ADEOS Attitude Determination from NSCAT Measurements

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Abstract–The NASA Scatterometer (NSCAT) is a spaceborne scatterometer which flew aboard the National Space Development Agency of Japan's ADvanced Earth Observing Satellite (ADEOS). The NSCAT instrument has proven to be remarkably sensitive and accurate, achieving a calibration of within a few tenths of a dB. The key source of calibration error for NSCAT σ^o measurements is the spacecraft attitude knowledge. Unfortunately, the attitude of the ADEOS spacecraft as determined by its onboard sensors is not as accurate as desired. Further, there appear to be biases in the spacecraft attitude between the ascending and descending portions of the orbit. The accuracy and stability of the NSCAT instrument makes it possible to use the σ^o measurements to infer the mean spacecraft attitude. This approach models the observed σ^o as a polynomial function of incidence angle and determines gain corrections to ensure consistency between different antennas (beam balance) while estimating the orbit-varying spacecraft attitude such that the beam balance correction is fixed over the orbit and with time. The result is improved accuracy and consistency of the σ^o measurements.

INTRODUCTION

While the NSCAT instrument has proven to be remarkably stable, NSCAT σ^o measurements are sensitive to errors in the spacecraft attitude. Observations over homogeneous distributed targets such as the Amazon rainforest, exhibit a small (up to a few tenths of a dB) inconsistency between ascending and descending passes of the sensor, suggesting that there may be small biases in the spacecraft attitude. In this paper a simple method for inferring the average spacecraft attitude from NSCAT measurements over distributed targets is described. By using targets distributed over the earth, the spacecraft attitude versus orbital position can be determined. With this attitude known, corrections to the σ^o measurements can be applied to better estimate the beam balance, improve the overall accuracy of the σ^o measurements, and ensure ascending/descending consistency. In the following sections the technique is described and some results are presented.

TECHNIQUE

Our ultimate interest in calibrating the scatterometer data is to obtain highly accurate measurements of σ^o. Such measurements must be consistent between the antennas and over the full measurement incidence (and azimuth) angle range. Inconsistencies arise due to calibration errors and uncorrected or time-varying changes in the parameters used to compute σ^o from the power measurement. An important source of such errors is uncertainty or error in the spacecraft attitude. Another source of error is the antenna gain beam-to-beam calibration error, termed antenna beam-to-beam bias.

By choosing homogeneous, isotropic target areas and assuming that the attitude is essentially constant over the target for each pass (but allowing for it to be different for ascending and descending passes), the spacecraft attitude can be estimated from the σ^o measurements. NSCAT makes measurements over a wide range of incidence angles, complicating the problem since the incidence angle dependence of σ^o over the target region must be accounted for. Since the dependence is unknown, it must be estimated from the measurements. The beam-to-beam bias must also be estimated from the measurements.

The n^{th} measurement of σ^o (in dB) over the m^{th} target region, denoted by $z_{n,m}$ is modeled as,

$$z_{n,m} = \sigma^o(\theta_n, m) - G_b(b_n, \theta_n) + G_a(b_n, r_m, p_m, y_m) + noise \tag{1}$$

where $\sigma^o(\theta_n, m)$ is the true value of σ^o of the surface at location m with observation incidence angle θ_n, $G_b(b_n, \theta_n)$ is the beam-to-beam gain balance error and $G_a(b_n, r_m, p_m, y_m)$ is the error in σ^o due to errors in the roll r_m, pitch p_m, and yaw y_n of the spacecraft used in computing σ^o from the measured power over the m^{th} target. The noise term is due to unmodeled target variability, the inherent variability in the signal power measurement due to communication noise, and short term attitude variations. The unknowns in this equation are the incidence angle response function $\sigma^o(\theta_n, m)$, the attitude and location independent beam balance term G_b, and the spacecraft attitude r_m, p_m, and y_m.

To solve for the unknowns a number of calibration regions are defined. These M regions are chosen to individually have a nearly homogeneous and temporally stable response. The regions are treated separately for ascending and descending passes. Regions are chosen over the range of orbit latitudes so that the average attitude versus orbit position can be determined. The average attitude over the orbit is assumed to be stable over a one week period. Attitude variations more rapid than this are part of the noise in Eq. (1). Region selection is described later in more detail.

Following the general approach outlined by Long and Skouson [1], the σ^o incidence angle response over each region is parameterized by a fourth order polynomial in $\vartheta = \theta - 40°$.

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The antenna beam-to-beam bias G_b is similarly modeled. In fitting a polynomial to actual σ^o measurements, the σ^o measurements are binned into small incidence angle bins based on the cell and beam number. The binned values are then fit (in dB) to obtain the polynomial coefficients. Equation (1) can be expressed in terms of polynomials as

$$P_f(b) = P_t - P_{bb}(b) + P_a(b, r, p, y) + P_r(b) \qquad (2)$$

where $P_t(b)$ is the true (unknown) σ^o versus incidence angle response of the surface over the calibration region which is independent of the beam; $P_f(b)$ is the polynomial fit to the actual σ^o measurements $z_{n,m}$, $P_{bb}(b)$ is the polynomial beam balance correction (G_b) for beam b; $P_a(b, r, p, y)$ is the polynomial fit to the σ^o error for beam b due to spacecraft attitude roll r, pitch p, and yaw y; and $P_r(b)$ is the residual error including noise. In writing this expression we are ignoring the error in σ^o due to the changes in incidence angle resulting from attitude errors.

Beam 3V is selected as the reference for antenna gain beam balancing, thus $P_{bb}(3\text{V}) = 0$. Since P_t is the same for all of the beams, Eq. (2) for beam 3V (the reference beam for which $P_{bb}(b) = 0$) can be subtracted from the same equation for the other beams to obtain

$$P'_f(b) = P_{bb}(b) + P'_a(b, r, p, y) + P'_r(b) \quad \forall b \neq 3\text{V} \qquad (3)$$

where $P'_f(b) = P_f(3\text{V}) - P_f(b)$, $P'_a(b, r, p, y) = P_a(3\text{V}, r, p, y) - P_a(b, r, p, y)$, and $P'_r(b)$ is the residual error.

As an approximation for small angles, for simplicity the attitude axes are assumed independent so that $P'_a(b, r, p, y)$ can be expressed as

$$P'_a(b, r, p, y) = P'_r(r, b) + P'_p(p, b) + P'_y(y, b)$$

where $P'_r(r, b)$ is the roll correction polynomial for roll r, and similarly for pitch and yaw. A fourth order polynomial, $P_r(b)$, is used to model the dependence of σ^o on attitude changes. To first order, $P'_r(r, b)$ can be approximated by $rP_r(r, b)$, and similarly for yaw and pitch. Thus,

$$P'_a(b, r, p, y) \approx rP_r(b) + pP_p(b) + yP_y(b).$$

With this approximation, Eq. (3) for each of the seven beams (beam 3V does not have a separate equation because it is the reference beam) for each region are stacked up to write a matrix equation relating the observed σ^o, attitude, and beam balance:

$$P = BY + noise \qquad (4)$$

where P contains the coefficients of the polynomial fits to the observed σ^o measurements (P'_f), B contains the coefficients of the polynomial fit to the attitude corrections (P_r, P_p, P_y), and Y contains the beam balance polynomial coefficients (P_{bb}) and the attitudes (r_m, p_m, y_m) for each target region.

While the system in Eq. (4) is over-determined, it is ill-conditioned. As a result, singular-value filtering is used to solve Eq. (4) to produce a least-squares estimate of Y. The smallest singular values (those with magnitude less than 3% of the largest singular values) are set to zero. This is within a natural break in the eigenvalues. Extracting the various coefficients from $\widehat{Y}$ gives the beam balance polynomial coefficients and the estimated attitude for each region.

TARGET REGION SELECTION

Previously, tropical rain forests have been used for scatterometer calibration because of their homogeneous response [1]. Since tropical rain forests are generally located near the equator they span only a limited range of latitude values. However, for this study, a wide range of latitude values is needed. To enable rapid selection of calibration targets, images made by the Scatterometer Image Reconstruction with Filtering (SIRF) algorithm are used. The SIRF algorithm generates enhanced resolution images of $\mathcal{A}$ and $\mathcal{B}$ where $\sigma^o(\text{in dB}) = \mathcal{A} + \mathcal{B}(\theta - 40^\circ)$. $\mathcal{A}$ is the incidence angle normalized σ^o while $\mathcal{B}$ is the incidence angle dependence of σ^o (see Fig. 1) [2]. Calibration regions are selected as pixels within a narrow (10°) range of latitudes which have a narrow range (1 dB and 0.05 dB/deg, respectively) of $\mathcal{A}$ values and $\mathcal{B}$ values.

The $\mathcal{A}$ and $\mathcal{B}$ images correspond to the average backscatter response over the one week imaging period. The 'standard deviation' image provides a useful measure of the temporal variation of the target. The standard deviation image is created as the standard deviation of the difference between each σ^o measurement covering the pixel and its forward projection [2]. The forward projection is the predicted σ^o value computed from the incidence angle and the $\mathcal{A}$ and $\mathcal{B}$ values for the pixels covered by the σ^o measurement. Small standard deviations indicate that there is little temporal variation. Larger values indicate temporal change or azimuth modulation. In selecting calibration targets, only locations with small (< 1 dB) standard deviations are used. Using the criteria mentioned, 60 target regions were selected over the globe as illustrated in Fig. 2.

RESULTS

Two approaches to modeling G_b were considered: 1) the beam balance is the same for ascending and descending and 2) separate beam balances are used for ascending and descending. While the results differ somewhat, there is general consistency between the approaches. A single beam balance is adopted for the result presented here. For simplicity, only the fore and aft antennas are used.

Figure 3 shows a plot of the estimated spacecraft attitude versus the orbit time (the time from the southern most node of the orbit). Symbols indicate attitude estimates for each region while the curves are second-order Fourier series fits to the data. In making the fit, separate means were used for ascending and descending to allow for a mean attitude bias error. Consistency in the pattern of the attitudes suggests that the average spacecraft attitude varied slowly over the orbit and has some bias

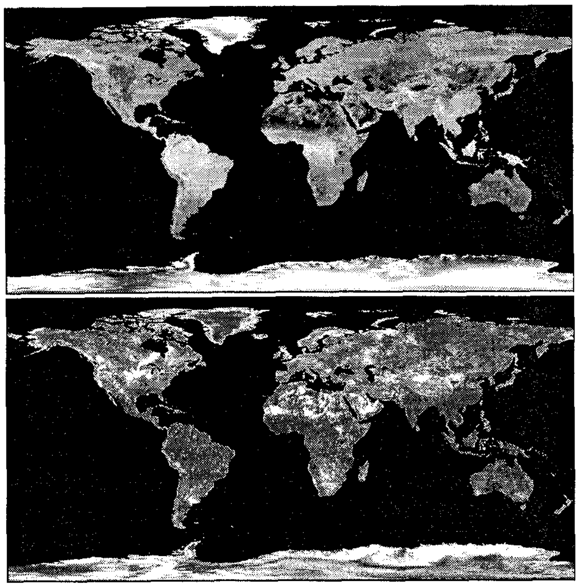

Figure 1: Top: SIRF $\mathcal{A}$ image. NSCAT 1996 JD 320-327 v-pol data. Greyscale range is -20 to -5 dB. Bottom: corresponding SIRF standard deviation image. Greyscale range is 0 to 1 dB.

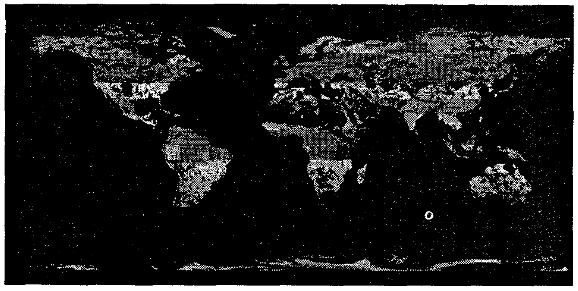

Figure 2: Map of selected target calibration regions. Each region is selected with $\mathcal{A}$ values within 1 dB, $\mathcal{B}$ values within 0.05 dB/deg, and standard deviation less than 1 dB.

between ascending and descending passes. Based on these results, the spacecraft exhibited little roll bias but significant (up to several tenths of a degree) swings in pitch and yaw.

Figure 4 plots the residual polynomials and the beam-to-beam balance polynomial. The residual errors are much smaller than before attitude correction and a small adjustment (less than 0.2 dB) is indicated for the beam-to-beam balance correction, with the largest adjustments at near swath.

CONCLUSION

A simple method for inferring the average ADEOS spacecraft attitude using NSCAT σ^0 measurements has been presented. The technique also yields estimates of the beam balance correction. Consistent variations in the spacecraft attitude with latitude suggest biases in the computation of the spacecraft attitude. A small but consistent bias in the spacecraft attitude between ascending and descending is noted. This may be due to the fact that different sensors are used for ascending and descending attitude determination.

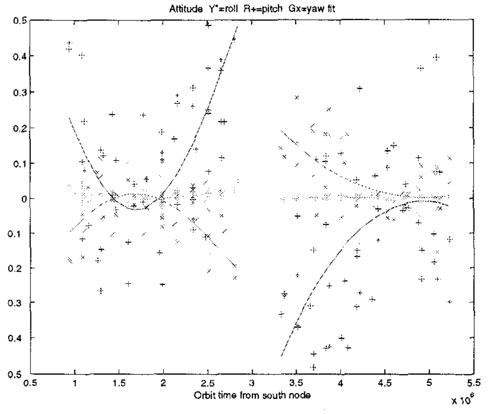

Figure 3: Estimated spacecraft attitude versus orbit time from southernmost point of orbit. Gap in center is the northernmost point of the orbit. The equator falls near the center of each data segment. '*' symbols are used for roll, '+' for pitch, and '×' for yaw. Lines show a Fourier series fit (see text).

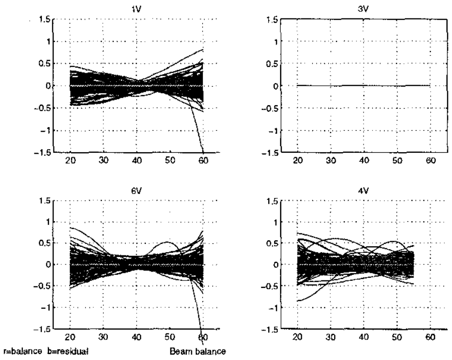

Figure 4: Plots of the residual error polynomials for each region (blue) and the beam-to-beam balance correction (red) for each beam. Beam 3V is zero since it is used as the reference.

REFERENCES

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