Spectrum INSTRUMENTS, INC.

SUMMARY OF TIME AND FREQUENCY SYSTEMS FEATURES AND CAPABILITIES

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INTRODUCTION

Modern GPS-driven time and frequency standards incorporate a wide range of features and capabilities. Spectrum Instruments offers both standard off-the-shelf products and custom designs that incorporate various combinations of possible features. This paper is intended to describe these features so that a potential user of time and frequency products can understand what is available. In particular, when specifying a custom product, the user needs to be aware of available features in order to be able to choose the optimal feature set. It is often possible to provide custom features within the time and frequency product that will greatly simplify the design of other parts of the user's system– frequently at a very low incremental cost. Spectrum's standard products are designed with flexibility in mind, and it is often possible to accommodate special user requirements with these products through simple and inexpensive adaptations.

GPS TIMING BASICS

One Pulse Per Second. The basis for all time and frequency functions in GPS-based products is the one pulse per second (1PPS, alternatively called PPS in this document) signal supplied by the GPS receiver. This signal is typically a short logic pulse, one edge of which is adjusted by the receiver to be "on time" with respect to the one second epoch of Universal Time (UT). In order to do this, the GPS receiver needs to know position. If position is unknown, the receiver can find its own position and solve for time by tracking four or more GPS satellites. This is what we call *dynamic mode,* and would be the mode used in moving platform applications. Alternatively, timing receivers can be told to use a known fixed position, in which case the receiver can solve for time by tracking only one (or more) satellites. This is called *static mode*, and it is the preferred mode to use in applications where the position is fixed.

Timing Accuracy. Of interest is the accuracy of the 1 PPS signal from the GPS receiver, which varies from manufacturer to manufacturer. Errors in the time of occurrence of the 1 PPS pulses from the GPS receiver consist of three parts: **bias** (a fixed offset due to uncompensated delay errors in the receiver/antenna system), **drift** (variations in timing over long periods due primarily to differences in satellites tracked over time), and **jitter** (short-term variations in timing from pulse to pulse). These error sources are inherent in the both the GPS system and the GPS receiver design and implementation. The sum of these errors can be as low as a few tenths of a microsecond up to a few microseconds, depending upon the receiver's manufacturer and design. The underlying noise due to granularity of the clock generating the 1PPS signal is deterministic on every pulse. Spectrum has devised a method of resolving the so-called negative sawtooth residual in real-time, yielding a timing accuracy of 5 nanoseconds of better. This high level of accuracy is possible because the timekeeping maintained within the GPS system is continuously adjusted to null out timing errors. GPS time is coordinated with UT, the standard for time around the world as maintained by all the organizations responsible for time standards and time dissemination.

Output Characteristics. The 1PPS signal is usually delivered to the host system in the form of a pulse of reasonable duration (microseconds to milliseconds) at TTL or RS-232 signal levels. In the case of TTL levels, it is useful to be able to drive terminated 50-ohm cables so that the pulse can be distributed to the host system without degradation due to the effects of cable capacitance.

Spectrum's standard products provide a one-millisecond wide positive pulse able to drive a 50-ohm load at TTL logic levels. In addition, they also include a "smoothed" PPS output (selectable by the user) that is derived from the from the internal primary reference oscillator (as opposed to coming directly from the GPS receiver). When the oscillator is phase-locked to 1PPS from the GPS receiver, timing accuracy is further improved in the smoothed PPS output because the signal is essentially without jitter. And because the smoothed PPS is derived from the internal reference oscillator, a coherency between the zero-crossing of the reference frequency and the leading edge of the 1PPS signal is assured.

GPS TIMING BASICS, contd.

Other basic timing signals based on the 1PPS signal can easily be provided. Examples are one pulse every 10 seconds, one pulse per minute or even one pulse per hour.

Time Message. The 1PPS signal provides an accurate time mark, but is ambiguous unless coupled with a time stamp. Most timing systems specify a time message that is transmitted (usually over a serial data port) that gives the date and time of day for each occurrence of the 1PPS signal. This time message is sent in between the 1PPS signals and may be specified to time-tag either the pulse that has just occurred, or to announce the one that is just about to happen.

Spectrum's standard products transmit a serial time message over a dedicated serial time port at user-selectable baud rates. The user may specify one of a number of standard message formats, or may request a custom time message.

Network Time Protocol. NTP is a protocol used to disseminate time over a local or wide-area distributed computer network. It is widely used to maintain time across the Internet. GPS timing systems are the primary clock sources for time servers requiring the highest possible accuracy, and Spectrum timing products are well suited for this application. The only special requirement imposed for NTP application is that a particular event within the serial time message needs to be synchronized to the 1PPS epoch. Spectrum can supply timing products that emulate the operation of other network clocks for which software drivers are readily available.

Common View. In system applications where the relative timing between a number of physical locations need to be kept to the highest possible accuracy, a technique called *common view* may be employed. This technique involves controlling which satellites are being used by all receivers in the network so that to the maximum extent possible, they each use the same satellites to derive timing information. Such a system requires that the host be able to select the satellites to be used and provide this information to the timing system.

FREQUENCY STANDARD BASICS

Frequency sources with extremely high accuracy and stability can be achieved by slaving or *disciplining* a free-running source (reference oscillator) to the 1PPS GPS timing pulse. This is possible because the 1PPS signal has **zero clock rate error** when averaged over time. Since the GPS system does not allow any time error to accumulate, we are able to take advantage of this fact in designing frequency sources slaved to the precise timing information from GPS. A number of techniques may be employed in these designs, depending upon the system requirements.

Design Considerations. A fundamental tradeoff that has to be made is between the short-term stability of the reference oscillator and the required stability of the frequency of the oscillator while being disciplined. In order to achieve high accuracy while being disciplined, the control loop must have a long time constant. The result of this is that the loop can't correct for short-term variations in the oscillator output frequency. Spectrum products optimized for phase-coherency have an adaptive time constant in the control loop that will respond quickly to any disturbance of the oscillator, and then return to the quiet stability of the longer time constant once the oscillator has been restored to an in-phase condition with respect to PPS. In a few unique situations, a fixed time constant may be preferable to the dynamic control scheme. For those cases, the dynamic time constant may be suspended by the user.

FREQUENCY STANDARD BASICS, contd.

Another basic requirement that drives the design is the stability over time required of the output when the GPS signals are lost for any reason. (When GPS is not available, the information required to correct the output frequency also is unavailable.) This requirement is usually referred to as *holdover stability*. Crucial to achieving the desired performance is the choice of the basic frequency source (oscillator). Possibilities range from low-cost crystal oscillators (VCXO) at the low end of the performance range, to expensive, high-performance ovenized crystal oscillators (OCXO) at the higher end. Even rubidium oscillators can be used, but these are rarely needed except in very special circumstances.

The choice of reference oscillator frequency is dictated by system requirements, and 10 MHz has emerged as a virtual standard. However, any oscillator frequency in the range of 1-30 MHz can be used.

Spectral Purity. A significant cost factor in designing frequency sources is the requirement for spectral purity. Three separate requirements are usually specified: phase noise, harmonic levels and non-harmonic spurious levels. Spectral purity and temperature stability are the two primary things which determine the selection and cost of the reference oscillator to be used. The following requirements are representative of what can be achieved at moderate cost using a high-quality SC-cut 10 MHz OCXO as the reference oscillator:

Phase Noise:

Offset from Carrier	SSB Phase Noise
10 Hz	-124 dBc
100 Hz	-139 dBc
1 KHz	-149 dBc
10 KHz	-151 dBc

Harmonics: <-50 dBc

Non-harmonic Spurs: < -70 dBc (1 MHz to 100 Mhz)

Output Characteristics. Frequency outputs can be either sine or square wave. In the case of sine wave outputs, the level can be up to 10 dBm and the load is usually specified to be 50 ohms. In the case of square wave outputs, the levels are usually TTL and drive capability to handle 50 ohm terminated cables is possible and desirable. Multiple outputs can be provided.

Ancillary Outputs. Ancillary outputs derived from the reference oscillator can easily be provided when they are an integer sub-multiple of the basic frequency. Output frequencies that are not harmonically related require more sophisticated derivation techniques.

Spectrum's standard products typically use 10 MHz as the reference oscillator frequency, and provide both sine and square wave outputs. They also provide square wave decade-spaced outputs down to 1 kHz.

SYNTHESIZED FREQUENCY OUTPUTS

Outputs at frequencies other than simple submultiples of the reference oscillator frequency can be provided through frequency synthesis techniques. These outputs can be in the range of 1-50 MHz and can have the same accuracy and stability as the reference oscillator. Outputs can be sine or square waves with the same levels and drive capability as given above. A typical example might be a 10 MHz system in which an ancillary frequency output of 1.544 MHz (T1 clock frequency) is required in a wireless base station application. This output can be provided from a synthesizer circuit using the 10 MHz as the reference source, and the stability and accuracy characteristics would be as good as those of the reference oscillator.

In Spectrum's TM-4-based product series, the ability to specify a synthesized output as described above is a low-cost optional feature.

FILTERED CLOCK OUTPUTS

In some applications, there are requirements for low-frequency clock signals that are synchronous with the 1 PPS signal. An example might be a 25 Hz clock signal to be used as the frame clock in a TDMA wireless system. The signal must be synchronous to the 1 PPS so that all base stations in the TDMA network will have synchronized frame clocks. Spectrum has developed a proprietary technique for generating a synchronized clock signal in the range of 0.1 Hz to 100 kHz, using the reference oscillator frequency as the reference and synchronizing (and maintaining synchronism) to the **average** of the 1 PPS signals from the GPS receiver. This technique is not limited to clock frequencies having an integer relationship to 1 Hz. For example, a frequency of $16\frac{2}{3}$ Hz can be generated with every third 1PPS signal being aligned with the rising edge of the clock output. The technique used provides a high degree of correlation between physically separated systems due to the filtering process inherent in the method. The accuracy and stability of these filtered clock signals is as good as that of the reference oscillator.

CUSTOM FREQUENCY OUTPUTS

Spectrum can provide custom frequencies up to 250 MHz using various techniques, depending upon specification requirements. Some frequencies can be generated with readily-available components, while others may require custom components or oscillators. Generally, for best performance, a VCXO operating at the desired frequency is phase-locked to the internal reference oscillator and then filtered for optimum signal quality. Other techniques may also be employed, depending upon the required frequency.

IRIG TIME CODE OUTPUTS

IRIG time codes are standards for dissemination of time information in a format suitable for transmission and recording as analog signals. Originally developed for use in missile test range instrumentation, these codes are still in common use for a variety of other applications. IRIG Document 104-70 specifies all the details for the entire group of codes.

<u>IRIG B</u>. By far the most commonly used IRIG code is IRIG B. This code has a one second frame rate, and the 100 bits which comprise a time code message each have an interval of 10 milliseconds. The baseband pulses have widths of 2, 5 and 8 milliseconds, depending on their function and value. The rising edge of a particular one of the 100 pulses in a frame is designated as the "on-time" edge and is intended to be synchronous with the one second epoch of UT. The code provides day-of-year, hours, minutes and seconds of time information in BCD format. IRIG B may be provided as baseband pulses or as an amplitude-modulated 1 kHz carrier, modulated by the baseband pulse stream. In the case of the modulated carrier, a particular zero crossing is defined as the "on time" crossing. Time resolution of one millisecond (or better) can be readily obtained by examining the carrier signal along with the demodulated data bits.

<u>Other Available Codes.</u> All of Spectrum's standard products provide IRIG B in baseband and modulated carrier outputs as an option. Other IRIG codes can be readily provided, including high-resolution IRIG-G.

EVENT TIME-TAGGING

Event time-tagging is a feature that allows the time-of-occurrence of external events to be captured and automatically sent to the host. The resolution of time-tagging in Spectrum products is typically 100 nanoseconds. The hardware buffers events as they occur and makes them available to the host processor on demand. Because hardware and software limitations place certain restrictions on the time-tagging process, attention has to be paid to minimum latency time between events, maximum continuous event rate, and maximum number of events buffered. Multiple channels of event time-tagging can be provided in custom designs.

Spectrum standard products provide a single channel of event time-tagging with 4 millisecond minimum event latency, 30 event-per-second maximum rate, and a buffer capacity of 23 events. These parameters can be altered in custom designs. Either the rising or falling edge of the input can be selected as the event trigger.

PROGRAMMED OUTPUT PULSE

Programmed output pulse is a feature that allows for a single pulse or a pulse train to be generated at a specified time. The resolution for specifying the time of occurrence is typically 100 nanoseconds. In Spectrum products, any time in the future may be specified for the occurrence of a single pulse or the first of a series of pulses. In repetitive mode, the first pulse will occur at the specified time and subsequent pulses will occur at a specified repeat interval time. Repeat interval time can be selected with a resolution of one millisecond and a range of 1 to 99,999,999 milliseconds (100,000 seconds). The output pulse has a user-programmable variable width and a programmable polarity. Multiple channels can be provided in custom designs.

HOST INTERFACES

Simple Serial Interface. Most GPS time and frequency standards provide some type of host computer interface to allow the user to communicate with the device. This allows the user to set up the unit to operate as desired, input initial information and to monitor the operation and status of the unit. Software designed to run on Windows-based PCs is provided to facilitate this communication and to provide a simple, user-friendly interface. The most common interface is a standard serial data channel with RS-232 electrical interface. Units so equipped can be easily connected to a PC serial COM port with a readily available serial cable. Other electrical interfaces may be provided such as TTL, RS-422 or NMEA.

Other Host Interfaces. A number of other host interfaces are possible. These include other serial interfaces and protocols such as USB, SCSI or IRDA. Standard parallel bus interfaces such as VME, PCI, or ISA may also be employed for unit-to-host communications. If a parallel interface is specified, this also implies a particular mechanical, power source and connector arrangement as called for in the bus specification.

User Programming. Spectrum standard products communicate with the host using a set of simple ASCII messages over a serial data (COM) port. Users can write their own host software to communicate with these products using guidelines and documentation provided by Spectrum. The control channel can be configured to broadcast status messages to the host on a preprogrammed schedule (broadcast mode) or to send messages to the host only on request (polling mode).

START-UP CONSIDERATIONS

GPS Receiver. The GPS receiver has several start-up modes, depending on what information it has available.

A *cold start* occurs when the receiver has no knowledge of its position. In this case, the receiver has to do a systematic search to find satellites to track. Once one satellite has been found, the receiver can obtain time and date. Once three satellites have been found, the receiver can find a 2D position, and with four satellites it can calculate a 3D position. Additionally, the receiver needs to obtain the GPS-to-UT time offset from the satellite data stream, which can take up to 13 minutes. Once all of the above is accomplished, the timing of the 1PPS signal can then be accurately adjusted. A cold start can take as long as 30 minutes.

A *warm start* occurs when the receiver has position, date and time, almanac and UT offset information, but does not have recent satellite ephemeris information. In this case, the receiver can find satellites quickly (usually within a few seconds) and then can collect ephemeris from each in about 30 seconds. A warm start typically takes 45 to 60 seconds.

A *hot start* occurs when power has been off for less than 30 minutes or so. In this case, the receiver has all the information it needs and only has to find satellites and adjust the 1 PPS signal. A hot start usually takes about 10 seconds.

Back-Up Battery. In order to avoid having to do a cold start every time, GPS receivers maintain date and time, and also retain position, almanac and ephemeris information with main power off via a stand-by voltage provided to the receiver. This is usually supplied by a back-up battery, which may be a lithium primary battery or a small rechargeable battery. Current is only drawn from the battery when main power is off, and the stand-by current is usually a few microamps. Spectrum standard products all provide for a back-up battery.

Site Survey. Site survey is a feature that can be provided to aid in the installation of timing equipment at fixed sites. Upon initial installation, the unit can be told to perform a site survey. This involves averaging a large number of position calculations (usually 10,000) in order to derive a very accurate position. Once obtained, the receiver adopts this position as the fixed position and automatically enters the static timing mode.

Oscillator Tuning. Tuning of the reference oscillator can't start until the GPS receiver is running and the 1PPS signal is valid. In Spectrum products, this condition is called *Time Valid*. If the reference oscillator is an ovenized crystal oscillator (OCXO), then a warm up time of 3 to 5 minutes is provided to allow the oven temperature to stabilize prior to starting the tuning process. Once tuning starts, the time required to reach a given frequency accuracy depends on the design of the control loop and on various characteristics of the oscillator. For example, a system using a VCXO reference oscillator slaved to the GPS by means of a hardware phased-lock-loop can reach stability within a few seconds after Time Valid occurs. On the other hand, a high performance system using an OCXO will require many hours (and in some cases, days) to reach its (much higher) ultimate level of accuracy.

Fast Start. Spectrum has developed a technique for speeding up the tuning process in high-performance systems. This is called *Fast Start.* To implement the Fast Start feature, certain tuning parameters are periodically stored in a non-volatile memory for later use during start-up. This technique allows the tuning to achieve target accuracy much faster than an ordinary start, and it can be tailored to meet the specific needs of a particular application. An additional advantage of Fast Start is that an indicator can be supplied to the host system when a target accuracy has been attained. This can be very beneficial in allowing the host system to start using the frequency outputs at the earliest possible time (when minimum acceptable accuracy has been reached).

HARDWARE DESIGN CONSIDERATIONS

Input Power. Timing equipment requires a source of external power to operate. This may be AC mains power or DC power from the host system. Since power requirements are modest, timing equipment is often designed to take a wide range DC input, and AC wall adapters are used for those cases where it is desired to use an AC power source. Most Spectrum standard products are designed to be DC powered from a 10 to 35 VDC source, with some products operating at 5 VDC. AC power adapters are available for 110 VAC or 220 VAC operation.

Mechanical Packaging. GPS time and frequency references come in many mechanical forms. Examples include board level products with or without front panels, partially or fully enclosed products, and rack-mounted products. In custom designs, we can design a product to exactly fit the customer's mechanical requirements. Spectrum designs are power efficient and use a high degree of integration, and therefore can be packaged in space saving form factors for situations where space is at a premium.

Fault Monitoring. Time and frequency references are usually critical components in the host system, and usually operate unattended. For these reasons, fault monitoring deserves serious attention in the design of these systems. GPS receivers used in Spectrum products provide a feature called TRAIM (Timing Receiver Autonomous Integrity Monitoring) which detects satellite and receiver problems which might cause excessive errors in the reported time or the accuracy of the 1 PPS signal. Spectrum products can make use of this intelligence as part of an overall fault monitoring strategy. Additionally, we can provide hardware and software checks for faults such as shorted or open antenna cable, failure of the reference oscillator, missing reference outputs, inadequate input voltage, over/under temperature and a wide range of other checks as desired for a particular application.

Panel Indicators. Most applications require front panel indicators (usually LEDs) to provide operators and service personnel with status information. Examples are power on/off, time valid, reference ready, normal/coast, antenna or other faults detected, and so forth. In custom designs, Spectrum can provide any indicator required. In addition, Spectrum can provide informational displays for any customer requirement.

Antenna Considerations. Spectrum has a number of standard antennas available for normal types of installations having cable runs up to 200 feet. For longer runs, repeater amplifiers provide an easy way to accommodate greater distances using economical RG-58 cable. Custom antenna arrangements for special requirements can also be provided.

Integrated Solutions for Custom Applications. Spectrum's engineers can work directly from customer specifications or can help in their development. Additionally, after the product is developed, Spectrum can assist in the integration process to assure that the product performs as required in the customer's system.

For high-volume applications, Spectrum has developed a set of precise time and frequency functions that can be incorporated into an FPGA. With this approach, it is feasible to integrate a complete GPS time and frequency standard onto a customer's own printed circuit card, providing the lowest possible system cost. An integrated systems approach like this would typically consist of an off-the-shelf GPS receiver module, the FPGA, the reference oscillator and a small number of standard electronic parts.

Environmental Specifications. It is very important to properly specify the environment in which a GPS time and frequency product will work. It is also important not to over-specify in this regard, because the environmental requirements can be a major factor in establishing cost. Here are some guidelines:

Operating Temperature: At the low end, 0° C is easy, -20° C is not difficult, and -40° C or lower is difficult and expensive. At the high end, +50° C is easy, +70° C is not difficult, and +80° C or higher is difficult and expensive. *Be sure to specify the maximum rate of change of temperature,* as this is very important in designing the control loops.

Humidity: Usually not a problem as long as condensation is avoided.

Shock and vibration: Most timing products are designed to good commercial practices and will withstand reasonable shock and vibration without damage. Vibration can cause performance problems due to its effect on oscillators. If a specific vibration performance specification is required, there are added costs in design, qualification testing and manufacturing. Spectrum designs typically have minimal (usually zero) adjustments to minimize potential problems due to shock and vibration.

<u>Other Requirements.</u> Some other design requirements to consider are:

Regulatory Requirements: Avoid imposing blanket regulatory requirements unless absolutely necessary. It is much more cost effective in both design and production to specify exactly what is required.

Reliability: Calculated MTBF is of little use in determining the ultimate reliability that will be obtained in the field. Spectrum will be happy to supply actual measured reliability data on comparable products and extrapolate to an expected reliability for any custom design using measured data as baseline.