Improved Timing Calibration of QuikSCAT

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***Abstract*- Since being launched in June 1999, QuikSCAT has successfully and accurately measured ocean wind vectors. Current research is attempting to increase performance beyond the original design parameters in order to increase the utility of the data. Timing calibration is critical to this effort. Timing information is used to determine instrument performance as well as to calculate the location of each measurement on the Earth's surface. This paper reports a method of obtaining high-precision time validation measurements through the use of the QuikSCAT Calibration Ground Station (CGS). The QuikSCAT CGS passively records satellite transmissions as it passes overhead. Analysis of CGS data can determine the arrival time of each QuikSCAT pulse to within microseconds. Utilizing the high stability of the onboard pulse repetition interval clock, along with CGS observations, precise instrument timing can be determined during a portion of the orbit, which enables more precise determination of the timing throughout the entire orbit. The improved timing is able to support the requirements of advanced data applications.**

I. Introduction

SEAWINDS on QuikSCAT has operated continuously since its launch in June of 1999. Since that time advanced data applications have been developed to take advantage of its favorable geometry and resolution. SeaWinds' performance has met, and in most cases exceeded design specifications. However, the reliability of advanced applications are heavily dependent upon improved calibration accuracy of the data beyond specifications. For this reason, we are interested in evaluating the performance of SeaWinds in increasingly accurate terms.

A fundamental parameter of SeaWinds operation is timing. For each transmit pulse the instrument records the echo backscatter and key instrument parameters such as current time, position, and pointing. The current time associated with the data, referred to as a timetag, is obtained through communication with an onboard GPS receiver. However, once received, GPS time signals are transformed in a series of steps before they are linked to measured SeaWinds data. This process takes an uncertain amount of time and thus slightly degrades the accuracy of the timetags. The design requirements of SeaWinds require timetags to be within several milliseconds, a minimal value in terms of the nominal resolution measurements. Yet, it is desired for many current applications to resolve the timing to pulse based levels, within microseconds. This refinement in accuracy presents a significant challenge because of uncertainty in the processing delay of the GPS timing signals. The basic timing of the SeaWinds instrument is based upon the PRI, which has an approximate value of 5.4 ms. All measurements less than one pulse are relative, based on previous recorded values of time.

The SeaWinds Calibration Ground Station (CGS) has been set up to provide independent measurements of time, frequency, and power for SeaWinds. Through the use of the CGS, precision time validation measurements can be obtained. The CGS timing has been calibrated to precise levels and thus is able to provide the accuracy desired for advanced data applications. This paper first presents background on the Calibration Ground Station and discusses its limits on accuracy and precision. It then reviews the procedure used to validate CGS timing and determine an absolute reference. In the conclusion, findings are summarized and topics of future investigation proposed.

II. CGS Operation

The SeaWinds CGS was constructed to provide a high level of measurement accuracy and stability while operating autonomously. It is able to measure instrument timing, power, and frequency with great accuracy.

Prior to each satellite pass it calculates the predicted pointing angle to SeaWinds and when the pass will occur. Just before the satellite travels overhead, the CGS positions its antenna in the appropriate direction. The position is held constant during data reception for each beam. The constant antenna position is made possible due to a wide main lobe on the CGS antenna, which minimizes the sensitivity to pointing errors.

Based on the predicted arrival time of the transmitted satellite pulse, the CGS calculates the capture start time. This start time is based on a GPS reference and begins at the nearest second prior to the calculated arrival. Factoring in transmission delays and propagations times, the accuracy of the start time is within 0.50 μs. Typically each capture is 10 seconds in duration, though sometimes 20 second captures are made.

Once the capture begins, data is received and digitally sampled at a rate of 5.1875 MHz. The A/D converter is controlled by a phase locked loop synthesizer which is driven by the GPS reference. The stability of the reference is within 1 part per billion (10^{11}). The aperture stability is better than 200 ps. Thus the A/D is time stable within strict tolerances.

III. Timing Calibration

An absolute timing reference is needed to calibrate the associated timing parameters on QuikSCAT. The CGS provides this reference. The first step is to accurately determine the arrival time of each pulse. Once it has been verified, the

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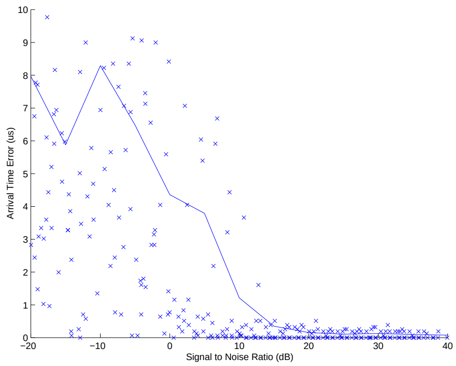

Fig. 1. Simulation results of pulse arrival time error versus SNR. The plot represents the results of over 900 individual simulations.

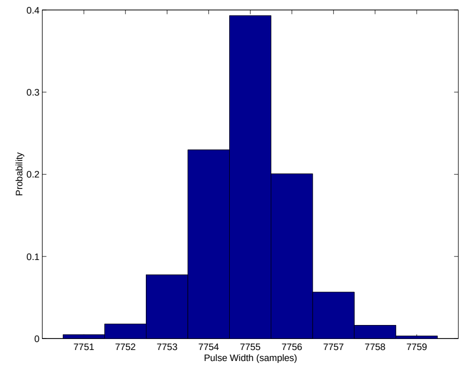

Fig. 2. Histogram of the pulse width determination results in CGS samples. The mean value is 7754.92 samples, or 1.49492 ms.

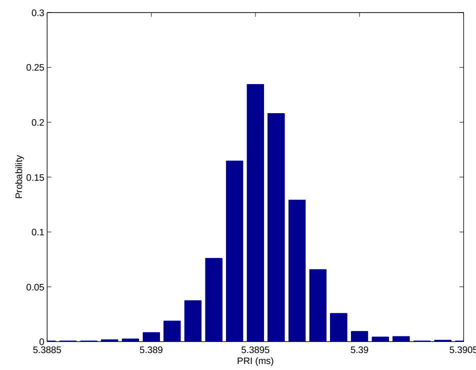

Fig. 3. Histogram showing the PRI of SeaWinds as determined by the CGS. The mean is 5.389527 ms, with a standard deviation of 227 μs.

pulse width and pulse repetition interval (PRI) can be confirmed. With basic pulse scale timing verified the absolute timing of the instrument can be derived.

A. Pulse Scale Timing

The first step of instrument time determination is to accurately and precisely determine, using the CGS recorded data, pulse scale timing measurements. First, the arrival time of each pulse is determined. Since the measurements are noisy, some variation of the estimated timing may occur. We evaluate accuracy of the arrival time estimation process through simulation.

A simple simulation is created by generating a pulse similar in power and duration to actual CGS recorded pulses, but with a known arrival time. Appropriate levels of additive Gaussian noise are then included. Pulse arrival time is determined by windowing the sample data set with a rectangular window of length equal to the duration of a transmitted pulse, 1.5 ms. The maximum response of the output for this operation corresponds to the trailing edge of the pulse. This operation is similar to a matched filter, with unknown amplitude and frequency. The simulation determined arrival time is compared to the generated truth data for varying degrees of additive noise. Fig. 1 shows the arrival time error as a function of pulse signal-to-noise ration (SNR). It shows that for a SNR over 15 dB the accuracy is limited by the resolution of the A/D, 0.193 μs. However, even for pulses with an SNR of –20 dB, the arrival time error is less than 9 μs.

With arrival time verified by simulation, the next step is to verify the average width of a transmitted SeaWinds pulse as received by the CGS. This is done by varying the width of the window filter to obtain a maximal response. For this procedure over 600 pulses of actual CGS data were tested. Each was filtered by several windows of varying width. Based on the peak response of each filter, the width of the pulse was determined. Fig. 2 shows the results of this procedure. The mean value of the data is 7754.92 CGS samples, or 1.49492 ms. The standard deviation of the data is 1.18 samples or 0.227 μs, only slightly larger than the minimum resolution of the A/D converter.

The final step of pulse scale timing is to determine the nominal PRI of SeaWinds. This is done by differencing the estimated time of arrival of two consecutive, like polarization pulses. For this analysis, several thousand pulses were analyzed. To improve arrival time estimation quality, only pulses with a positive SNR are used. Fig. 3 shows the results. The figure shows the mean PRI to be 5.389527 ms. The standard deviation as shown is 227 μs. However, this is primarily due to pulse shortening and lengthening as the instrument approaches and recedes from the CGS. Accounting for this phenomenon reduces the standard deviation to 0.053 μs.

These estimated values for pulse width and PRI coincide with values obtained using other SeaWinds data analysis techniques and verify the time stability of the CGS.

B. Absolute Reference Time Determination

With the accuracy of pulse arrival time at the CGS affirmed, it is possible to derive a value for absolute reference time corresponding to SeaWinds. This is done by comparing the arrival time of a given pulse as determined by the CGS to the arrival time of the same pulse based on SeaWinds

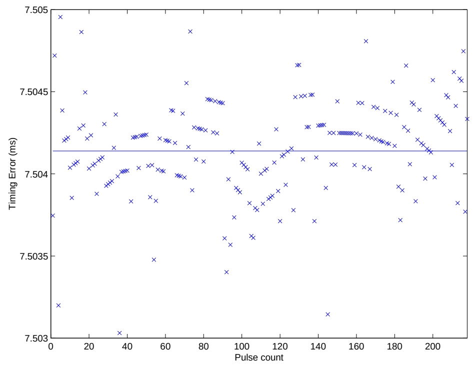

Fig. 4. Plot of arrival time error for one CGS capture. Each point indicates a single pulse. The line represents the mean error value.

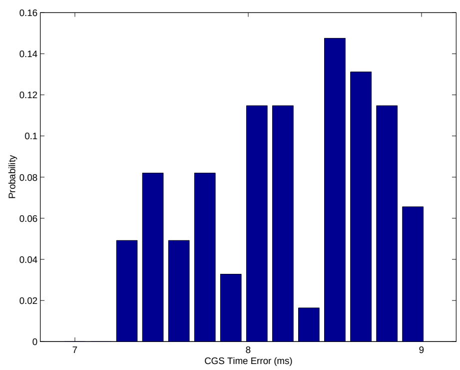

Fig. 5. Histogram of the arrival time difference between telemetry data and CGS data. The plot shows a random distribution between 7.2 ms and 9.2 ms. The mean value is 8.2 ms.

telemetry data. The telemetry based arrival time is calculated by using the proper telemetry timetag and then factoring in the time of propagation from the instrument to the CGS. Alternative pulse ambiguities are eliminated by comparing polarization and power levels between the CGS and telemetry data sets.

Fig. 4 shows the results of one CGS capture. For this particular capture, the plot indicates that the time error is 7.5042 ms. This means that the telemetry data reported that the pulse should arrive at the CGS 7.5 ms before it actually did. The variance in the pulses is due to the low SNR of some of the pulses and is similar to the variance levels shown in Fig. 1.

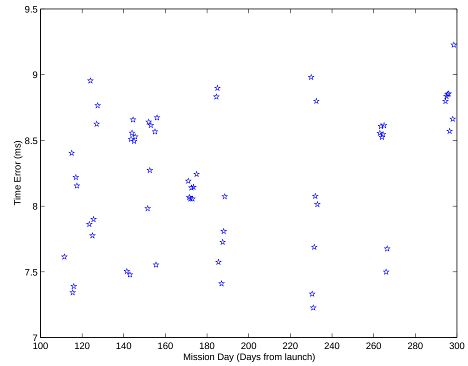

Fig. 6. Time history of the arrival time difference. The plot shows the time error as a function of days since the launch of QuikSCAT.

Fig. 5 shows a histogram of the capture error for 61 separate captures over the first year of the mission. It shows that the time error ranges randomly between 7.2 ms and 9.2 ms, with a nearly uniform distribution. The figure suggests that there is a mean time error of about 8.2 ms, with a standard deviation of ± 1.0 ms. Fig. 6 shows the same set of data as a function of days after launch.

It is important to note the effects of these time delays on actual QuikSCAT wind products. Data used in this analysis is selected so that it spans an entire year, ensuring the consistency of the observed time bias. The mean bias of 8.2 ms does not effect the final wind product because it is a constant. However, the variance of each time measurement does have a very small effect on the final wind product. The error in time measurement corresponds directly to an error in the azimuth direction. The SeaWinds antenna rotates at a rate of $0.108°$/s. Thus, a ± 1 ms error corresponds to a $\pm 0.108°$ error in azimuth. Using a range of 1245 km, the nominal range of the outer beam, this error corresponds to a location error of ± 2.17 km on the ground.

IV. Summary

SeaWinds timing has proven to be consistent and reliable. Its nominal difference from an absolute time reference has been shown to be 8.2 ms. The variation is shown to be ± 1.0 ms. The mean timing bias has no significant effect on SeaWinds wind estimation since, in the mean, the error is consistent for every pulse. The variation of timing does effect wind estimation, though the effect on the ground is a location error of ± 2.17 km.