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High-Accuracy Ranging Using Spread-Spectrum Technology

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Abstract

Small satellite formation flying is an important new technology. Of prime importance in formation flying is the need to determine high-accuracy real-time satellite-to-satellite range and velocity information. Spread spectrum technology is usually used for this purpose, but there are limitations to this approach.

Traditional spread-spectrum ranging involves either one-way ranging (e.g. the GPS constellation) or round-trip ranging. Both of these are useful, but each has limitations.

One-way ranging requires highly accurate synchronized clocks on each satellite. Time synchronization, as well as frequency stability, is required and time synchronization is difficult to achieve between satellites. If the ranging accuracy requirements are stringent these requirements are especially difficult to meet.

Two-way ranging eliminates the need for high-accuracy synchronicity between satellites, but when using traditional spread-spectrum ranging techniques the achievable chipping rate limits the resolution. This paper shows how other techniques can be used to generate much more accurate information than traditional spread-spectrum allows.

The paper describes a step-by-step approach to extracting integer code range, sub-chip code phase and carrier phase information from a coded waveform. The method demonstrated in the paper explains qualitatively at each step how this is done, and then explains quantitatively at each step how to determine the expected system performance.

The paper addresses in detail the quantitative limits on achievable performance. From these limits the requirements for system frequency accuracy and the tradeoffs between signal-to-noise ratio (SNR) and range updating are developed.

Introduction

Satellite formation flying requires real-time high-resolution, high-accuracy spread spectrum ranging between satellites. This paper discusses a method that can be used to achieve this. Both resolution and accuracy are covered in this paper. This paper assumes that there are two satellites (although the concepts herein are extendable to n satellites) and that a round-trip radio path between the two is established. This paper does not discuss how such a round-trip path could be implemented; it focuses on the information content of the waveform itself. It is assumed that a "Perfect Radio Mirror" satellite exists and reflects the modulated waveform back to the originating satellite.

The only information that passes between satellites is the information contained in the modulation waveform. This paper describes a method for extracting the required information and develops a set of quantitative parameters associated with this process.

The ranging system consists of a local transmitter, a local receiver and the "radio mirror" that reflects the coded signal from a remote location back to the originating satellite. The mirror satellite is assumed (to a first order) to be distortion-free in amplitude, frequency and time. The local receiver, since it is co-located with the transmitter, has available to it a perfect replica of the transmitted code and carrier.

The ranging system is also assumed to function as an inter-satellite communications link. This is achieved by multiplexing data on the ranging PN code.

Baseline System Definition

A particular baseline system is postulated that has the characteristics shown in table 1.

Table 1
Baseline System Definition

Carrier Frequency:	12 GHz
PN Code Rate:	300 Mcps
PN Code Modulation Type:	BPSK
Maximum Range:	10 km
Communications Rate:	128 kbps
Ranging Accuracy:	0.5 cm

Other carrier frequencies, modulation rates and modulation types can also be analyzed as shown herein. For the scheme presented here, it is required that the PN code clock and the 12 GHz carrier are coherent in the sense of having a common reference signal.

This coherency provides for the condition that each 300 Mcps (Mega-chips per second) chip contains exactly 40 cycles of the 12 GHz carrier, and that the zero-phase point of each chip corresponds to the zero-phase point of one cycle of the 12 GHz carrier. This locking of the modulation and the carrier is necessary for the technique that follows, and in practice is easy to achieve by simply phase-locking both clocks to a common high-stability master system reference oscillator.

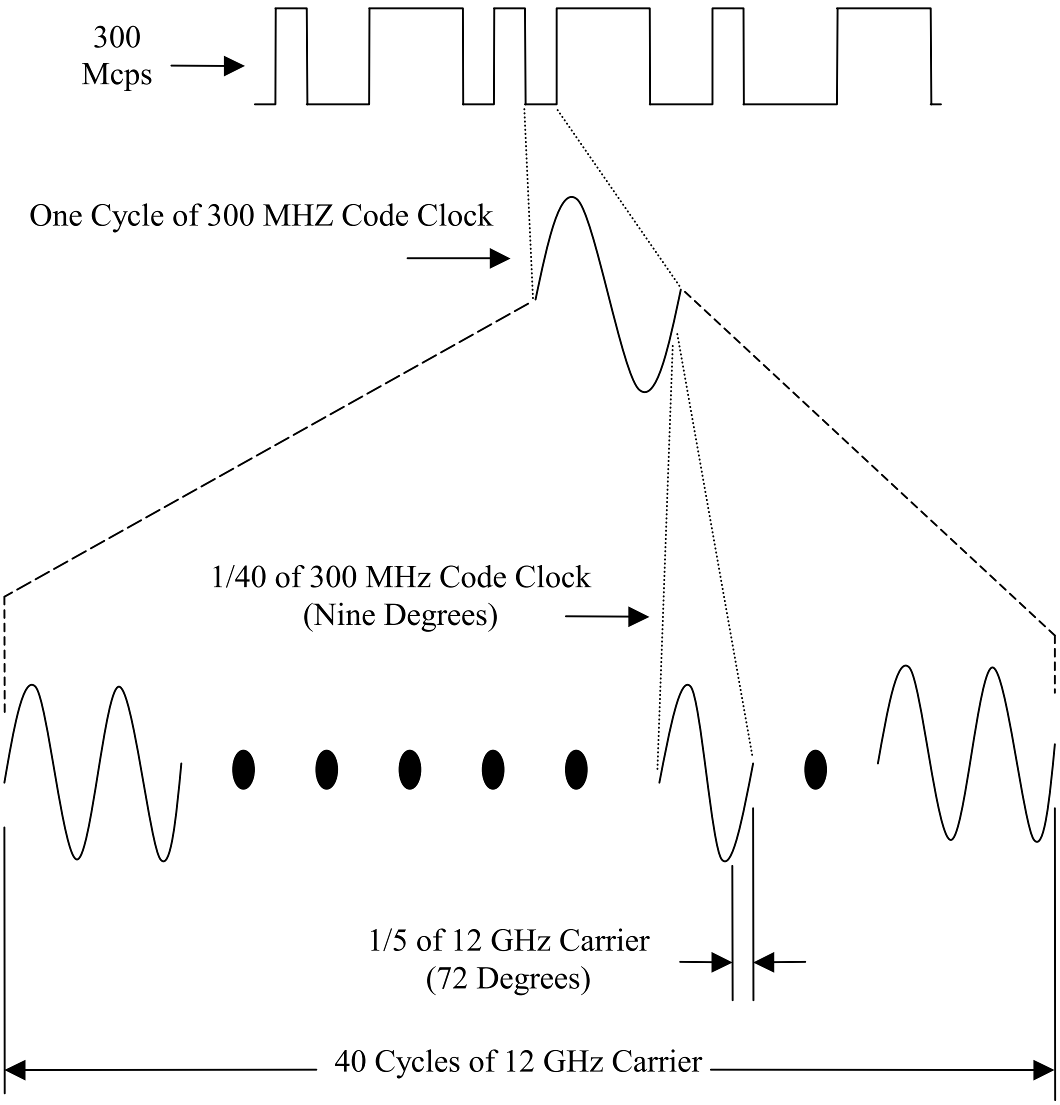
Waveform Information Content

There are three components of information in the waveform:

- The integer chip value (which particular chip has arrived)
- The sub-chip code phase value (exactly where within an integer chip the arrival occurs)
- The 12 GHz carrier phase value (the carrier phase at the instant of arrival)

Together, these components provide, in a step-by-step fashion, for resolution to a high degree of accuracy. The composite ranging waveform is shown in Figure 1.

To extract this highly accurate information from the waveform, it is necessary to develop a method for going from one level of resolution (e.g. integer chip) to the next level of resolution (e.g. sub-chip code phase). It is assumed that the radio mirror satellite (satellite in this sense means a co-located transmitter and receiver pair) reflects this coded waveform perfectly, with the particular relationship between the three information components preserved.



Information Content of Spread Spectrum Waveform
Figure 1

Integer Chip Ranging

Any particular satellite contains, among other things, two identical but independent code generators. The transmit code generator runs continuously, beginning at system startup, rolls over at terminal count, and continues to run as long as the system operates. The receive code generator code-locks to the received signal, which is itself a time-delayed replica of the transmitted signal. The binary numerical difference between the two code generator registers at any particular instance is the round-trip distance (in chips) from the originating satellite to the mirror satellite. If the chipping rate is 300 Mcps, each chip corresponds to one meter in absolute distance.

The length of the PN code required depends on the maximum range of the system. In order to measure a round-trip distance of, for example, 20 km, with one-meter chip resolution, a code of 20,000 chips or greater is required. If practical, maximal-length code generators are used, this implies a code generator of 15 bits (32,768 chips) or longer.

Sub-Chip Code Phase Ranging

After determining the integer code chip received by the satellite, the next step is determining exactly where within the chip the reflection occurred. This is referred to as sub-chip code phase ranging.

The Receive code generator, which is code-locked to the reflected code, is running at a code-locked frequency of 300 MHz. This can be thought of as each chip having embedded within it exactly one cycle of a 300 MHz clock. The phase of this “implied clock” is dependent upon the reflected path length and can be measured.

The purpose of sub-chip code phase ranging is to define a particular cycle of 12 GHz carrier phase to be used for the finest level of ranging, carrier phase ranging. Since there are exactly 40 cycles of 12 GHz carrier in each 300 MHz chip, and since the 300 MHz and 12 GHz clocks are coherent, a particular cycle of 12 GHz carrier can be selected by the sub-chip code phase. This is similar to an M-ary PSK demodulation problem, where M is 40.

All that is required to develop this information is a phase detector to compare between the received and transmitted sub-chip code phase and a filter to band-limit the noise power. The filter’s bandwidth determines the signal-to-noise ratio (SNR) for this measurement and also limits the rate at which the system responds to a change in information. The system update rate varies inversely with SNR and accuracy.

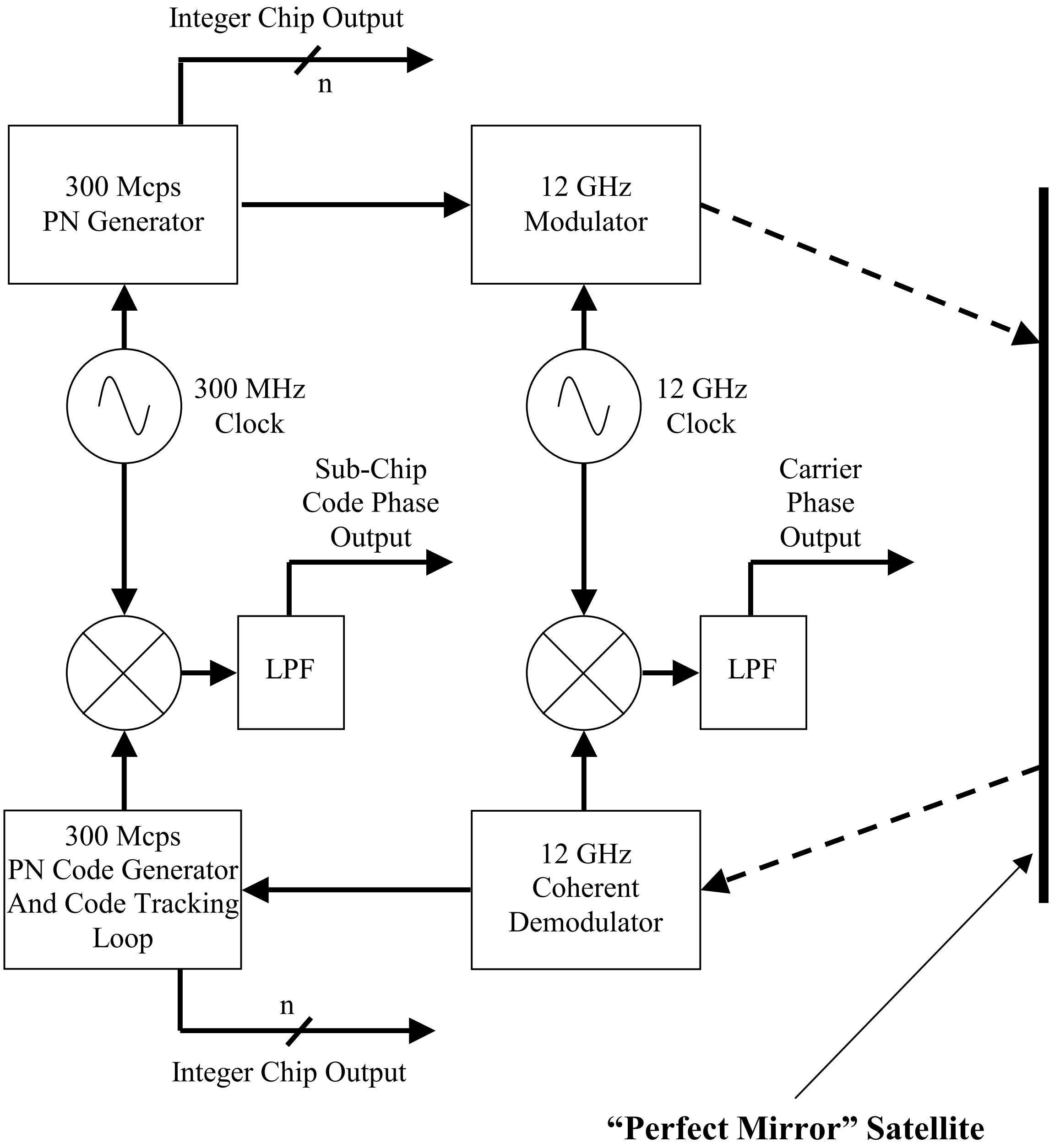
For example, a system design requiring one-half centimeter accuracy only requires 72 degrees of resolution at the 12 GHz carrier level, which corresponds to 5-ary PSK demodulation (72 degrees is one-fifth of 360 degrees). This implies that the 300 MHz phase resolution problem is the driving requirement for achieving the overall accuracy.

Carrier Phase Ranging

The final level of ranging precision is achieved by measuring the 12 GHz carrier phase of the reflected signal. The received signal carrier is recovered by common methods and a phase-locked local oscillator is generated that is a replica of the received carrier. The replicated carrier is compared to the transmitted carrier in a phase detector, followed by a low-pass filter, and the phase difference is measured. The same tradeoffs of SNR vs. update rate as in sub-chip code phase apply here as well.

System Block Diagram

The basic system for extracting the required information is shown in figure 2. Where the existence of the "Perfect Radio Mirror" satellite is assumed.



Ranging System Block Diagram

Figure 2

A 300 MHz clock drives a PN code generator creating a unique 300 Mcps PN code. This 300 MHz clock is phase-locked to the master system high-stability, Low phase noise reference oscillator, typically a USO crystal or rubidium source.

The 300 Mcps PN code is used to modulate a 12 GHz carrier, which is phase-locked to the same master reference oscillator. This generates the modulated 12 GHz ranging waveform with all the required information.

The 300 Mcps PN code and the 12 GHz carrier are phase coherent, as required, because they are derived from the same reference oscillator. Filters, amplifiers, mixers and other ancillary components are not shown for reasons of clarity, however the effects on the waveform of any of these devices must be considered.

The modulated 12 GHz carrier is transmitted to the mirror satellite. The mirror reflects the signal back to the originating satellite without distortion

Upon receiving the reflected signal, the BPSK signal is demodulated yielding the 300 Mcps PN code as its output. It is important to note that the 12 GHz demodulator is a coherent type, such as a Costas loop or other carrier-recovery loop. This is necessary in order to generate a local 12 GHz carrier that is phase-coherent with the received modulated waveform’s carrier.

A PN code generator and coherent code tracking loop process the received 300 Mcps data. This results in synchronization of the receiver PN code generator to the received PN code and also the synchronization of a 300 MHz clock so that it is phase-coherent with the received 300 Mcps modulation code.

The integer state of the receiver PN code generator reflects exactly which PN code chip is being received at that instant. The phase of the 300 MHz clock at any instant indicates the phase of the sub-chip code being received.

At this point, all the information required to determine the range between satellites is present. How this is derived from each piece of information is described below.

Integer Code Phase

The transmitted integer code phase is generated locally (at the transmitter). The received integer PN code phase is recovered locally. Determining the integer chip distance between the satellites is simply a matter of subtracting one digital word from the other.

It should be noted that, with this measurement the actual distance is one-half the measured distance because the system measures the round-trip propagation distance of the modulated signal, which is twice the one-way propagation time.

Sub-Chip Code Phase

Since the transmitted PN code clock phase is generated locally, and the received PN code clock phase is recovered from the signal, the two can be compared in a phase detector to determine the exact phase offset between the two.

In the example system the phase discrimination problem at this stage is the most difficult part of the ranging process because there are 40 cycles of carrier per code chip. This implies a phase discrimination requirement of 1/40, or nine degrees. The exact SNR requirements necessary to achieve this are examined below.

Carrier Phase

The transmitted 12 GHz carrier phase is generated aboard the signal's originating satellite and, when received, the reflected 12 GHz carrier phase is coherently demodulated. Therefore an exact representation of the original 12 GHz carrier phase is derived. At this point, the transmitted and reflected signals are compared in a phase detector and the phase difference determined. The accuracy requirements at this stage are relatively modest for the postulated system, because only 72 degrees out of 360 must be discriminated, as illustrated in figure 1.

Overall Accuracy Requirements

Two parameters drive the achievable system accuracy: overall timing accuracy and SNR. This section examines the timing accuracy requirements for each level of ranging. The next section examines the SNR requirements for each level of ranging.

Timing Accuracy Requirements

Integer Code Ranging

The receiver code generator is code-locked to the received PN-coded signal, which is a mirrored replica of the transmitted PN-coded signal. The received signal code clock is, therefore, effectively phase-locked to the transmitted code clock (neglecting higher-order effects such as jitter). Since the two clocks are the same, differential clock errors are (to a first order) zero.

Therefore, the only significant error to consider is when the distance to the mirror satellite (x chips away), as indicated by the integer code phase, is measured as x ±1 chips away. The worst-case measurement is at maximum range, so the allowable error is one chip divided by 20,000 chips (10 km maximum range times 2 times 1 chip/m), or 50 ppm. This is the upper error limit for any reasonable communications or ranging system using this technique.

Sub-Chip Code Phase Ranging

The accuracy requirement for sub-chip ranging is developed similarly to the requirement for integer chip ranging. In order to make an error, the satellite must decide that it received:

N integer chips plus (m±1)*[(one carrier cycle)/40]

Compared to what was actually received:

N integer chips plus (m)*[(one carrier cycle)/40]

So, in order to make an error in sub-chip ranging, a timing error of 1/40 of a chip time (defined hereinafter as a sub-chip) must occur. The maximum range of 10 km (20 km round-trip) corresponds to 800,000 sub-chips. One sub-chip error out of 800,000 sub-chips is 1.25 ppm, a modest requirement.

Carrier phase Ranging

For the case of a 12 GHz carrier, the wavelength is 2.5 cm. For an accuracy of 0.5 cm at the maximum range of 10 km (20 km round-trip), the accuracy requirement is 0.5 cm/20,000m, or 0.25 ppm. This implies that the worst-case timing accuracy requirement for the entire ranging system is therefore 0.25 ppm, which is well within the accuracy of any reasonable high-quality reference oscillator.

Signal to Noise Ratio Requirements

The detection of the phase of a signal in real-time is primarily a function of the signal SNR. To a first order, SNR can be improved arbitrarily by narrowing the receiver bandwidth, but as the receiver bandwidth narrows, the achievable update rate decreases. Optimal system design depends on balancing these two parameters. Before discussing these parameters, it is convenient to first discuss the communications channel.

The Communications Channel

Expanding upon our previous example, assume that the communications channel has a simple 128 kbps link in a spread-spectrum system. The transmitted data and the PN code are combined together in an exclusive-or gate at the transmitter. The output of this stage is either the PN Code or the inverted PN Code, depending upon whether the data is a zero or a one.

At the receiver, the output of the code tracking loop phase detector (prior to the loop filter) is monitored for 180° transitions. These transitions represent the transmitted data.

This system works well as long as certain conditions are met. The data rate ideally should be several orders of magnitude lower than the chipping rate and the data must have "random" statistics, i.e. approximately equal numbers of ones and zeros and only short runs of ones or zeros.

Assuming these conditions are all true, data can be passed through the link without degrading the ranging performance. Since this is a BPSK system, where essentially many chips are integrated to form one data bit, the common BPSK criteria of 9.6 dB E_b/N_0 for a 1 X 10^{-5} bit error rate is a reasonable performance expectation.

A convenient way to analyze the ranging system is to assume that the system must pass the transmitted data, and that the link has been "sized" accordingly. This requirement places a "floor" on the available signal power present. Therefore, we can assume for this analysis that a 10 dB SNR is present in a 128 kHz bandwidth.

Ranging Channel SNR Requirements

The requirements of the communications channel have defined the SNR available for ranging at the receiver. This information can now be used to estimate the performance of the ranging system

Integer Code Ranging SNR Requirements

The receiver code generator will be phase-locked to the incoming coded signal using a phase-locked-loop with an associated closed-loop bandwidth. The communications channel has an SNR of 10 dB in a baseband bandwidth of 128 kHz. Since SNR can be improved in a system by decreasing the system bandwidth (again, to a first order), the following table shows achievable phase-locked-loop bandwidths, SNRs and update times. The update rate calculation is based on a step function change and uses the relationship t_r=(0.35/BW).

Table 2
SNR vs. Update Rate

Bandwidth	**SNR**	**Update Time**	**Update Rate**
128 kHz	10 dB	2.7 usec	370 kHz
1.28 kHz	30 dB	270 usec	3.7 kHz
128 Hz	40 dB	2.7 msec	370 Hz
12.8 Hz	50 dB	27 msec	37 Hz

Phase-locked-loop tracking with at least 30-40 dB SNR inside the loop is easily achievable. So a range of solutions exist that support both the required tracking SNR and the required update rate. For example, the integer code range can be updated at approximately a 1 kHz rate with reasonable SNR within the loop.

Sub-Chip Code Phase Ranging SNR Requirements

Sub-chip code phase ranging is similar to the problem of detecting M-ary PSK where, in this case, M=40. This is another case where SNR is traded against update rate to arrive at an acceptable compromise.

Again using the technique of trading bandwidth for SNR, we can adjust the update rate of the system to support the required SNR.

The SNR required to decode BPSK, as mentioned above is on the order of 10 dB. For PSK modulations of order greater than 4, closed form expressions relating SNR and symbol error rate do not exist. However, an over-bounded relationship between the two can be developed.[1]

For M>4, the probability of error can be approximated in the over-bounded sense as:

$$P(e) = 2erfc\sqrt{\frac{2E_S}{N_0}\sin^2\frac{\pi}{M}} \tag{1}$$

where *erfc(x)* is the complementary error function, defined as:

$$erfc(x) = \frac{2}{\sqrt{2\pi}}\int_x^\infty e^{\frac{-z^2}{2}}\,dz \tag{2}$$

From figure 3 below (developed from equation 1), it can be seen that accurate 40-ary PSK demodulation requires a SNR of approximately 30 dB.

Using the same assumptions as in the case of integer code ranging, this implies a maximum bandwidth on the order of 1.28 kHz for an update rate of 273 usec, which permits an update rate of 3.7 kHz, again a reasonable number.

Carrier Phase Ranging SNR Requirements

Carrier phase ranging is another M-ary PSK problem, where M=5. According to figure 4 below (also from equation 1), this will require a SNR on the order of 10-12 dB, which we can easily provide with a bandwidth of about 100 kHz and which will not compromise our update rate.

Conclusion

This paper has presented a technique for communication and ranging between satellites. The technique has been shown to provide for high-accuracy inter-satellite ranging with reasonable update rates and high data rate communications.

This paper also developed the basic structure for transmitting and receiving the ranging signal. The information content of the modulated waveform was examined in detail and a method for quantitatively analyzing the achievable performance with respect to ranging accuracy and range update rates was presented.

1. Smith, David R., Digital Transmission Systems, Second Edition, Van Nostrand Reinhold, New York, 1993.

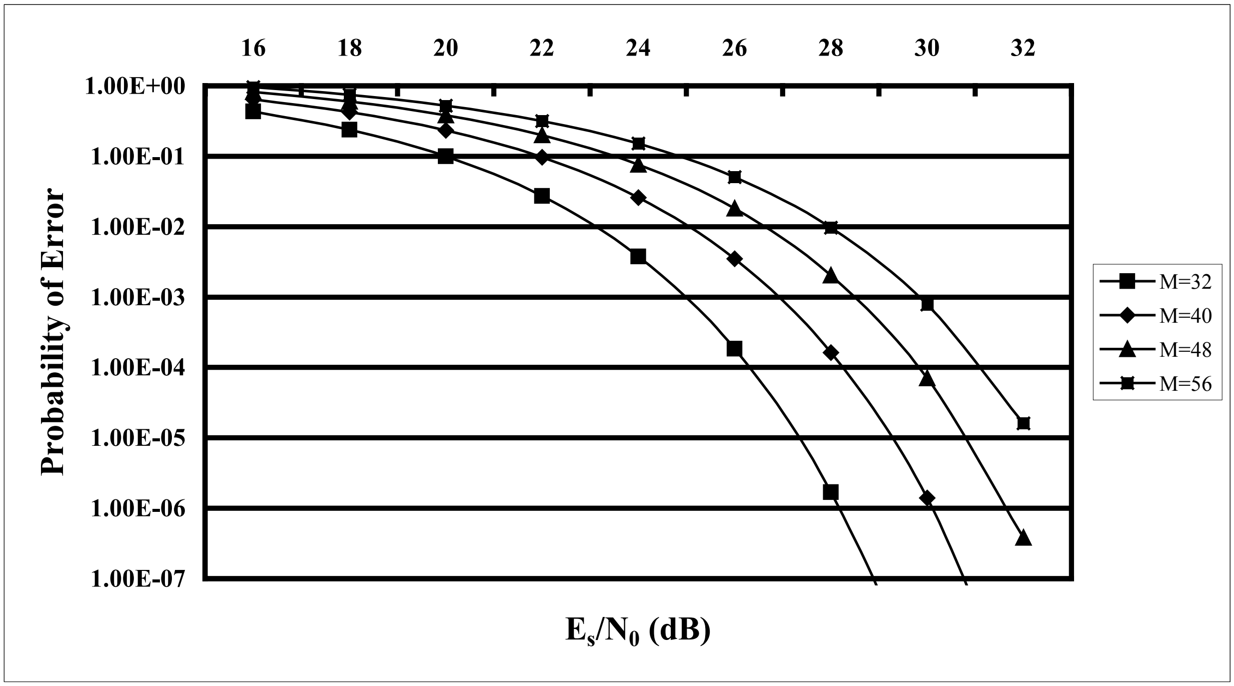


Figure 3
Probability of Error vs. SNR

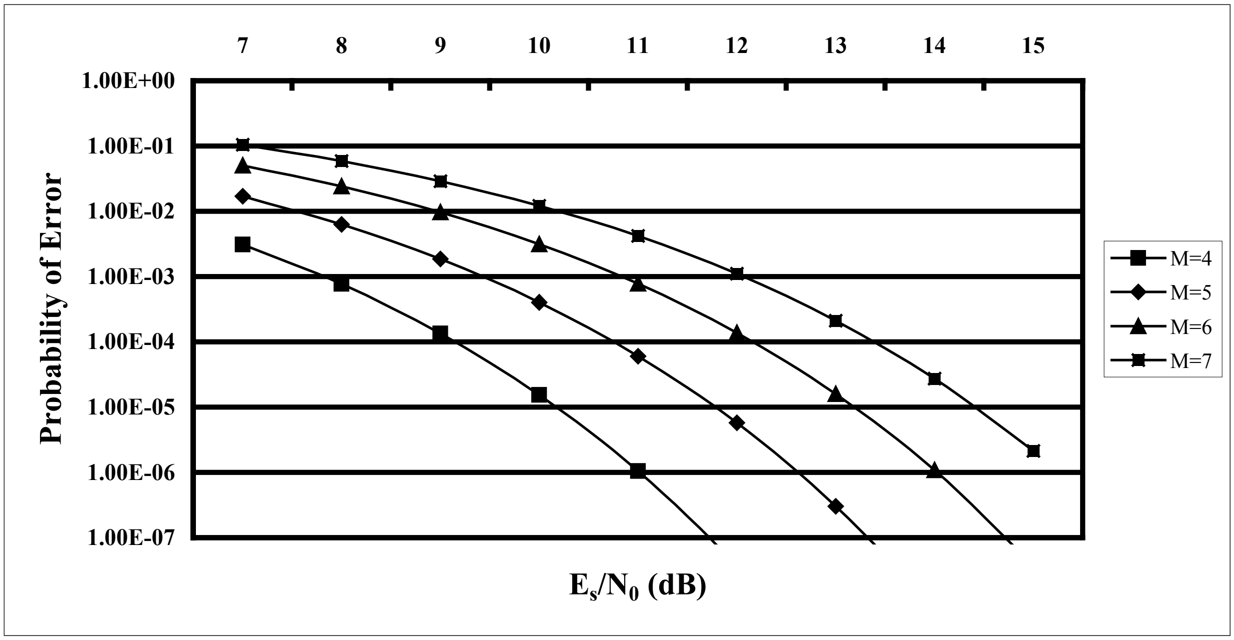


Figure 4
Probability of Error vs. SNR

Biography

Gary Mitchell graduated from Arizona State University with B.S.E. and M.S.E. degrees in 1978 and 1981, respectively, both in the area of electrical engineering. He has worked at several aerospace and communications companies, including Motorola, Unisys and Comtech Data Corporation. Mr. Mitchell joined AeroAstro in 2000 and is AeroAstro's Chief RF Engineer.