Calibration and Evaluation of Blackbeard Time Tagging Capability

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Abstract. The Blackbeard instrument is a broadband radio receiver on the ALEXIS (Array of Low Energy X-ray Imaging Sensors) satellite. It detects and records transient VHF radio signals. During November and December of 1996, the Los Alamos Portable Pulser (LAPP) facility was used to transmit 31 broadband pulses to Blackbeard to evaluate the instrument's time tagging accuracy. LAPP firing times were used in conjunction with propagation delays to compute estimated times of arrival (ETOAs) for pulses reaching Blackbeard. ETOAs were compared to Blackbeard reported times of arrival (RTOAs), which were computed using information returned by Blackbeard and an algorithm presented in this paper. For the 31 pulser shots received by Blackbeard, the mean difference between ETOA and RTOA was 1.97 milliseconds, with RTOAs occurring later than ETOAs. The standard deviation of the difference was 0.43 milliseconds. As a result of the study, the algorithm used for accurate Blackbeard time tag studies has been modified to subtract 1.97 milliseconds from reported times of arrival. The 0.43 ms error standard deviation is now used to describe the uncertainty of Blackbeard time tags.

Introduction

The Blackbeard instrument is a broadband radio receiver on ALEXIS, a small satellite launched in April of 1993 into an 800 km, 69° inclination orbit with a period of approximately 100 minutes. The instrument is a fixed-rate, 150 Msample/s, 8-bit digitizer which takes its input from either of a pair of wideband subresonant monople antennas and a single-conversion VHF receiver. There are two bands from which it can sample: a low band from 28 to 95 MHz and a high band from 108 to 166 MHz. Sixteen highpass and lowpass analog filters permit further subdivision of either band. The signals which most commonly trigger Blackbeard are radio emissions from lightning and other thunderstorm electrical processes. One such type of emission has been recorded much more often than all other types combined: TransIonospheric Pulse Pairs (TIPPs). TIPPs are powerful pairs of pulses with individual pulse durations of a few microseconds and typical inter-pulse separations of 50 μs. Such events were not reported in the literature prior to observations by Blackbeard. Details concerning the Blackbeard instrument and subsequent data acquisition are described in Holden et al. [1995] and Massey and Holden [1995].

When a signal exceeds the Blackbeard trigger threshold during an arm period, timing information is recorded in addition to the electric field waveform of the triggering event. The timing information makes it possible to estimate the time of arrival (TOA) of the event at the satellite in Universal Coordinated Time (UTC). In the past such information has been useful for studies attempting to correlate events recorded by Blackbeard with events recorded and time tagged by ground-based receivers or other satellite-based receivers. In performing such studies, the absolute accuracy of Blackbeard time tags was not well-characterized, but was believed to be within 10 ms.

In September of 1996 Blackbeard recorded a TIPP event which occurred in close temporal approximation to a powerful transient event recorded by ground-based HF/VLF receivers located at Los Alamos National Laboratory in Los Alamos, NM. The difference between the Blackbeard TOA and the ground station TOA was 230 µs. The small time difference between the time tags made the event a candidate for the first simultaneous recording of a TIPP event by the Blackbeard instrument and a ground-based receiver. The event rates observed by the ground station and satellite at the time of trigger suggested that the probability of the near-simultaneous triggers being merely a coincidence was 1 in 10^4.

In order to verify that the two observations were of the same event and to try to locate the source of the event based, in part, upon the difference in the times of arrival, it was necessary to evaluate the timing accuracy of the Blackbeard instrument (the timing uncertainty of the ground station was known to be ~1 µs). A Blackbeard timing uncertainty of 1 ms versus 10 ms translates to a location uncertainty of a few hundred kilometers versus a few thousand kilometers.

The Blackbeard calibration study described here was performed during November and December of 1996 using the Los Alamos Portable Pulser (LAPP) facility. The goals of the study were: 1) To develop a robust algorithm for determining Blackbeard TOAs; 2) To evaluate the Blackbeard timing accuracy and the associated TOA algorithm; and 3) To correct the Blackbeard timing algorithm for biases which were found to exist.

Experimental Setup

The Los Alamos Portable Pulser radiates an electromagnetic pulse (EMP) from a 13 m steerable dish located at Los Alamos National Laboratory. The duration of an emitted pulse is less than 20 ns and the peak pulse power is ~1 GW in a 100 MHz bandwidth. The signal source is a marx bank generator which feeds a broadband bi-planar dipole antenna at the focus of the dish. The feed is linearly polarized and has been optimized for transmission in the VHF portion of the radio spectrum. The LAPP facility is pictured in figure 1. GPS timing and pulse transmission diagnostics allow us to determine absolute pulser firing times with an uncertainty of less than 100 nanoseconds.

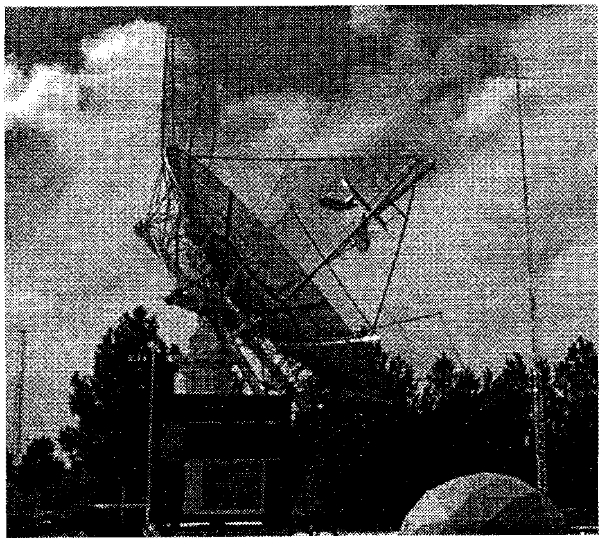

Figure 1. The Los Alamos Portable Pulser.

For the timing study, Blackbeard was programmed to make timed acquisitions of LAPP pulses. In this configuration, the trigger threshold of the Blackbeard digitzer was set to an amplitude of zero, so that the instrument would trigger immediately upon arming. Thus in order to receive LAPP pulses, it was necessary to schedule Blackbeard arm times to coincide with the estimated times of arrival of LAPP pulses at the satellite. We used timed acquisitions to receive LAPP pulses rather than to attempt to trigger on the pulses themselves because the noisy VHF radio spectrum over North America greatly reduces the detectability of LAPP pulses.

In order to time LAPP pulse transmissions properly for each calibration attempt, Blackbeard was armed at 30 ms after a predetermined UTC minute for a pass which occurred within view of the LAPP facility. The range delay to the satellite was calculated in advance and used to determine the LAPP firing time which would deliver the pulse to Blackbeard as closely as possible to the 30 ms offset. For pulses fired during the study, the LAPP programmed delays ranged between 19 and 27 ms after the predetermined UTC minutes, corresponding to ranges between 800 and 3200 km.

The Blackbeard digitizer records during this study were either 7, 21, or 35 ms in duration (corresponding to 1,3, or 5 Mbytes of 8-bit data sampled at 150 Msamp/s), depending on the configuration of the acquisition system. All acquisitions were made using the full bandwidth (from 28 to 95 MHz) of the low band. Figure 2 shows a time series and time-frequency spectrogram for a LAPP pulse as received by Blackbeard. The horizontal lines in the spectrogram are communication carriers (primarily North American television and radio stations). The pulse is the broadband transient signal which occurs between 100 and 150 μs. The frequency dependent delay exhibited by the signal is a result of dispersion by the ionosphere. Note that the pulse is not visible in the time series waveform, illustrating the difficulty in detecting the pulse and why it was necessary to utilize timed acquisitions.

The ALEXIS orbit provides two or three satellite passes within view of the LAPP facility approximately every 12 hours. For the study trigger attempts were typically made on one or two passes per day. Normal operation consisted of a single arm period per pass, but on a few occasions two arms per pass were made. With two arms per pass, acquisitions occurred approximately 5 minutes apart.

During November and December of 1996, 50 Blackbeard calibration attempts were made using the LAPP facility. Of the 50 attempts, 31 resulted in the successful acquisition of a pulse by the Blackbeard instrument. Of the 19 misses, one occurred because Blackbeard was 10° below the earth's horizon. The other 18 misses occurred as a result of Blackbeard arm time jitter.

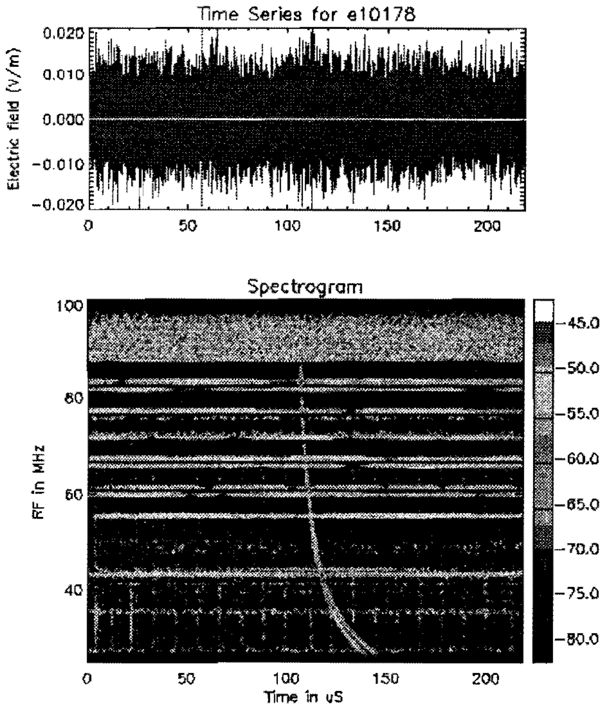

Figure 2. A LAPP pulse as received by Blackbeard.

Blackbeard does not always arm at the exact preprogrammed arm time. This characteristic is referred to as arm time jitter and is believed to result from jitter in processing software commands on the spacecraft. During calibration attempts, the jitter was as large as +/-30 ms for some arms, but was typically less than 10 ms. In some instances the jitter was large enough to cause Blackbeard to miss the pulse transmitted by LAPP. Longer records (21 or 35 ms rather than 7 ms) were taken later in the study in order to increase the probability of receiving the LAPP pulses in the data records.

It is important to note the fact that arm time jitter does not affect the accuracy of Blackbeard event time tags. Despite the fact that the instrument may arm up to tens of milliseconds early or late, Blackbeard records this fact and retains the ability to determine time tags with much greater accuracy than its characteristic arm time jitter. The lack of correlation between timing errors and arm time errors is shown later in this paper.

After each calibration attempt was made, the acquired Blackbeard data record was analyzed to determine whether the pulse was received. If the pulse was present, its position within the data record was determined and recorded as a Mbyte number and image number. Records are divided into Mbytes, which consist of 2^{20} points (6.99 ms) each; Mbytes are subdivided into 64 images, which consist of 2^{14} points (109 μs) each. In addition to the Mbyte and image numbers, other pertinent timing information was recorded. If no pulse was present in the Blackbeard record, the timing information was used to determine the reason for not receiving the pulse (if the reason was not already evident; e.g. the pulser was not fired).

Algorithm

The following algorithm was used to determine Blackbeard reported times of arrival:

$$RTOA \quad = \quad TRG - \frac{T\_POS}{150 \times 10^6} + \frac{(MB-1) + \dfrac{(IM-1)}{64}}{150} \quad \text{sec} \tag{1}$$

The algorithm starts with the absolute Blackbeard trigger time, *TRG*, as reported by the ALEXIS clock with a resolution of one millisecond. Then, because the trigger position within the data record is not fixed, the trigger position indicator variable, *T_POS*, is used to determine the time of the first point in the data record. This is accomplished by dividing *T_POS* (which is in bytes) by the sampling rate (150 Msamp/s) and subtracting the result from the trigger time, *TRG*. *T_POS* is quantized into byte multiples which correspond to 1 ms time intervals, so both the trigger time and the offset from the trigger time to the start of the record have 1 ms resolution. From the start of the record, the position of the event within the record is determined from the Mbyte number, *MB*, and the image number, *IM*. Because both *MB* and *IM* are numbered beginning with 1, it is necessary to subtract 1 from each to ensure that an event occurring in the first image of the first Mbyte occurs at the beginning of the data record. *MB* is converted to seconds by dividing by the sampling rate. *IM* is converted to seconds by dividing by 64 (the number of images per Mbyte) and dividing by the sampling rate. The *MB* and *IM* time offsets are added to the time of the beginning of the record to get the Blackbeard reported time of arrival, *RTOA*. Corrections for event locations within individual images were not made because the corrections would be fairly small compared to the overall timing uncertainty (an image is about 109 μs in length).

RTOA should not differ much from *TRG* for events which actually trigger Blackbeard (unlike the LAPP pulser shots, but like most TIPP events), because the trigger times and the event times are usually the same. An analysis of past recorded TIPP events showed this to be true.

Results

The algorithm was used to time tag the 31 pulser shots received by Blackbeard during the LAPP study. For these events the Blackbeard RTOAs were compared to ETOAs, which were based on LAPP timing and range information. The largest source of error in calculating ETOAs was the uncertainty in satellite position (~5 km); the uncertainty corresponds to a potential timing error of less than 20 μs, a small number compared to the Blackbeard uncertainty discussed below.

The distribution of the resulting differences is shown in figure 3, a histogram of the Blackbeard RTOAs minus ETOAs. The mean difference is +1.97 ms; the standard deviation of the differences is 0.43 ms. We were surprised to find such a small standard deviation, considering that there are two points in Blackbeard processing where resolution is restricted to 1 ms (as mentioned above, *TRG* and *T_POS* both have 1 ms resolution). A Monte Carlo simulation was run to simulate Blackbeard time tag uncertainty following multiple processing steps which limit resolution to 1 ms. The simulation showed that the expected standard deviation of the difference error following two restrictions of resolution to 1 ms was 0.41 ms, a number in good agreement with the experimental result of 0.43 ms.

The data indicate that there is a +1.97 ms time tag bias when Blackbeard timing information is used in conjunction with timing algorithm (1). Thus 1.97 ms should be subtracted from times generated using equation 1 in order to generate the best possible estimates of actual event times of arrival at Blackbeard. The resulting times should have an error characterized by a zero mean and 0.43 ms standard deviation.

Equation 2 shows a corrected algorithm for computing *TOA*, the best possible Blackbeard estimated time of arrival:

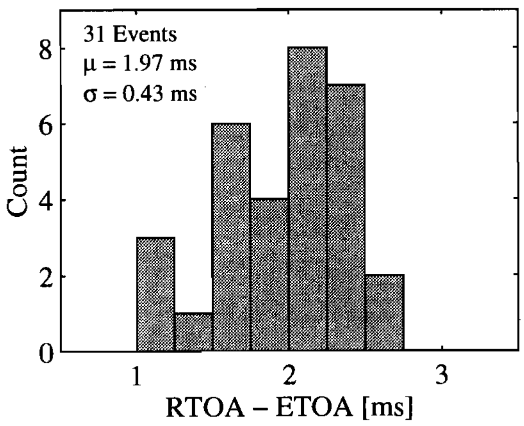

Figure 3. Histogram of Blackbeard time tag errors.

$$TOA \quad = \quad TRG - \frac{T\_POS}{150 \times 10^6} + \frac{(MB-1) + \frac{(IM-1)}{64}}{150} - .00197 \quad \text{sec} \qquad (2)$$

The only difference between equations 1 and 2 is the subtraction of 1.97 ms to minimize the timing error. Equation 2 has been implemented for Blackbeard timing studies in which high accuracy time tags are desired.

The source of the ~2 ms bias may be the result of delays which were not accounted for properly in Blackbeard processing or may result from bias in the WWV clock used by the ALEXIS ground station. Tests performed in November of 1996 (during the timing study) showed that the WWV clock output times which were ~0.8 ms later than those output by a GPS receiver known to be accurate to 1 μs. It is likely that this error accounts for ~0.8 ms of the 1.97 ms bias (the sign of the error is consistent with this statement).

It was mentioned earlier that arm time jitter, differences between scheduled Blackbeard arm times and actual Blackbeard arm times, is present; but does not appear to effect timing accuracy. Figure 4 shows a scatter plot of time tag errors versus arm time errors for the 31 successful calibration pulses described in this study. There is no apparent correlation between the two variables (correlation coefficient = -0.0042). This fact indicates that the arm time errors do not affect the absolute time tagging accuracy of Blackbeard.

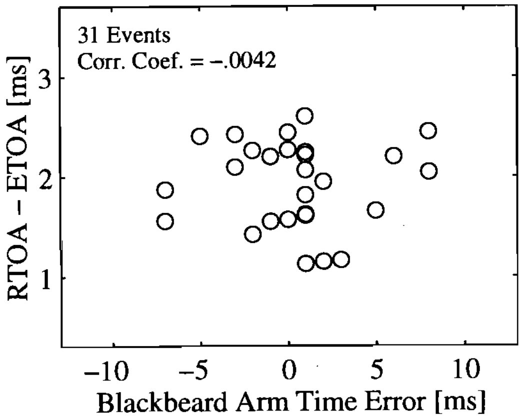

Figure 4. Scatter plot of Blackbeard arm time errors versus Blackbeard time tag errors.

It was also noted during the study that the distribution of errors (figure 3) was narrowed slightly when Blackbeard time tags were calculated using satellite timing information recorded closest in time to when the data was recorded, rather than using the timing information from when the data was downloaded. Thus when high accuracy time tags are desired, timing information recorded most closely to when the data was taken should be used.

Conclusion

The timing accuracy of the Blackbeard instrument on the ALEXIS satellite was evaluated using the Los Alamos Portable Pulser, a ground-based EMP generator. Using the information derived from 31 pulses received by Blackbeard, the study showed that time tags computed from Blackbeard timing information and an algorithm presented here are characterized by a mean error of +1.97 ms and a standard deviation of 0.43 ms. As a result of the study, the algorithm was modified to subtract 1.97 ms in order to produce high accuracy time tags. The 0.43 ms has been adopted as a measure of the uncertainty of Blackbeard time tags. It was also shown during the study that arm time jitter exhibited by the Blackbeard instrument does not affect the accuracy of its time tags and that higher accuracy is obtained if time tags are calculated using timing information recorded most closely in time to when the data was taken.

Acknowledgments

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