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# A Direct Sequence Spread-Spectrum Modem Design
# for Time Transfers via Geostationary Satellites

D. D. Davis and D. A. Howe
Time and Frequency Division
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80303

## Abstract

The National Institute of Standards and Technology (NIST) is developing a direct sequence spread spectrum (DSSS) modem. This development is part of a program to do various time transfer experiments using geostationary satellites. The purpose of the program is to exploit low-cost present and future commercial satellite resources in order to achieve timing accuracy of a few nanoseconds or better in a two-way time transfer scheme.

The modem's technical specifications will be presented. The modem has the capability for variable PN sequence chip rate from 102.3 kchips/s to 2.5 Mchips/s. This is because many aspects of time transfer experiments are affected by the DSSS chip rate, for example, occupied bandwidth and power (hence, satellite transponder cost), resolution, accuracy, processing gain, and time to acquire lock. Two types of codes can be selected: (1)Gold code of length 1023 bits, and (2)truncated maximal length sequence (MLS) of length 10,000 bits.

Functionally the modem operates with an AT-compatible computer. The computer is used to (1)select the modem's operating configuration, (2)send and receive data (using the modem's communications capability) to another earth station, and (3)provide a convenient resource for scheduling time transfers, computing the involved stations' clock-difference in real-time, and storing results.

## Introduction

The Time and Frequency Division of the National Institute of Standards and Technology continues to do research in satellite-based time synchronization. Such systems provide higher accuracy than HF and VLF methods since signal path delay is better known and delay instability is lower. In previous years, time transfer experiments were designed around a fairly limited number of space-segment resources. However, today a multitude of satellite communications opportunities exist. This writing will specify modulation-demodulation (or "modem") signal parameters and describe development of equipment at NIST which is suited to present-day satellite resources for two-way time transfers. A large number of references exist on the subject of the two-way technique, however the direct-sequence spread-spectrum modem called Mitrex[*] has been used successfully in experiments since 1983 (1). The Mitrex experiences together with results from the military's Global Positioning System will serve as a starting point for specifying aspects of two-way modem characteristics.

## The Direct Sequence Spread-Spectrum Technique

Most of what follows will show that a spread-spectrum signal modulation represents good use of the resources in geostationary communications satellites, the type used in most 2-way satellite time transfers (2, 3). Figure 1 shows where a spread-spectrum modem is used in a typical satellite earth station which is set up to do two-way time transfers. There are three general categories of spread-spectrum techniques: (1) direct-sequence, (2) frequency-hop, and (3) chirp. There are also hybrids or combinations of these three techniques which can be used to take advantage of specific properties.

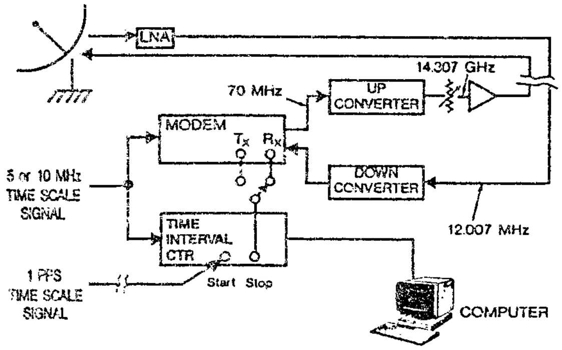

Fig. 1. Generalized equipment scheme used in two-way time transfers which shows the use of the DSSS modem.

Spread-spectrum signals using direct-sequence modulation provide the highest resolution range measurements, hence the highest resolution in timing. This property is due to the high speed of the PN sequence representing "1" and its inverse "0". Synchronization to the sequence at a receiver must be to within one chip (one bit in the sequence) in order to decode the overlying data. Typically the synchronization is good to at least one percent of one chip. Therefore, the inherent timing resolution between a transmitter and receiver is better than the time period corresponding to one-percent of a chip (4). The relatively high speed of the PN sequence translates into a short period for one chip, hence better inherent timing resolution. The ability to resolve time at a receiver is key to establishing improved levels of precision and accuracy. Experience with the Mitrex modem operating at the chipping rate of 2.5 Mchips/s indicates long-term reproducibility to ± 1 ns (5). This suggests that the Mitrex scheme has a timing uncertainty of 0.5% of the

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[*] Identification of a commercial company does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that any identified entity is the only or the best available for the purpose.

chip length. Furthermore, a NIST-designed GPS receiver using a DSSS format at 1.023 Mchips/s (the C/A code) has also shown reproducibility to ± 2 ns which is 0.4% of the chip length (6).

### Type of PN Code

One of the most important aspects of the two-way timing system described here concerns the specification of the PN code. The type of code, its length, and its chip rate determine limitations of timing performance. Many aspects of these timing systems are affected by chip rate, for example, occupied bandwidth and power (hence transponder cost), resolution, accuracy, acquisition of lock time, and processing gain. For this reason, the modem will have a variable chip rate with a range which is compatible with commercial satellite resources and which uses these resources effectively. The positive experience gained with GPS points to specifying the same or similar type of code (Gold) and length (1023 bits). Important properties of good codes of length L are: (1) codes should have a balance of "ones" and "zeros," (2) autocorrelation function is two-valued with difference of 1/L, (3) cross correlation function from dissimilar codes is below $1/\sqrt{L}$ relative to the peak in the autocorrelation function, and (4) there are enough different codes to satisfy present and future network capacity.

There appears to be no overriding reason not to use Gold codes, the other prevalent type being maximal length sequence (MLS). Truncated MLS codes such as used in the Mitrex modem have the small advantage of hardware simplicity if an even power-of-ten number of chips occur over a convenient time interval, in this case 10,000 bits every 4 ms. Alternatively, a Gold code of length 1023 requires that a signal be generated which can deliver 1023 bits over some convenient (and variable as mentioned above) interval of time. The Mitrex modem has achieved widespread use by time standards laboratories which are experimenting with two-way time transfers via satellite. For reasons of compatibility, it would be desirable to include an option to do two-way time exchanges with the Mitrex modem.

There is a limitation of six MLS codes which meet the requirements described above (7). This may be adequate for present needs but is restrictive in terms of future needs. On the other hand, Gold codes are sets of linear nonmaximal codes generated by a combination of linear maximal codes of equal length. Where a large number of codes is required, Gold codes are preferred. In the case of code length 1023 bits, there are 1024 separate possible codes and in all likelihood more than six with particularly good properties. GPS uses thirty-six Gold codes generated from two MLS codes.

One should note that the GPS Gold code of length L = 1023 is almost ten times shorter than the truncated MLS code of length L = 10,000. This will result in poorer cross-correlation performance and lower processing gain for the GPS Gold compared to the truncated MLS codes. Accuracy limits of both types should be similar at similar chip rates if precautions are followed which reduce the possibility of an accuracy error due to code interference. The use of different codes to carry different information on the same frequency is called code division multiple access (CDMA). Two-way time transfer requires that two different sets of data be exchanged. Operation at the same frequency is desirable so CDMA is used (2, 3). If there is no phase coherence among the DSSS signals which combine in the CDMA scheme, then there will be no accuracy error in a DSSS timing signal (8). This is the main precaution to be observed.

### Equipment Used in NIST Design

The NIST spread-spectrum modem works in conjunction with an AT-compatible computer. Precise timing, RF and modulation, and signal-structure aspects are in electronics outside the AT-compatible computer. Although the modem cannot work without a PC-AT interconnection, we have commonly referred to these external electronics as the "the modem." As such, the modem consists of three main printed-circuit boards: (1) a transmit board (called Tx) consisting of RF, analog, PN generator, and digital control circuitry, (2) an analog receive board (called Rx-analog) having RF and other analog functions, and (3) a digital receive board (called Rx-digital) that contains the PN generator and other digital functions.

Figure 2 shows the scheme of the equipment. A 70 MHz intermediate frequency is used as the input to the Rx portion of the modem; 70 MHz is also used as the output from the Tx portion. This frequency is commonly used for most upconverters and downconverters incorporated in satellite earth stations. Some frequency agility around 70 MHz is required to take advantage of low cost earth terminals called very small aperture terminals (VSAT) which are becoming more readily available from various manufacturers. NIST has done a number of experiments using VSAT apparatus, and results show that they can be used effectively in 2-way satellite timing (9).

The NIST designed modem automatically makes the difference between the external reference 1 pulse/s and Tx (1 pulse/s as transmitted) equal to zero ± 0.1 ns. This is done by internally adjusting the phase of the 5 or 10 MHz reference feeding the PN generator on the Tx board. The phase is adjusted using a slewable divider and is made to coincide with the external 1 pulse/s reference signal. (In the hardware implementation, the PN sequences are contained in EPROM so there are no actual MLS registers.)

### Tx Board

Figure 3 shows a block diagram of the modem Tx board. The electronic functions are indicated along with pertinent control functions (or interface lines).

The reference frequency signal usually originates from a frequency standard's 5 or 10 MHz output. The input of the modem is selectable between 5 and 10 MHz. A 10 MHz reference for remaining functions of the Tx board originates from a phase microstepped VCXO (voltage controlled crystal oscillator) which is locked to the external reference frequency. The internal 10 MHz signal can be advanced or retarded in 100 ps increments, and its purpose is to put the 1 pulse/s inverted sequence "on time" (see previous section).

A 70 MHz synthesizer is used to generate the Tx carrier. This synthesizer has a range of ± 500 kHz in 10 kHz increments. The variable frequency function is necessary to accommodate low-cost VSAT RF earth stations. These terminals often synthesize a microwave transmit signal which is close enough to the desired transmit frequency to meet regulatory requirements but which is not the exact assigned frequency. Tx frequency agility in the modem will compensate for any frequency offset which is present using low-cost VSAT's. A second use for this frequency agility is to compensate for any error in the usual 2.3 GHz frequency offset between receiving and retransmitting through the satellite transponder. This function would be necessary if the receiving earth station had no receive frequency agility of its own.

The PN generator has its clock rate (or chip rate) determined from a variable modulo divider with 10 MHz input

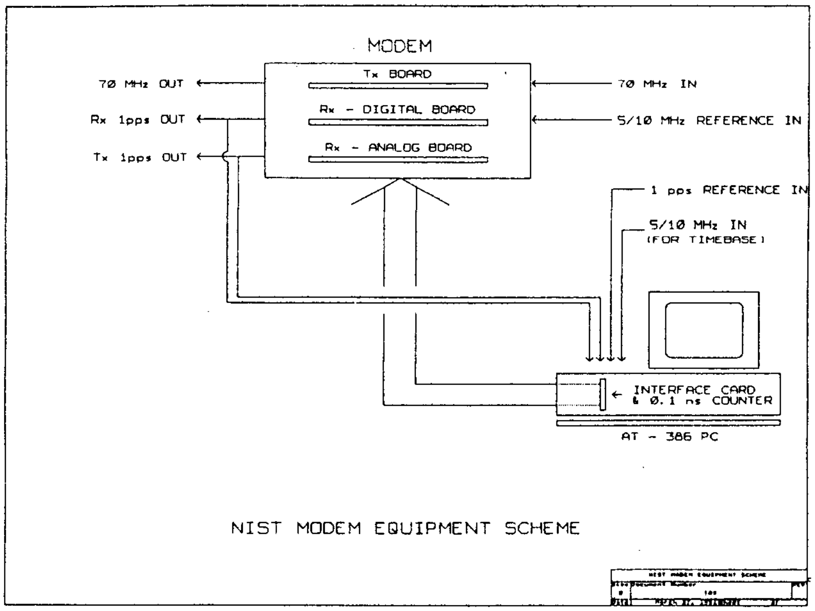

Fig. 2. The modem consists of three printed-circuit boards and a time-interval counter and interface card which is used in a 80386 computer.

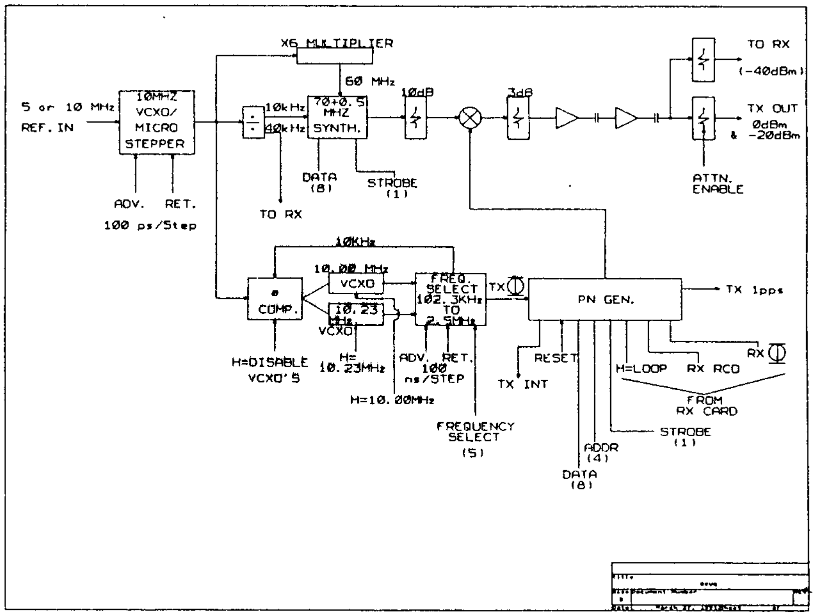

Fig. 3. Block diagram of the Tx portion of the modem. It consists of a 70 MHz RF generator, PN sequence generator, and bi-phase modulator.

and generating an output over the range of 102.3 kHz to 2.5 MHz (corresponding to 102.3 kchips/s to 2.5 Mchips/s). One of two VCXO's can be enabled as the source for the variable divider, either 10.23 MHz (for Gold sequences) or 10.00 MHz (for truncated MLS sequences). The phase of the PN clock can be incremented in 100 ps steps.

There are 36 Gold code sequences and eight truncated MLS sequences which can be selected. The Gold codes are identical to those used in the GPS C/A code and the chip rate is variable between 102.3 kchips/s to 2.046 Mchips/s. The eight truncated MLS sequences are compatible with the Mitrex modem and have a fixed rate of 2.5 Mchips/s. All sequences are programmed into a 64K × 8 EPROM IC.

Since the PN sequence chip rate is variable from 102.3 kchips/s to 2.5 Mchips/s, the frame rate is also varied (frame rate is chip rate divided by number of chips in the PN sequence). The 1 pulse/s modulation is simply a 1 bit/s data transmission. The rest of the 1 s period is normally occupied by the unaltered PN sequence. With no significant degradation, one can transmit communications data between 1 pulse/s bits as long as the PN sequence is still tracked in the demodulation and the 1 pulse/s bit is properly identified with a unique time frame marker. Data transmission capability has been included in this modem, and the rate of the communications data capability varies from 10 bits/s at 102.3 kchips/s to 50 bits/s at maximum chip rate.

The PN sequence (code) can be changed without perturbing the phase of the sequence. Two or more codes can be transmitted sequentially to construct additional different codes whose length is a multiple of 1023 chips for Gold codes and 10,000 chips for truncated MLS codes.

Table 1 summarizes the modulator specifications. Reference input and output timing pulses are TTL-compatible.

## Rx Boards

The demodulator portion of the modem consists of two printed circuit boards--the Rx-analog and Rx-digital boards. As the names imply, the Rx-analog board contains analog circuitry such as the RF amplifiers, mixers, and filters. The Rx-digital board contains digital circuitry such as the PN generator, synthesizers for L.O. (local oscillator) frequencies, and several digital control functions.

Figure 4 shows a block diagram of the demodulator. From the 70 MHz source (usually the output of a microwave downconverter), the signal is first fed through a reed relay which can select the output of the Tx board for an internal modem loop test. After going through a switchable 20 dB attenuator, the signal is split and amplified into two signal channels, one is designated the "punctual" (P) channel, the other is designated the "early-minus-late" (E-L) channel. the demodulator's PN generator has two outputs, one which is the P (punctual), or on-time, PN sequence and the other which is the E-L PN sequence.

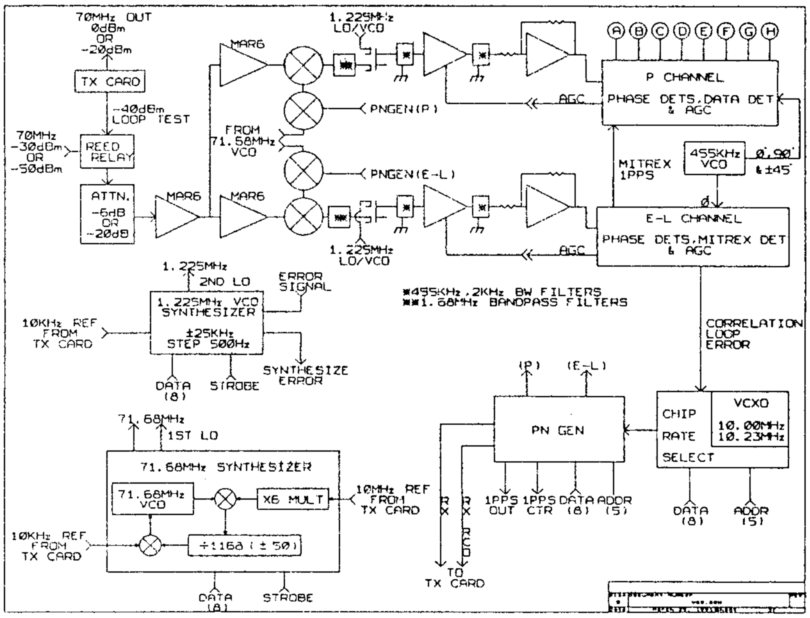

Fig. 4. Block diagram of the Rx portion of the modem. It consists of two separate triple conversion receiver sections, one for punctual (P) correlation and one for early-minus-late (E-L) correlation. The purpose and action of each are described in the text.

Two isolated 71.68 MHz signals are generated from a synthesizer. The "P" PN sequence is mixed with one 71.68 MHz signal and then mixed with the "P" RF channel's signal. The "E-L" sequence is mixed with the other 71.68 MHz signal and then mixed with the "E-L" RF channel signal in a similar way.

A 1.225 MHz signal from another synthesizer is mixed with the newly created 1.68 MHz difference frequency of the P and E-L channels. This second frequency conversion produces a difference frequency of 455 kHz in both channels which is filtered and amplified.

A 455 kHz VCO (referred to 40 kHz from the 5 or 10 MHz external signal) generates signals at four phases 0°, 90°, and ±45°. These signals are variously phase-compared to the 455 kHz IF signal of the P channel to track the RF carrier, demodulate the communications data, and indicate carrier lock (phase-coherent tracking with the feedback error signal applied to the 1.225 MHz L.O. synthesizer is possible over a frequency range of ±25 kHz). A 455 kHz VCO signal at 0° phase is used as the reference for the phase detector of the E-L channel. The output of this phase detector represents the error signal from cross-correlation of the received PN sequence with the PN sequence as generated by the Rx (demodulator's) PN generator. This error signal advances the phase of the Rx PN generator until it is "on time." That is, the cross-correlation to the received PN sequence is unity.

Table 2 summarizes the demodulator specifications. An output 1 pulse/s timing signal is available which is TTL compatible. The time difference between the external 1 pulse/s reference and the 1 pulse/s as received (demodulated by the modem) can be measured using a time-interval counter which is integrated with the computer interface card.

## AT-Compatible Computer and Interface and Counter Board

The modem is controlled by an AT-compatible personal computer with 80386 CPU. A 386 AT-compatible machine was chosen for several reasons:

1. Open architecture is flexible and adequate to handle control data, data saving, calculations, and interfacing to other equipment.
2. AT-compatible electronics are readily available in a variety of physical sizes and arrangements.
3. Consumer demand and competition in the PC industry have brought prices down to where it is inexpensive.
4. A large base of software and programmers make software development more efficient.

In addition, the 80386-based computers have the advantage of a 32-bit architecture with an associated large addressable memory space. The 80386 CPU also has a larger, more useful instruction set compared to any of its predecessors.

The hardware consists of the computer and hard disk storage with keyboard, monitor, and a plug-in interface card to the modem. The card also includes the necessary circuitry to measure time intervals to a resolution of one-tenth nanoseconds using the same 5 or 10 MHz external reference as the modem itself. An interpolator measures the occurrence of the normal start and stop trigger pulses relative to the zero-crossings of the external reference signal. The counter readings are latched and sent to an interface portion of the card which allows the counts to be read by the AT-compatible buss.

The counter has a self-calibration feature for the interpolation circuit which establishes accuracy to better than ± 1 ns. This calibration is done automatically (thru associated AT software) and can be done as often as once every few minutes. Reproducibility of the counter readings is ±0.1 ns over a period of 30 min or more under normal operating conditions.

Under software control, the modem is configurable in any mode as described in this writing. Time-interval counter data and communications data can be read, stored, and analyzed, and data can be transmitted via a telephone modem to another location.

## Direction of Development

As of this writing, the Tx board, Rx boards, and computer interface card are complete. The software development is an on-going task and is a specification only. Software control adequate for testing the modem is expected to be completed by summer of 1991. DOS is the operating system and code will be written in C language with a limited number of assembly routines.

The versatility of modem control by means of a 80386 AT-compatible computer offers many future options as this modem project proceeds. As such, much of the work will move to development at the software level as the hardware is specified, completed, and debugged. We plan to integrate other existing computer programs as tools and extensions of the computer into other tasks such as earth station automation.

## Acknowledgement

The authors gratefully acknowledge the work of John Lowe, Xiao Cuiying, and Victor Zhang in development and debugging much of the hardware.

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Table 1

**SPREAD SPECTRUM MODULATOR SPECIFICATIONS**

Frequency (IF frequency) and source impedance of device:
70 MHz coherent with reference input frequency. 50 ohms source impedance.

| | | |
|---|---|---|
| Output power level: | Selectable -20 dBm and 0 dBm. | |
| Code modulation method: | BPSK | |
| Types of codes: | 1. Gold<br>2. Truncated MLS | |
| Number of Gold codes: | No less than 36 | |
| Number of Truncated MLS codes: | 8* | |
| Gold code (chip) rate: | Selectable | 2.046 Mchips/s<br>1.023 Mchips/s<br>409.2 kchips/s<br>204.6 kchips/s<br>102.3 kchips/s |
| Truncated MLS code (chip) rate: | 2.5 Mchips/s* | |
| Gold code (bit length: | 1023 chips | |
| Truncated MLS code (bit) length: | 10,000 chips | |
| Gold code bit rate: | Variable | 2000 bits/s at 2.046 Mchips/s<br>1000 bits/s at 1.023 Mchips/s<br>400 bits/s at 409.2 kchips/s<br>200 bits/s at 204.6 kchips/s |
| Truncated MLS code bit rate: | | 100 bits/s at 2.5 Mchips/s |
| Ref. input frequency signal: | Selectable | 5 MHz<br>10 MHz |

Accepts sine or square wave signal and terminates at 50 ohms with a sensitivity of -10 dBm.

Ref. input time signal (must be coherent with ref. input freq.):
1 pulse/s
Positive-going trigger. Threshold adjustable from +0.5 to +2.0V.

Ref. output time signal (as transmitted) : 1 pulse/s

Time on positive-going edge of at least +3.5 VDC pulse relative to system ground with a source impedance of 50 ohms and duration of one chip.

| | |
|---|---|
| Communications date rate (Gold code): | 10 bits/s at 102.3 kchips/s<br>20 bits/s at 204.6 kchips/s<br>40 bits/s at 409.2 kchips/s<br>50 bits/s at 1.023 Mchips/s<br>50 bits/s at 2.046 Mchips/s |
| Communications data rate (trunc. MLS) : | 50 bits/s at 2.5 Mchips/s |

An internal slewable divider will be incorporated which divides the external 5 or 10 MHz reference signal to a signal which represents 1 pulse/s as transmitted. The divider will be automatically slewed so that the 1 pulse/s as transmitted is within 100 ps of the external reference 1 pulse/s time signal.

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*Duplicates format of Mitrex model 25000

## Table 2

## SPREAD SPECTRUM DEMODULATOR SPECIFICATIONS

Freq. of operation (IF freq.):
70 MHz automatically tunable over ±25 kHz. (Automatically acquires correct "center" of freq.) Terminated at 50 ohms.

Input level sensitivity:
Adjustable -60 dBm max. sensitivity
to 0 dBm min. sensitivity

Types of codes (same as modulator):
1. Gold
2. Truncated MLS

Number of Gold codes: No less than 36
Number of Truncated MLS codes: Eight*

Gold code (chip) rate: Selectable
2.046 Mchips/s
1.023 Mchips/s
409.2 kchips/s
204.6 kchips/s
102.3 kchips/s

Truncated MLS code (chip) rate: 2.5 Mchips/s*

Gold code (bit) length: 1023 chips
Truncated MLS code (bit) length: 10,000 chips

Gold code bit rate: Variable
2000 bits/s at 2.046 Mchips/s
1000 bits/s at 1.023 Mchips/s
400 bits/s at 409.2 kchips/s
200 bits/s at 204.6 kchips/s
100 bits/s at 102.3 kchips/s

Truncated MLS code bit rate: 250 bits/s at 2.5 Mchips/s

Ref. input frequency (for lock acquisition): 5 MHz or 10 MHz.

Accepts sine or square wave signal and terminates at 50 ohms with a sensitivity of -10 dBm.

Ref. output time signal (as received): 1 pulse/s

Timed on positive-going edge of at least +3.5 VDC pulse relative to system ground with a source impedance of 50 ohms and duration of one chip.

Communications data rate (Gold code):
10 bits/s at 102.3 kchips/s
20 bits/s at 204.6 kchips/s
40 bits/s at 409.2 kchips/s
50 bits/s at 1.023 Mchips/s
50 bits/s at 2.046 Mchips/s

Communications data rate (trunc. MLS): 50 bits/s at 2.5 Mchips/s

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* Duplicates format of Mitrex model 25000.