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Signal Characterization for TDRSS Support of Range Safety

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ABSTRACT

This work involves the analysis of signal attenuation using the NASA Tracking and Data Relay Satellite/Space Network to provide range safety and flight termination system support for expendable launch vehicles and the space shuttle. We found that at least one of the two operational TDRSS satellites could provide flight termination operating at about 250bps. Lowering the data rate could provide a larger link margin. The other satellite's signal would be attenuated below an acceptable link margin due to rocket exhaust. Lowering the data rate could provide a larger link margin.

1.0 Introduction

One of the most critical range services is that of evaluating real-time tracking and telemetry data to provide command sequences for range safety. This work involves the analysis of the communication system used for the NASA Tracking and Data Relay Satellite/Space Network (TDRSS) to provide range safety and flight termination system support for expendable launch vehicles and the space shuttle. The concept and feasibility study of this approach can be found in Ref. 1. The range safety idea can be expanded to include critical communication for vehicles from launch, orbit, and reentry.

The current method for providing range safety commands for US ranges requires ground-based antenna systems to maintain a UHF link with vehicles. Currently the Eastern range (ER), and the Western range (WR) rely on multiple ground stations to support the command destruct system. The range operations control centers (ROCCs), one at the WR, and one at the ER evaluate real-time tracking and telemetry data and provide command sequences for range safety. Some of these stations reside in foreign locations, with the associated rules, regulations, and logistics issues. New concepts for providing range safety have been investigated because of the costs associated with maintaining antenna systems, ground station horizon coverage limitations, and UHF frequency band crowding.

The TDRSS system has been considered to support range safety. The space portion of TDRSS fleet consists of several satellites in geosynchronous orbit, and can provide hemispheric coverage for the ER and WR. The ground segment is located near Las Cruces, NM with a remote terminal Guam. Use of the TDRSS would eliminate downrange stations and provide "seamless" coverage between launch-head (local) and space-based communications. The TDRSS/SN would provide maximum coverage for all potential launch trajectories, and provide centralized control.

Space-based ranges may provide a more flexible, robust and technologically advanced solution. They offer increased reliability and global coverage augmenting or eliminating ground-based tracking systems currently used. In addition, modern and future communication systems are often based on digital spread-spectrum communication modulation. Spread-spectrum is a modulation technique that separates signals by codes and transmits different signals in the same time and frequency space. It provides an inherent degree of immunity to noise and jamming. We examined some of the issues involved in converting to a modern space-based network from an analog ground-based network. These include, data rate, link margin, and effect of rocket exhaust on signal transmission.

2.0 NASA Tracking and Data Relay Satellite/Space Network (TDRSS)

The TDRSS system is a communication signal relay system that provides tracking and data acquisition services between low earth orbiting spacecraft and NASA/customer control data processing facilities.[2,3] The system is capable of transmitting to and receiving data from customer spacecraft's over at least 85% of a customer's orbit. The TDRSS system consists of several satellites in geosynchronous orbits, a dedicated ground station, and remote station. Two satellites form the nominal operational TDRSS service at 41^{o}W, and 174^{o} W longitudes. The other satellites in the constellation provide ready backup in the event of a failure to an operational spacecraft and, in some specialized cases, resources for target of opportunity activities. A third satellite operates at 285°W with limited service with a ground station in Guam that could possibly provide global coverage.

The TDRSS ground segment is located near Las Cruces, New Mexico and consists of two functionally identical ground terminals known collectively as the White Sands Complex. Customer forwarded data is uplinked from the ground segment to the TDRS, and from the TDRS to the customer spacecraft. Customer return data is downlinked from the customer spacecraft via the TDRS to the ground segment and then on to the customer designated data collection location.

The TDRSS offers several services that are summarized in Table 1. Forward service is defined as the communication path that generally originates at the customer control center and is routed through the TDRSS to the customer spacecraft. Return service is defined as the communication path that originates at the customer spacecraft and is routed through the TDRSS back to the customer control center or other customer-specified destination. Single access service, is a dedicated customer service utilizing the steerable single access antennas. Single access services support higher forward and return customer data rates. Services are available within a specified range of S or Ku band frequencies unlike the multiple access service that is fixed frequency. Multiple access service is a shared capability from which up to five return services can be run simultaneously. The multiple access service are more readily available than the single access service however they support lower forward and return data rates.

		FREQUENCY	SERVICE	MAX. DATA RATE	SERVICES PER TDRS
SINGLE ACCESS	S-BAND	2020.4 MHz - 2123.3 MHz	FORWARD	300 kbps	2
		2200 MHz - 2300 MHz	RETURN	6 Mbps	2
	K-BAND	13.747 GHz - 13.802 GHz	FORWARD	25 Mbps	2
		14.887 GHz - 15.119 GHz	RETURN	300 Mbps	2
MULTIPLE ACCESS	S-BAND	2103.1 MHz - 2109.7 MHz	FORWARD	10 kbps	1
		2284.5 MHz - 2290.5 MHz	RETURN	100 kbps	5*

* GROUND STATION LIMITED

Table 1 Services of TDRSS system

TDRSS supports the following modulation schemes: bi-phase shift keying (BPSK), qudrature phase shift keying (QPSK) and staggered qudrature phase shift keying (SQPSK). Data formats supported are non-return to zero and Bi-Ø - Level (BiØ-L), also known as Manchester.

3.0 TDRSS communication

The TDRSS system uses a digital spread spectrum method of communication. Spread spectrum describes a modulation technique that transmits in the same time and frequency space as other signals, but the signals are separated by codes.[4] Spread spectrum modulation provides, a resistance to jamming, allows multiple users to access the same channel, and, signals can be transmitted at low power. Basically, the spread spectrum system transmits a signal over a frequency much wider than the minimum bandwidth required to send the signal. The fundamental premise is that, in channels with narrowband noise, increasing the transmitted signal bandwidth results in an increased probability that the received information will be correct. If total signal power is interpreted as the area under the spectral density curve then signals with equivalent total power may have either a large signal power concentrated in a small bandwidth or a small signal power spread over a large bandwidth. Then at the receiving end, the signal is de-spread.

The process gain (Gp) is what actually provides increased system performance without requiring a high SNR. This is described as,

$$G_p = BW/R, \tag{1}$$

where, BW = RF bandwidth, and R = data rate in bits/second. The baseband signal is spread out over the full bandwidth. Then at the receiving end, the signal is de-spread by the same amount by a correlation with a desired signal generated by the spreading technique. When the received signal is matched to the desired signal the baseband signal is retrieved.

Direct sequence spread spectrum (DSSS) is probably the most widely recognized form of spread spectrum. The DSSS process is performed by multiplying an RF carrier and a binary pseudo-noise (PN) digital signal. First the PN code is modulated onto the information signal using one of several modulation techniques (e.g. BPSK, QPSK, etc). Then, a mixer is used to multiply the RF carrier and PN modulated information signal as shown in Fig. 1. This process causes the RF signal to be replaced with a very wide bandwidth signal with the spectral equivalent of a noise signal. The signals generated with this technique appear as noise in the frequency domain. The wide bandwidth provided by the PN code allows the signal power to drop below the noise threshold without loss of information.

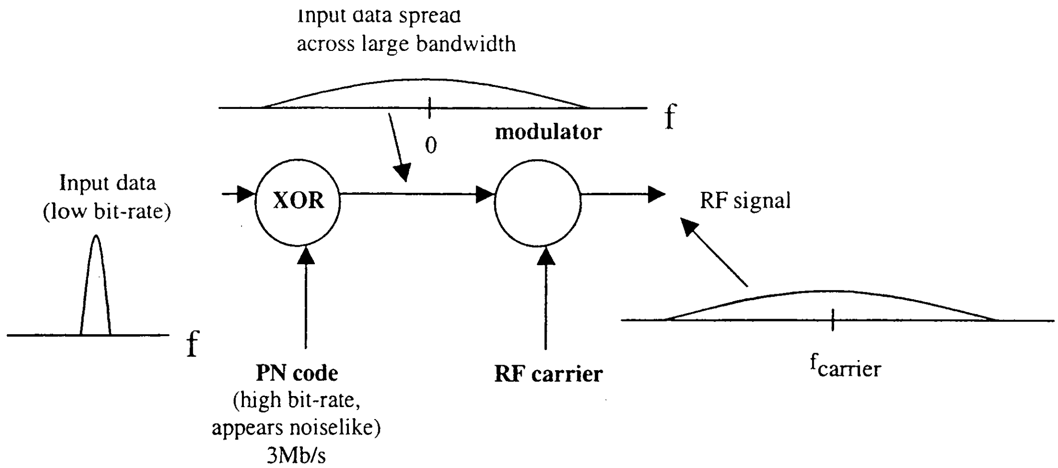

Figure 1 Schematic diagram of DSSS transmitter

The demodulation process consists of multiplying the incoming RF signal with the same PN code used in the transmitter as shown in Fig. 2. Using the same PN code in the receiver as in the transmitter despreads the bandwidth of the received signal to that of the input to the transmitter. Otherwise, the input to the demodulator will have a large bandwidth and appear noise-like. The resulting signal is then demodulated, and the bits recovered using a correlation process. Signals encoded with different PN codes will generally not interfere because the codes are usually chosen to be uncorrelated.

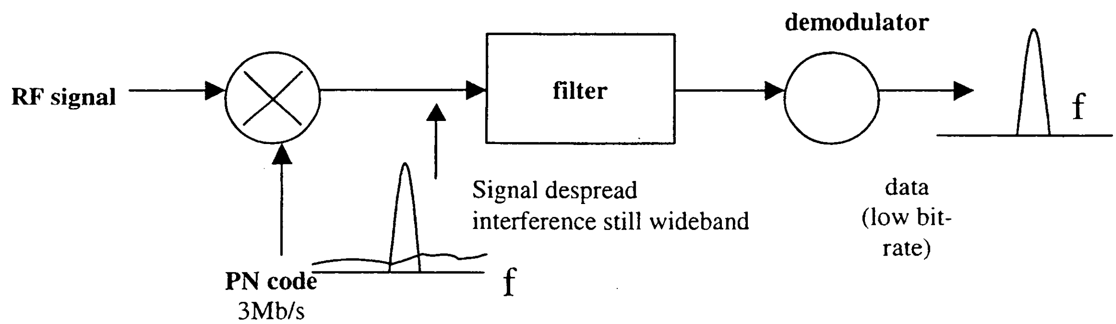

Figure 2 Schematic diagram of a DSSS receiver

A detailed link budget analysis of the TDRSS - vehicle (forward) link has been previously performed.[1] The link margin can be written as,

$$M_L = E_b/N_o(\text{rec}) + G_p - E_b/N_o(req) - PL, \qquad (2)$$

where each parameter in Eq. (2) is measured in decibels. The value of PL was taken to be 1.0dB, and the value of $E_b/N_{c(\mathrm{rec})}$ = -21.4dB from the analysis. The value of BW is 6MHz for TDRSS, which gives G_p = 43.8dB at 250bps. The value of $E_b/N_{o(req)}$ depends on the bit-error rate (BER) that can be tolerated and the type of modulation used and are usually widely available. We considered binary phase shift keying (BPSK) modulation in our study which is commonly used and available with TDRSS, and a BER = 10^{-5}. A common practice is the use of convolutional encoding of data with a ½ code, Viterbi decoding with a constraint length of 7, and a 32-bit path memory, which gives $E_b/N_{o(req)}$ = 5.1dB. The results show that the static link margin to be 16.2dB at 2106.4 MHz, at a data rate of 250bps. Note that the convolutional encoding used here increases the amount of data transmitted by a factor of two.

Different values for data rates and $E_b/N_{o(req)}$, will give different values of M_L. We showed the link margin as a function of bit-rate in Fig. 3. for a constant value of $E_b/N_{o(req)}$ = 5.1dB. The results show how the link margin is increased by decreasing the bit-rate. For larger values of $E_b/N_{o(req)}$, the data is shifted down by the difference between the two values, and similarly for smaller values of $E_b/N_{o(req)}$.

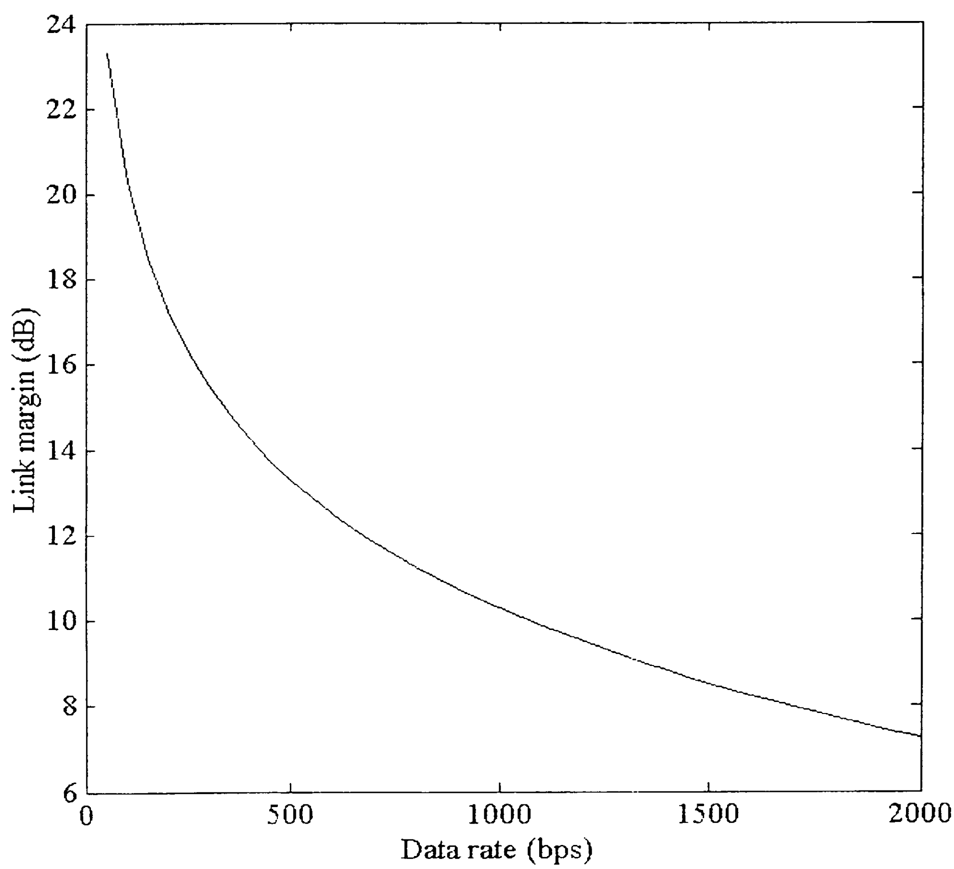

Figure 3 Link margin as a function of data rate for $E_b/N_{o(req)}$ = 5.1dB.

4.0 High-alphabet encoding

Currently, flight termination is provided by an analog FM system. Messages are encoded using a series of tones in what is known as a high-alphabet scheme. There are 7 tones plus 1 pilot tone. The pilot tone is not used in the alphabet. Each character consists of two tones. Because the tones are sequence independent, the number of characters in the alphabet is

$$7^2 - \sum_{i=1}^{7} i = 21. \tag{3}$$

Each message consists of 11 characters. Because the message is sequence dependent, there are $21^{11} = 3.5 \times 10^{14}$ possible messages. A message is transmitted in 111.4mS, and the start between two messages is 180mS, for a rate of 5.5 messages/sec.

We considered implementing the high-alphabet system digitally to be equivalent in terms of the number of possible messages. Considering the number of messages, $\log_2(3.5 \times 10^{14}) \approx 50$ bits are needed to represent all messages. If each character is represented by five bits, then, each message would consist of 5 bits/character x 11 characters = 55 bits. Therefore, approximately 55 bits can be used to replace the high-alphabet method in a digital system to have the equivalent number of messages. Note that the number of bits do not include any dead spaces or headers between characters or messages.

Another way to implement the current high-alphabet system is to digitize the analog signal. The tone frequencies range from 7.35kHz to 13.65kHz. Therefore, to properly digitize the signal, a sampling frequency greater than 27kHz must be used. At this sampling rate, digitizing a message for 111.4ms results in $0.1114 \times 27000 \approx 3000$ bits.

5.0 Effect of rocket exhaust on communication signals

Rocket exhaust has been known for some time to have significant effect on communication to and from launch vehicles. This is primarily because rockets generate exhaust plasma clouds containing a high density of free electrons.[5,6] It has been found that the attenuation of a microwave signal by rocket exhaust plasma can be modeled as a diffraction problem, where the exhaust plasma is replaced by a diffracting object.[7,8] This model has shown to be useful, but it is only valid for relatively small angles from the vehicle axis. An improved model would allow for the effects of scattering at larger angles. Such an approach would allow the modeling of both diffraction and multipath fading.

We considered a conducting sphere to model an exhaust plume to include the effects of reflection at larger angles than those typically used with diffraction. It has been shown that the scattered (diffracted) field in the forward direction of an obstacle does not depend on the detailed shape of the obstacle.[9] This phenomenon has been observed experimentally with a scale model of a rocket.[7] Therefore, the scattering by a sphere in the forward direction is a typical diffraction pattern and our approach is consistent with previous results with respect to diffraction. The diffracted field due to rocket exhaust has been previously described.[8] In addition, general solution describing the scattered field from a sphere at all points in space has also been described in detail.[10]

We used the flight trajectory from a launch vehicle to find the angle (α) involved between a launch vehicle at the TDRSS satellites measured along the vehicle axis from the front of the vehicle. The flight trajectory was from a Space Shuttle mission, STS-103 on 12/20/90 from Kennedy Space Center, Fl on a 90 degree launch azimuth. To establish the link margin as a function of time, we needed to calculate the attenuation as a function of angle. For small values of α, the attenuation will be due to multipath effects due to reflection from the plume, and for large values of α will be due to diffraction. In terms of multipath effects we considered the average symbol energy-to-interference ratio of 1, and the phase to be uniformly distributed. In this case it can be shown that an additional 3dB if required by the degraded channel to achieve the same performance as an unfaded channel.[11] At larger angles, attenuation will be due to diffraction. Using the same geometry as in Ref. 8, we used the lower envelope of the diffraction of the plume. These results are shown in Fig. 4 as the attenuation of link margin as a function of α.

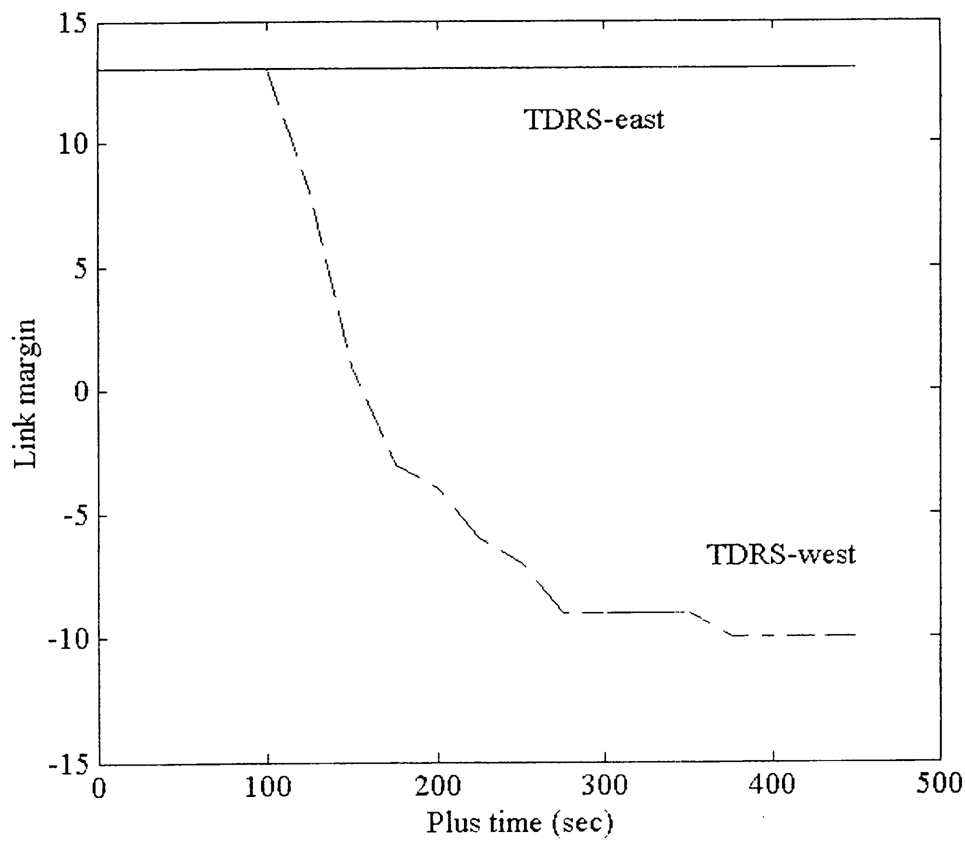

Figure 4 Link margin as a function of time for STS-103 at 250bps.

6.0 Conclusion

We found that a flight termination method using the digital spread-spectrum system available with the TDRSS system can meet the requirements for bit-rate and link margin. Bit-rates in the vicinity of 100-250 bps seem to the most probable with link margins in the vicinity of 13 dB. We found that at least one of the two operational TDRSS satellites could provide flight termination operating at about 250bps. Lowering the data rate could provide a larger link margin. The other satellite's signal would be attenuated below an acceptable link margin due to rocket exhaust.

7.0 References

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