Bit Error Rate Evaluation of GSTDN/TDRSS Communication Links

Randall E. Coffey* and George M. Lawrence†
University of Colorado, Boulder, Colorado
and
James R. Stuart‡
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Statistical studies of telemetry errors were made on data from the Solar Mesosphere Explorer Satellite. An examination of frame sync words within the data stream, as received at the ground station, indicated a wide spread of bit error rates among stations. A study of the distribution of errors per station pass revealed a tendency for the station software to add an even number of spurious errors to the court. Ground station reporting of observed errors was found to fall into one of three major types of error distributions discovered. A detailed examination of instrument science data, using a fourth-order wild point algorithm rejecting dropouts and other system errors, yielded on average a random bit error rate of 3.1×10^{-6} with 99% confidence limits of $(2.6\text{-}3.8) \times 10^{-6}$. The system errors were typically found to be from 5 to 100 times more frequent than the identified random errors.

Introduction

THE accuracy of transmission to the ground of digitized data collected onboard a spacecraft is of prime concern to communication analysts. A useful performance criteria of the end-to-end communication system is the bit error rate (BER). In general, the measured BER of the information at any point along the communication path is the sum of two sources of error: 1) a random error, and 2) a system error. The dropouts, sync losses, etc., are easy to detect and ignore, but the random, single-bit errors may contaminate the science data in subtle ways. A study of the error inherent in a communication link allows science users to design algorithms for the detection of data wild points, thus increasing the reliability of the data. Methods for detecting errors are useful in locating and reducing error sources and may be used to evaluate current communication systems. In addition, this information could help in the design of future communication systems.

Background

General approaches to predicting BERs were published in the late 1940s.[1] Since then the application of elegant coding schemes has produced a steady decline in error rates of the RF portion of the communication link.[2,3] These theoretical approaches do not fully account for a variety of system error sources injected into the data stream and seen by the ultimate user of the information. As such, BER figures based on these methods have neglected the nonrandom events included in the transmission of data. A method of empirically determining BERs from the received data would present a more meaningful picture of the error rate.

The assessment of the actual BER is always difficult because the information content of a bit stream is usually not known a priori. Past attempts to calculate BERs used an error inspection of a known sample of bits from the data stream. This information, with statistical inference methods, was used by Rohde[4] in 1970 to determine the BER. As it will be seen, the measured error distribution is strongly affected by the influence of nonrandom and non-normal error sources. This behavior violates the basic use of these early approaches in calculating the BER.

Analysis

The intent of the study is to identify random bit errors in the system, for example, in the competition between receiver noise and the digital signal at the ground station. An operational estimate of the BER is given by the ratio of the number M of observed random bit errors to the total bits examined N.

If the BER is small compared to 1, the distribution of the observed errors M will be a Poisson distribution with an expectation value $X = \text{BER} \cdot N$. The probability distribution is given by

$$P(X,M) = \frac{e^{-X} X^M}{M!}$$

With the expected value of $P(X,M)$ as small as 10^{-5} or 10^{-6}, it becomes difficult to observe a large enough sample to get good statistics on X so that analysis of error estimates (confidence intervals) becomes important. Given M observed errors, the maximum likelihood estimator for X is M. Confidence limits on X have been obtained[5] by studying sums over $P(X,M)$ as a function of X. For $M < 200$, the limits are asymmetrical and noticeably different from those obtained with the traditional square root of M error estimates. In comparison with the use of Poisson statistics, Rohde's estimator is unnecessarily complicated and nontransparent.

A practical problem arises in having to decide, on real data, whether a given bit error is random, noise induced, or whether it is caused by software confusion, external noise bursts, sync losses, or other system errors. A comparison of the time and statistical behaviors can be used to make a distinction. The random errors have a low probability and are therefore isolated in time. The system errors tend to be found in bunches and bursts, with time constants determined by the science time constants, or frame times, etc. The random errors by definition will obey Poisson statistics, and the system errors may not. These distinctions are used in the analysis of telemetry data.

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*Systems Engineer, Ball Aerospace Systems Division. Member AIAA.

†Senior Research Associate, Laboratory for Atmospheric and Space Physics.

‡SME Deputy Project Manager. Member AIAA.

Application

The noise statistics of a set of data from the Solar Mesosphere Explorer (SME) will be examined. This satellite was recently placed into a circular, sun-synchronous, low-altitude, polar orbit for a global investigation of the creation, transport, and destruction of the Earth's mesospheric ozone layer. SME's attitude control is accomplished by spin stabilization at 5 rpm and magnetic torquing. The basic unit of science data is a limb scan at each spin.

SME's payload consists of six instruments. The four limb scanning instruments (the four-channel i.r. radiometer, i.r. spectrometer, uv spectrometer, and visible spectrometer) and the two solar instruments (the proton alarm and solar spectrometer) have an average combined data rate of 279 bits/s. SME is compatible with the future geostationary Tracking and Data Relay Satellite System (TDRSS), and is currently communicating through the worldwide 2-GHz Ground Spacecraft Tracking and Data Network (GSTDN). A functional diagram of SME's return-link through a typical GSTDN station is shown in Fig. 1.

SME carries a NASA standard transponder (compatible with the TDRSS or GSTDN) with a 5-W transmitter. In the GSTDN return-link mode the telemetry is $Bi\phi - L$ formatted and binary phase shift keyed (BPSK) modulated for transmission through two 5.5 dbi (peak) side beam antennas carried on SME. The downlink telemetry has two data modes: 1) a real-time (512-bits/s) mode, and 2) a playback mode (8.192 kbits/s) of recorded data. When received on the ground the telemetry is processed and formatted by the Digital Data Processing System (DDPS) software at each ground station.[6] The DDPS software formats the data into 4800-bit blocks for transmission to the Mission Control Center in Boulder, Colorado, by way of the NASA communications network (NASCOM). The downlink noise analysis[7] shows a worst-case margin of 13.7 dB for a BER of 10^{-5}. However, the thresholds in the transponder are set for the 10^{-5} design level so that for part of a pass, there may be a bit error rate approaching 10^{-5}.

Results

Wild Point Analysis

The measured bit error rates were obtained from two sources: science data from the SME's four-channel i.r. radiometer (IRR), and the data stream frame sync words (FSW). The frame sync words are a fixed bit pattern common in digital transmissions and can be easily inspected for errors. The science data were chosen in the SME case because a large sample of bits were available for error inspection. In order to inspect the science data, it is necessary to know something of its normal fluctuations to detect suspected random errors which occur in the data words.

The science data words may vary with each limb scan, making it necessary to set a threshold which differentiates between random and noise induced fluctuations. This requires some knowledge of the properties of the data behavior. The noise inherent in the science data collection is usually found in the least significant bits of the data words. For this reason the random error inspection focused on detecting bit errors contained in the most significant bits in each data word. The threshold defining the range of bits to be inspected in each data word determines the sample size used in the random error search.

To begin the analysis, the raw data from the IRR is stored in the Science Data Base (see Fig. 1) and flagged for quality according to system checks (e.g., polynominal i.d., block counters, etc.). Only data which are totally "error free" are considered for further analysis. From the 581 orbits inspected, 95,493 "error-free" spins were produced. Using the data from each of the four channels per spin, 36 words per channel, and 12 bits (0-4095 data numbers) per word, the initial sample contained 1.65×10^{-8} bits. This sample would represent 39 days of continuous operations.

The science data are nominally smooth functions (during each spin) along the 36-word scans in each channel, as illustrated in Fig. 2. To detect suspected errors, each data word (data number) was compared to adjacent words using a fourth-order algorithm. If a data word deviated by more than 200 data numbers from the value predicted by its neighbors, the spin was declared to contain a wild point. As previously mentioned, the number of bits inspected in each data word depends on the threshold selected to bound the noise characteristics of the data. Using a 200 data number deviation to detect word errors would inspect the four most significant bits of each data word. The sample size with this level is 5.5×10^{-7} bits.

The initial search to find wild points from the data set yielded about 1000 spins containing suspected errors. The science data from these spins were examined graphically to see whether they were random, isolated bit errors. In general, they were not.

The formation of the science data often involves amplifiers and analog to digital converters which are sensitive to noise transients on the spacecraft. Such transients are obviously not due to data transmission errors. These transients were detected by noting the time coincidences among data taken at the same time interval. The 36 point scans in each channel of the science data are measured by corresponding times but are placed in telemetry as adjacent, separate words in the data stream. Therefore an observed time coincidence of errors is highly unlikely to be random. Formation of the SME science data at 2.44-ms intervals causes the time coincidence process to be somewhat analogous to noise filtering used in RF communications links, where noise is detected and removed in a wide bandwidth of the signal path.

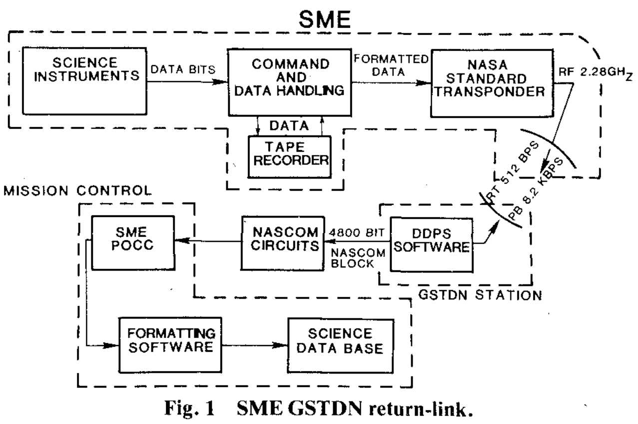

Fig. 1 SME GSTDN return-link.

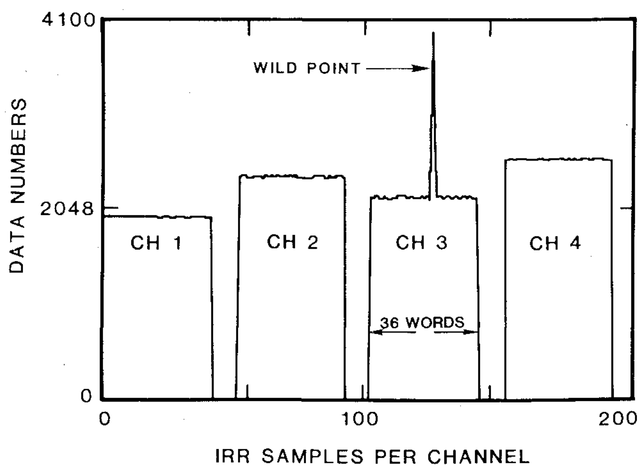

Fig. 2 Data from the IRR instrument with a wild point event in channel 3.

The majority of the 1000 spins inspected contained noise spikes or dropouts occurring simultaneously in all four channels. The time coincidence logic showed a major rejection rate (1%) on the science data caused by events other than random communication errors.

In order to examine the random bit errors, the wild points in the science data were detected in anticoincidence. This is, only those spins with a wild point in one and only one channel were counted. Under this stipulation, 173 errors were found.

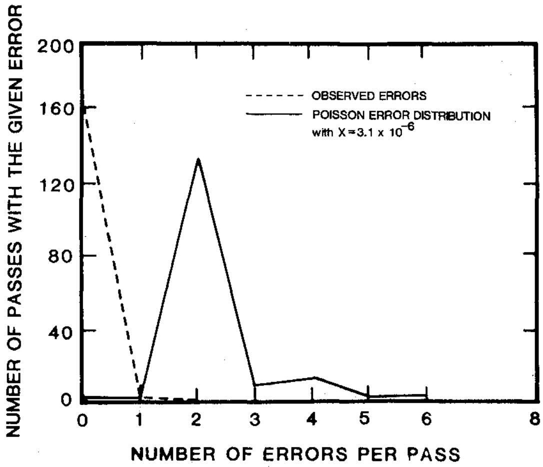

Fig. 3 Distribution of errors per pass—GSTDN type 1.

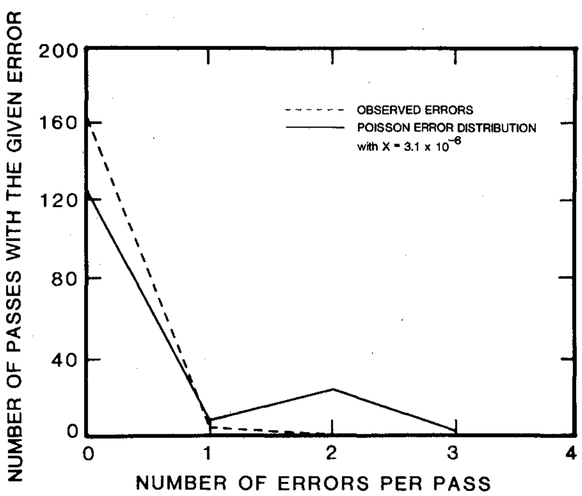

Fig. 4 Distribution of errors per pass—GSTDN type 2.

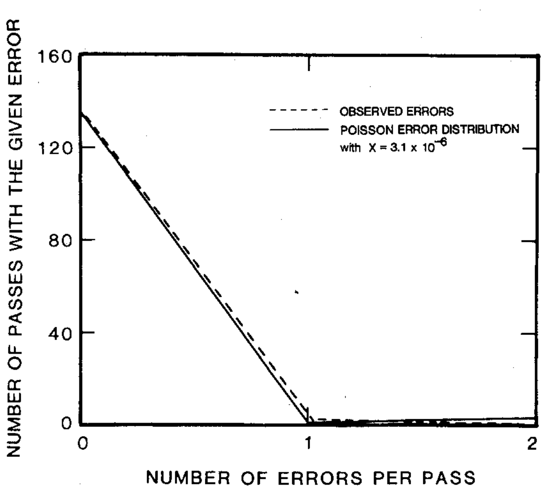

Fig. 5 Distribution of errors per pass—GSTDN type 3.

The science scans containing these errors, when plotted, were found to contain single wild points as shown in channel 3 of Fig. 2. Furthermore, the distribution of the deviations shows peak errors at binary (64, 128, 256, 512, 1024, 2048) values as is expected for bit errors. The 173 errors correspond to a BER of 173/(95,493 spins $\times$ 4 bits $\times$ 4 channels $\times$ 36 words) = 3.1×10^{-6}. The upper and lower 99% confidence limits from this sample are 3.8×10^{-6} and 2.6×10^{-6}, respectively.

Similar results are obtained by examining errors in only three of the four channels, or by thresholds set to examine the two or three most significant bits. The areas of binary peaks of the deviation spectra agree within a factor of 2 with the errors found with the threshold-coincidence method.

Sync Word Analysis

Prior to formatting the data for transmission, the DDPS software at each ground station performs a bit comparison on the frame sync words placed into the data stream by the command and data handling (CDH) unit onboard SME (see Fig. 1). FSWs are flagged in error if one or more bits are incorrect and are not grouped according to the number of errors found. Assuming error-free encoding of the FSWs by the CDH, the observed errors indicate the overall (random and system) BER of the RF portion of the downlink.

Representative frequency plots of the number of FSW errors per pass, as recorded by DDPS, are shown in Figs. 3-5 for the most frequently used GSTDN stations. The data shown were filtered to exclude burst errors, lock drops, sync losses, and other known and identifiable sources of error. The data were also accumulated to average the influence of weather, slant range, and possible operator induced error at each station. Inspection of the results provided three general classifications of error histories.

The first type (Fig. 3) shows distinctive error peaks at even intervals of FSW errors per pass. The highest occurrence of error (two FSW errors per pass) was characteristic of six of the 11 GSTDN stations contacted. Stations in the second type (Fig. 4) exhibited a similar pattern but with a majority of error free passes followed by a lower number of passes with two FSW errors detected. Two out of the 11 GSTDN stations contacted fell into this category shown in Fig. 4. These error distributions are not described by a Poisson distribution. Therefore the errors are not random, but are predominantly systematic. The remainder of the stations were grouped in the type 3 errors, as shown in Fig. 5, where a high number of zero error passes were reported and only a very few occurrences of two errors per pass.

Shown in Figs. 3-5 is the Poisson distribution of the random error with the expectation value of 3.1×10^{-6}. The previous assumption of a strong influence from systematic error is reinforced by the difference between the observed error and the expected random contribution determined from the wild point analysis. The system-attributable error is seen to be from 5 to 100 times larger than the random predictions in Figs. 3 and 4. However, type 3 GSTDN stations correlate closely to the predicted random influence. The ground stations have a choice between DDPS software phase II or phase III. The occurrence of spurious, even numbers of errors (types 1 and 2) is found to be correlated with the preferred use of phase II software at the ground stations.

Conclusions

An examination of the University of Colorado's Solar Mesosphere Explorer Satellite's communication link was performed. Error calculations based on frame sync words showed a large variability in error rates from station to station. A study of the error distributions suggests the ground station software was creating incorrect error counts. An improvement in system error reporting is possible by modification of existing DDPS software to exclude error counting during acquisition and termination phases of ground contacts.

A method of estimating the random error found in communication links based on a fourth-order wild point analysis was discussed. This method may be applied to data bit streams in which the information content exhibits small or predictable variation.

When this method was applied to SME instrument science data, the random error was found to have an average influence of 3.1×10^{-6}. A comparison with GSTDN error reporting demonstrated system errors to be from one to two orders of magnitude more common than the random error.

Although the overstatement of error rates by the ground station software did not influence the information content of the bit stream, the estimation of link error rates based on GSTDN error reporting alone will produce misleading link evaluations.

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