NASA Scatterometer (NSCAT) Pre-Launch Calibration Results and Post-Launch Calibration Plan

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Abstract -- The philosophy and approach for calibrating NSCAT are described. Pre-launch calibration test results and plans for the post-launch calibration campaign are presented.

INTRODUCTION

The NASA Scatterometer (NSCAT) is scheduled for launch aboard the Japanese Advanced Earth Observing Satellite (ADEOS) in February 1996. The NSCAT instrument is a Ku-band radar which measures global ocean surface wind speeds and directions at 50 km resolution. The wind measurement is accomplished by first measuring the normalized backscatter cross section (σ_0) of the ocean at three different azimuth angles and two different polarizations using eight fan-beam antennas.[1] Wind vectors are then retrieved during ground data processing using an empirical geophysical model function which relates σ_0 to wind speed and direction. The accuracy with which the ocean surface wind can be estimated is a sensitive function of the radiometric accuracy of the σ_0 measurements. For this reason, NSCAT must be a highly calibrated and stable instrument. This paper describes the philosophy, approach, and results of the NSCAT calibration effort.

CALIBRATION PHILOSOPHY

In general, an estimate of the ocean σ_0 can be obtained by applying the following form of the radar equation:

$$\sigma_0 = \frac{P_r}{X} \qquad \text{where,} \qquad X = \frac{P_t G_a^2 G_r \lambda^2 A}{R^4 L (4\pi)^3} \qquad [1]$$

Here P_r is the echo return power detected at the receiver output, P_t is the transmit power, G_a is the antenna gain, G_r is the receiver gain, λ is the transmit wavelength, A is the effective illuminated area, R is the slant range to the measurement cell, and L is the system loss. X is referred to as the ***composite radar parameter.***

It is clear that σ_0 measurement accuracy is thus a function of both how accurately P_r can be measured and how accurately the value of X can be estimated.

The error in determining P_r is typically referred to as communication noise. This error is random in nature and is due to the statistical uncertainty inherent in measuring any noise-like signal. In general the magnitude of this error will be a function of measurement SNR, integration time, and bandwidth. The statistics of communication noise are well understood and described thoroughly in Reference [1].

The process of estimating the value of X is referred to as system calibration. Calibration uncertainty is thus the cumulative uncertainty in knowing the values of each of the radar system parameters which comprise X. The accurate measurement of these system parameters is the primary goal of instrument calibration.

The error in determining the value of X can be modeled in the following way:

$$X_{true} - X_{meas} \equiv B + r(t) \qquad [2]$$

Here, B represents a bias or time-invariant error component and $r(t)$ represents a time-varying or random error component.

Biases are introduced by systematic errors associated with the pre-launch calibration of each sub-system. Two types of bias errors affect NSCAT performance: absolute bias and beam-to-beam bias. Absolute bias is the time-invariant error in the measurement of σ_0 relative to its absolute true value. Beam-to beam bias, on the other hand, is the time-invariant error in the measurement of σ_0 by any one of the eight NSCAT antenna beams relative to any of the other beams. In general, an absolute bias will have a more severe impact on wind ***speed*** estimation, and a beam-to-beam bias will have a more severe impact on wind *direction* estimation. Because bias errors are time-invariant and deterministic, it is possible, given sufficient time, to detect and remove them post-launch. Thus, if post-launch bias removal techniques can be perfected, the existence of pre-launch biases will not limit the ultimate capability of the instrument.

Time-varying errors in the determination of X can be induced by spacecraft altitude knowledge uncertainties, antenna gain changes with temperature, RF component instabilities, and other like effects with time on orbit. Where possible these time varying changes will be tracked and a correction applied -- receiver gain fluctuations, for instance, will be tracked by using an internal noise source whose output is known accurately as a function of temperature. Other parameters, such as time varying distortions of the antenna gain pattern, are expected to be difficult to track. Thus, even after reasonable corrections are made, a residual time varying error component will remain. This will be a combination of "untraceable" but deterministic errors, such as the antenna gain variations, as well as truly random errors, such as spacecraft attitude uncertainties. Because this type of error is more difficult to correct, time-varying calibration uncertainty will limit the ultimate capability of the instrument. For this reason, instrument stability and the accurate characterization of time-varying effects is of paramount importance in scatterometer design and calibration.

To establish quantitative requirements for bias and time-varying calibration error a trade study was performed using the JPL COMPASS simulation.[2] In order to meet the aggressive NSCAT mission goals the following top-level calibration requirements were established:

(1) Total time-varying calibration error not to exceed 0.57 dB 1σ.

(2) Total pre-launch bias not to exceed 1.5 dB.

(2) Total post-launch absolute bias removed to within 0.5 dB.

(4) Total post-launch beam-to-beam bias removed to within 0.2 dB.

CALIBRATION APPROACH

To achieve the above calibration requirements a variety of techniques are employed. These techniques can generally be divided into two major classifications: pre-launch calibration testing and post-launch external calibration.

Pre-Launch Testing Methodology and Results

The primary goals of both pre-launch testing and on-orbit internal calibration are to a) determine the stability and repeatability of the NSCAT instrument, b) characterize or track time-varying calibration changes, and c) minimize pre-launch calibration biases. The achievement of these goals required special laboratory measurements under tightly controlled environmental conditions.

The gain patterns for each of the eight antenna beams were measured at the JPL near-field antenna range. In addition to measuring the peak gain, it is very important that the entire three dimensional pattern is measured accurately. This is because the NSCAT doppler processor effectively segments the narrow, long antenna pattern foot print on the ocean surface to form resolution cells (see Reference 1). To measure σ_0 the antenna gain in the direction of the center of each cell must be known.

As stated earlier, the NSCAT calibration effort is especially concerned with time-varying uncertainties in instrument parameters. An assessment of the possible variations in antenna gain with on-orbit thermal conditions was performed analytically using a thermal-structural-electrical model. These stability estimates were partially verified by thermal-vac testing on the antenna material. Experimental measurements made on prototype waveguides indicate that very little variation in loss should occur over the temperature ranges expected on-orbit.

The NSCAT electronics were calibrated under thermal-vac conditions. The thermal environment was varied so that calibration curves could be generated for each parameter as a function of temperature. To verify stability and repeatability, the thermal chamber temperature was cycled and the calibration test suite was repeated each time a specific temperature was revisited. Repeatability/stability was defined as the deviation of the parameter value at a given temperature and time from a mean value at that same temperature over the entire test period.

Key components calibrated in this fashion include the Transmit Power Monitor, which continuously telemeters the transmit power for use in ground data processing, and the Calibration Noise Source. The noise source has a nominal ENR of 18.5 dB and is viewed every eight minutes on-orbit in order to calibrate the NSCAT receiver. Thus σ_0 calibration accuracy is directly related to the accuracy with which both the noise source and transmit power monitor are calibrated.

Based on the test results and an extensive error analysis, NSCAT pre-launch calibration error has been estimated. These results are shown in Table 1 below. The time-varying calibration error (stability) and pre-launch bias for each key component are shown separately and in total. Note that the critical instrument stability is estimated to be 0.31 dB, more than adequate to meet mission requirements. The pre-launch bias of 1.04 will be removed to within 0.2 dB in the post-launch calibration effort.

Table 1: Pre-Launch Calibration Results

Parameter	Time-Varying Cal Error (dB)	Pre-Launch Bias (dB)
Antenna Pattern	0.21 (2-way)	0.81 (2-way)
Transmit Power	0.10	0.35
Receiver Gain	0.10	0.17
System Loss	0.10	0.48
Other (pointing, etc)	0.15	0.10
RSS Total Achieved	0.31 dB	1.04 dB
Required	0.57 dB	1.5 dB

Post-Launch External Calibration

Despite efforts to calibrate the system using pre-launch and internal techniques, significant calibration uncertainty may yet exist when the fully integrated system begins on-orbit operations. This has been the case for previous scatterometer systems[3]. For NSCAT there are several factors that may lead to remaining calibration error. Biases in the measurement of sub-system parameters, though small in and of themselves, may combine in the fully integrated system to be an unacceptably large total bias on the measurement of σ_0. The antenna patterns may deviate from those measured on the ground due to thermal distortion or unexpected electromagnetic interaction with spacecraft structure or other antennas. The calibration of internal references such as the noise source and the transmit power monitor may drift over the mission duration of three years. For these reasons the NSCAT project has identified several options for the removal of post-launch calibration uncertainty using external means.

a) Uniform, Isotropic Land Targets

Analysis of backscatter data from large, uniform, isotropic terrestrial targets such as the Amazon forest can be employed to detect and remove beam-to-beam biases[3]. With this technique several days worth of σ_0 data collected over the target area is recorded as a function of the measurement incidence angle. Because the target is carefully selected to be azimuthally isotropic (i.e. the backscatter cross-section is only a function of incidence angle), the true mean σ_0 at each incidence angle should be the same for each antenna. Relative biases between the antenna beams will be manifest as biases in the measurements of σ_0 at a given incidence angle. Although this technique is promising for the detection of beam-to-beam biases, it is inappropriate for the detection of an absolute bias because the absolute value of the target σ_0 is not likely to be known with sufficient accuracy. In addition this method probably can not detect time varying errors in instrument calibration due to the difficulty in separating the diurnal and seasonal changes of the target from a change in the instrument response.

b) Statistical Analysis of Ocean Surface σ_0

In a similar fashion to the technique described for land targets, ocean surface backscatter measurements can be collected and grouped according to incidence angle. Assuming that the global distribution of wind directions is uniform, the true mean σ_0 at each incidence angle should be the same for each antenna, Although the variance of the global ocean σ_0's is much greater than for land targets, the data set for the ocean targets is much larger and beam-to-beam biases may be detected in a comparable period of time. Like the land target technique, however, this method is inappropriate for the detection of absolute bias or time dependent calibration error.

c) Ground Stations

NSCAT calibration will be directly tested by the deployment of a "calibration ground station" capable of transmit and receive. The ground station receiver will be highly calibrated to accurately measure the signal transmitted by NSCAT as it flies overhead. The calibration ground station transmitter will, in turn, broadcast a known signal to be measured by NSCAT. Such a technique will obtain many parameters of interest. In addition to beam-to beam bias, this method will detect absolute instrumental biases to an accuracy equivalent to the absolute calibration of the ground station itself. If the ground station calibration is sufficiently stable, time varying changes in the NSCAT instrument can be detected. This allows NSCAT calibration to be monitored for potential drifts over the length of the mission. In addition, because the antenna patterns are measured directly, antenna beam pointing can be verified.A primary challenge with this approach is the absolute and relative calibration of the station itself. Atmospheric attenuation most also be accurately known.

CONCLUSIONS

A thorough pre-launch testing effort has demonstrated that NSCAT stability exceeds what is required to generate high quality wind data. A post-launch calibration plan, which includes the analysis of distributed targets and a special calibration ground station, will verify on-orbit performance and accurately remove residual biases.

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