had to correct for. The Fig. 2 shows the baseline roll axis motion as recorded.

For the DEM geocoding we have to take into account the relatively fast moving baseline vector, which requires using shorter orbit interpolators than for smoothly moving satellites like ERS or Radarsat. We perform the motion correction by compensating the high frequency motion components in the SAR raw data and use the remaining low frequency version of the baseline vector for InSAR processing and DEM geocoding.

4. INSTRUMENT PHASE ERRORS

The primary channel (transmit/receive) of the X-SAR instrument has a 12 m long and 40 cm wide antenna, radiating a 9.6 GHz chirp signal with a bandwidth of 9.5 MHz. In the receive path the radar signal runs through a wave-guide (WG) into the radio frequency (RF) electronics (RFE). The secondary channel uses a receive-only antenna of 6 m length, which was electronically steerable in the along track direction to enable alignment of the primary and secondary antenna beams. The reduced antenna gain (half-length) is well compensated by individual very Low Noise Amplifiers (LNA) installed directly behind each of the six 1m long panels. The received signals are combined in the X-band combiner box (XCB) and down-converted in the X-band down-conversion unit (XDC) to an intermediate frequency (IF) of 135 MHz, routed through a boom cable of approximately 100 m length and through the radio frequency adapter electronics (RAE) into the IF demodulator (IFD).

The transmit path is the same for both channels of the interferometer, therefore phase calibration of the transmit path does not have to be considered. However the two receive channels are designed differently and therefore show different phase variations. [5]

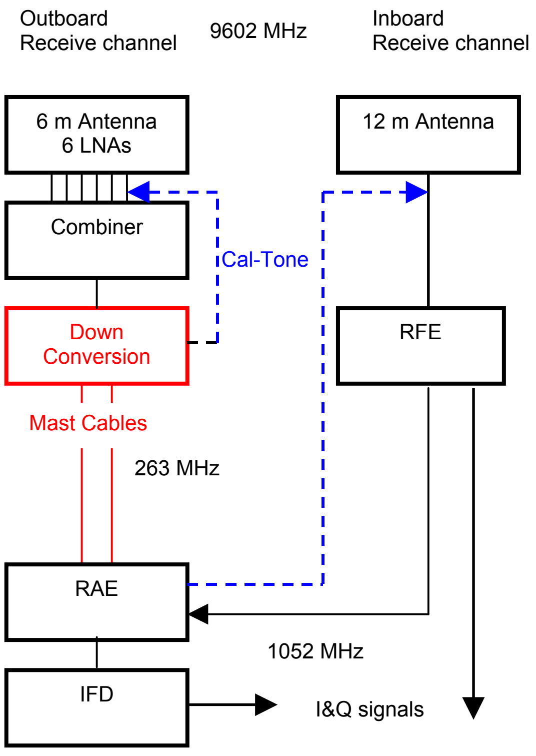


Figure 3: Blockdiagram of the X-SAR Receive channels

Coherence and Signal to Noise Ratio

Since SRTM is a single pass interferometry system, temporal decorrelation over land was therefor not an issue. Volume decorrelation over vegetation may occur, but was not noticed so far. The major decorrelation comes from thermal noise and the analog digital converter quantization noise together in the order of γ=0.93 while decorrelation due to signal azimuth ambiguity ratio (SAAR) and processor interpolation artifacts is only 0.99. The thermal and quanitization noise power was measured during receive only data takes. The received signal power is estimated routinely during the screening process. So we can predict the coherence dependent on the signal power S and the noise N in both channels for the whole mission using

$$\gamma_{Thermal} = \frac{1}{\sqrt{1+\frac{N_{primary}}{S_{primary}}}} \frac{1}{\sqrt{1+\frac{N_{secondary}}{S_{secondary}}}} \quad (1)$$

The actually measured coherence varies from γ=0.87 for low backscatter ocean data, over γ=0.93 for typical land data, to γ=0.95 for bright land scenes. We intend to "filter" the phase with 8 to 16 looks to reduce the corresponding thermal height error well below 4 meters for the observed range of coherence.

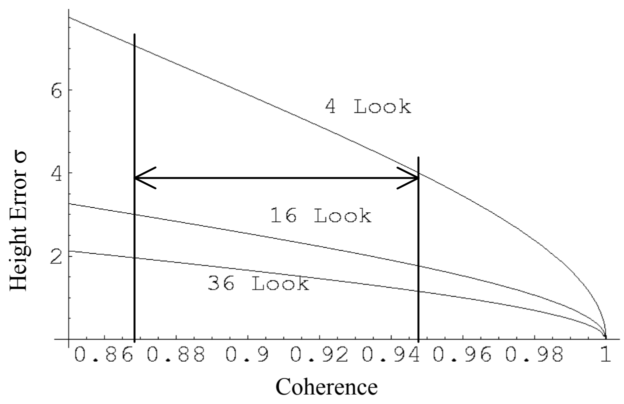


Fig. 4: SRTM X-SAR coherence range and height noise (1σ) depending on the number of looks

Phase Errors due to changing operating Temperature

The environmental temperatures of space systems cycle around the orbit from hot temperatures during sun illumination to very cold periods when exposed to the dark sky. Sensitive equipment has to be thermally controlled and protected as far as possible. Microwave components like wave-guides, coax cables, amplifiers, phase shifters and mixers alter the phase of the signal depending on their operating temperature, mainly due to the change of the electrical length of the signal path.
The X-SAR radiating antenna panels are made of carbon fiber and show nearly no thermal expansion.
The six LNA's have been installed in a heater-controlled environment. Their actual temperature was monitored and showed no variation after the initial switch on.
The receive signals from the six LNA's run through coax cables of approximately 3.5m length to the XCB. These cables have been mounted directly underneath the antenna panels. The experienced temperature changed only ±2°C over each orbit in an temperature range for all six cables between –7°C to –20°C for which the used GORE cables caused only a calculated variation of the receive phase of less than 0.3°, which is negligible compared to the mast phase variation. A typical orbit is shown in Fig.5.

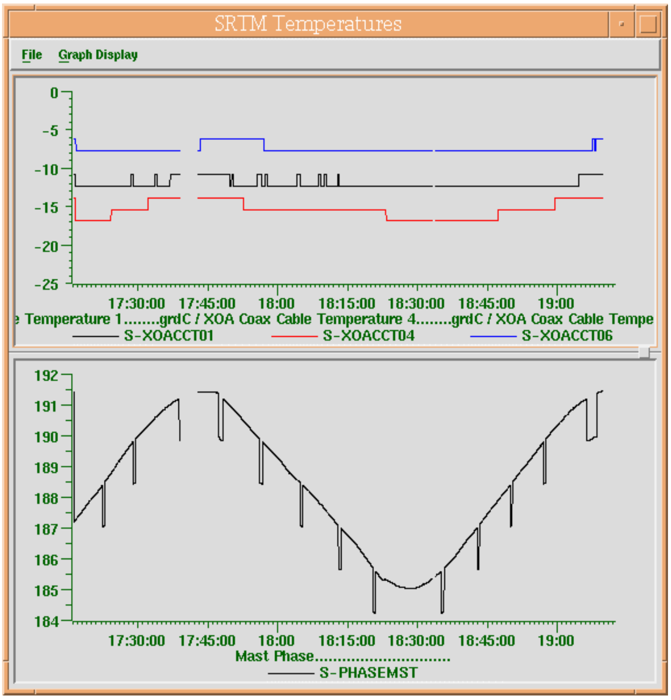


Figure 5: Coax cable temperature (top) variation and the measured mast phase variation (bottom) over one orbit

The signal combiner box (XCB) containing the phase shifters, switches and couplers was also temperature controlled to 30ºC (±1º) and had also not caused any significant phase variation.

A short cable with negligible phase error contribution connected the XCB and XDC.

Both IFD and RAE are mounted on a cold-plate which stabilized the temperature to 8ºC (±2º) and 10ºC (±2º) with no phase impact.

Phase Variation of the mast cables

Both, the radar receive signal at IF-frequency (135 MHz) and the 263 MHz signal used for the down-conversion at the outboard antenna run over the 100m long mast cables connecting inboard and outboard electronics and experience phase variations corresponding with the temperature of the cables. A 1052 MHz stable oscillator signal generated in the RFE was distributed via a 10m cable to the RAE, divided by four and sent at 263MHz via the up-link boom cable to the XDC. The 263 MHz local oscillator frequency was there multiplied by 36, as was the corresponding phase variation from the boom cables.

As expected, large temperature variations, between -25°C and +20°C, have been measured at the coax cables and identified as the major error source within the instrument. A direct continuous precise measurement of the phase shift has been performed during the whole mission.

For that purpose the 263 MHz oscillator signal used for the down-conversion in the outboard XDC was reflected back via the down link cable, then the two-way phase was measured using a phase detector ΔΦ in the RAE. The phase detector had an output phase resolution of 0.022º and the accuracy was measured to be one resolution step, which corresponds to a one-way X-band phase error of 0.4º, assuming identical phase variations on both the up link and down link boom cables.

Depending on the orbit position, the measured phase variation was up to 7º within one orbit. During the data processing this measured phase is divided by two (only one way for the radar signal), multiplied by a factor of 35.5 and added/subtracted from the radar signal phase. The sign has to be derived from a processed long ocean pass. An uncompensated mast phase error would result in height errors of more than 27 meters over a 20 minute or 1500 km long data take.

Phase errors from paparameter variations

The phase-shifters for the electronic beam steering in the azimuth direction change the path length from the antenna phase center to the XCB. The signal phase is the argument of the coherent sum of the signals in the six individual paths including the individual LNA's and individual phase shifters. A preflight characterization was performed for the phase shifters for all possible settings at the expected temperatures. Fortunately during the mission no antenna steering apart from an initial beam alignment setting was necessary and therefore this complicated phase correction is not necessary during the processing.

Depending on the operating frequency, variable attenuators cause significant phase offsets and have been characterized before flight. The prime and secondary channel gain setting attenuators (AGC-automatic gain control) operating at 135 MHz have only 0.3° to 1º phase offsets between settings causing errors of 0.5 m maximum. This has now also been verified with the evaluation of the extracted calibration-tone phase contained in the raw data. The attenuators controlling the cal-tone level and operating at 9.6 GHz are slaved to the AGC settings. These settings cause significant phase offsets in the cal-tone phase of up to 70º as measured preflight. This has to be taken into account if the cal-tone phase is used for calibration.

5. CALIBRATION TONE

A calibration-tone has been injected as a well-defined and stable signal into both channels. The phase difference between the cal-tones in the primary and secondary channel provides a powerful monitoring tool for the variations in instrument interferometric phase difference. For the secondary channel the cal-tone has been derived from the 263

MHz oscillator signal routed from the RAE over the mast to the XDC, divided by 2 and multiplied by 73 resulting in a CW-tone at 9599.5 MHz, which is 3.5 MHz below the RF center frequency and within the 10 MHz band width of the radar signals. The cal-tone has been injected via a switch box into each of the six LNA inputs and in addition, directly behind the summation point into the XCB.

For channel one, the cal-tone generator is located in the RAE and includes a cal-tone level attenuator as well, to adjust the cal-tone level to the signal level for different receiver gain settings. This X-band cal-tone was routed through a thermally protected coax cable to the primary channel injection point at a wave guide coupler right behind the antenna port.

After correcting the known errors due to the attenuator settings, the phase variation due to the mast cables and the phase variations caused by temperature variations of other cables, the cal-tone phase difference is used to derive the PLL oscillator error.

PLL oscillator phase errors

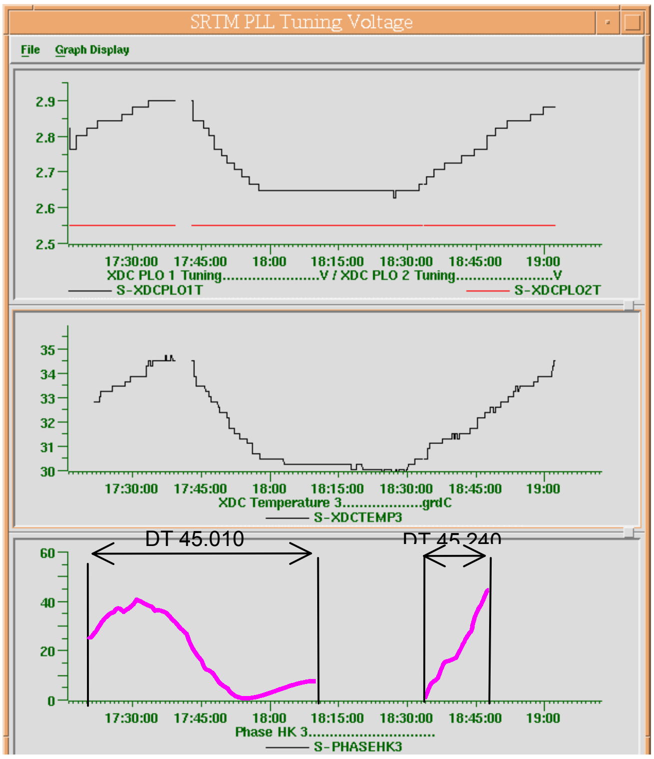


Figure 6: PLL tuning voltage (top) correlated with temperature variation (middle) and cal-tone phase (bottom).

Several phase locked loop (PLL) oscillators have been used in the instrument for up and down conversion of frequencies. All have been monitored by recording their tuning voltage and temperatures. Only one of them (XDC PLO1), responsible for the down-conversion of the X-band signal to 1186 MHz (which is a factor of 32) showed an unstable tuning voltage whenever the sun got into the window of the thermal control radiator and the temperature started to rise over 30ºC. This happend because of an non optimum thermal design of that box, at least for the northern part of the orbits. Post mission analysis indicated a correlation with a phase variation in the secondary channel derived from the cal-tone phase as shown in Fig.6. This phase error of up to 50º has to be compensated.

6. CURRENT CALIBRATION STATUS

Currently, our calibration efforts concentrate on a further reduction of the residual height errors, which are still in the order of a few meters due to motion remnants that are either not correctly measured or not properly compensated in the processor. We will continue to process data takes over ocean and compare the resulting heights with the sea level derived independently from tidal models. [6] This will allow us to assess the height error on different scales in great detail. Cross-comparison with C-Band DEMs processed by the JPL team has already shown a very high correlation between the residual errors and suggests that the baseline determination should be improved further. The height errors are now discussed on different scales in the following:

Thermal Noise – 30 m Scale

As discussed in the section on coherence, the thermal noise component of the height error is less than 4 m standard deviation or 6.4 m 90%-error in a single scene after filtering with 16 looks. The numbers were verified for a flat salt lake (Salar de Arizaro) in Argentine, and also between an ascending and descending SRTM DEM in the area of Gujarat, India.

Motion Aliasing – 8 km Scale

During the calibration phase it turned out that the 1 Hz AODA sampling rate was not high enough for the mast oscillations. Aliasing of higher frequency motion components caused periodic height ripples in the order of ±2 m. As a consequence the sampling was increased to 4 Hz and the ripples were reduced to less than 0.5 m.

Mast Oscillations – 50 km Scale

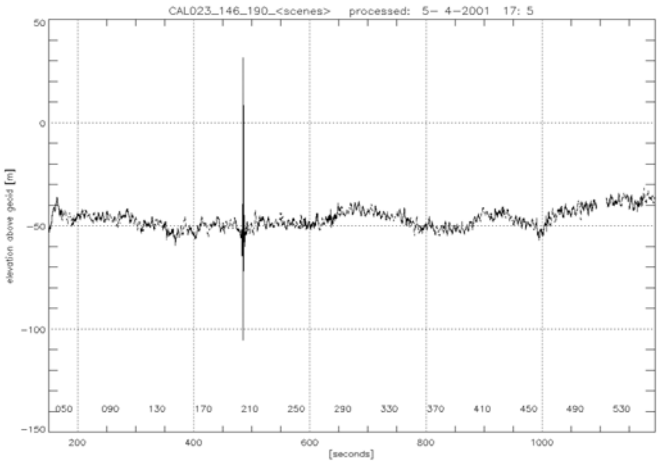
The Space Shuttle attitude control with its firings of the thrusters are the major cause for mast oscillations with a period of 7 seconds. The amplitude of these oscillations is in the order of ±4 cm. The residual error in that measure of only 0.5 mm causes DEM errors of ca. ±2.5 m.

Attitude Control Firings – 800 km Scale

About every 120 seconds the orbiter performs an attitude correction to keep the dead-band of ±0,2º in all axis which holds the baseline to the nominal baseline roll angle of 45º . We still find height error variations in the order of ±10 m with a 120 s period coupled with these events. These errors decreased after an improved alignment of the inertial reference unit (IRU) and the star tracker (STA) used for attitude determination within the AODA system.

Instrument and Attitude Stability – 5000 km Scale

Our calibration concept plans to use solely ocean surfaces before and after a continent to calibrate offsets and slow instrument induced trends in the global DEMs. The latest results on ocean data takes indeed showed we can fulfill the specification with only a few meters deviation over 8000 km. However, we need to investigate more data takes to confirm these results.



EMBED*Fig. 7: SRTM XSAR ocean height during a 8000 km data take.*

7. SUMMARY AND OUTLOOK

After the successful mission in February 2000 we look back on one year of extensive data analysis, testing of the processing system, verification and associated iterative reduction of the remaining errors. The excellent timing and positioning concept provides a product localization precision unknown so far. A careful characterization of all phase sensitive devices and the monitoring of their temperatures during the mission as well as the availability of a stable and reliable calibration signal is necessary to remove and compensate systematic phase errors caused by the instrument. Most of the devices behaved as designed, the system was very stable and no further correction is needed.

The overall SAR data quality is reliable and the processing system [7] robust enough to allow a global DEM production with minimum operator interaction. Some remaining large scale errors should be reduced further to allow for a simple global calibration without reference points over land. As they are systematic errors, obvious residual oscillations should be reduced further, even if the specification is met.

8. ACKNOWLEDGEMENTS

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