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N. Yannoni

JOURNAL DE PHYSIQUE
Colloque C8, supplément au n°12, Tome 42, décembre 1981 *page* C8-383

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N.F. Yannoni

Rome Air Development Center, Hanscom Air Force Base, Bedford, Mass. 01731, U.S.A.

Abstract.- This paper describes the application of precision frequency standards as the time base in navigation, communication and identification systems. Because these systems are placed in several different types of platforms, the frequency standard must be selected on the basis of compatibility with the weight, volume and power supply constraints exerted by the overall system configuration. Furthermore, the operational environment places additional control on the oscillator specifications which relate to sensitivity to changes of temperature and pressure, to vibration, and in certain cases, to exposure to radiation. Some examples of how the application governs the choice of the oscillator are given as well as a review of new technology developments which promise improvements in both performance characteristics and acquisition costs.

Introduction.- During the last decade, precision standards of frequency, and the clocks based upon them, have played increasingly important roles in the transmission of radio signals for a variety of applications. In this paper, we discuss the use of frequency standards in three applications: navigation, communication, and identification. The increasing use of digital modes of information transmission has sparked new demand for improved oscillators and clocks. These improvements reflect better operational performance under many different environmental conditions, and reductions in cost to allow widespread economical application. In the first section of the paper, a survey is offered of some of the principal navigation systems in use today which depend on precise time and frequency for their successful use. Following is a review of the application of precision oscillators and clocks to certain communication and identification functions. The choice of frequency standard in any of these systems is often governed by the operating environment more than any other factor, and a discussion of the trade-offs between performance, facility of use and oscillator cost is presented. Finally some concerns associated with the procurement of adequate standards are discussed, along with a short summary of some recent research and development activities which show promise of advancing the state of frequency standard technology.

Precise Time for Navigation

One of the earliest uses of time for navigation took place in the early 18th century when the British government awarded John Harrison 20,000 pounds for the development of a shipboard chronometer (1) which could be used for synchronization with the time scale at Greenwich, England, chosen by convention to represent zero degrees longitude. This effort occupied Harrison for nearly 50 years, but he produced a chronometer which maintained Greenwich time under seagoing conditions within one minute over a period of several months. This instrument's importance can be appreciated when we consider that it permitted the first reasonably reliable determination of longitude for seagoing vessels engaged in exploration, commerce, or military expeditions.

In the 20th century, the speed of ships and aircraft has led to systems for position location and navigation which place stringent demands on the available time and frequency technology. The principal ground-based radio navigation systems are known as Omega and Loran (2,3). Originally developed by the U.S. Navy, Omega uses VLF frequencies in the 10 KHz range. Radio signals at these frequencies have good stability and range both during the day time and at night. A network of eight transmitters provides practical global coverage and their signals, controlled by atomic standards, can be used for providing highly accurate time data and calibration for secondary standards. The time interval between the arrival of signals from a pair of transmitters at known locations is used to determine a hyperbolic line of position and two or more of these lines suffice to establish location. Since the signals are distorted by sky-wave propagation, corrections are required to use the system optimally. For general use, the Omega accuracy is one mile during the day and two miles at night.

There are two versions of the Loran system which have been implemented. These are Loran-A or Standard Loran and Loran-C. Standard Loran signals use frequencies between 1750 and 1950 KHz, resulting in differing day and night ranges. The most accurate results of Loran-A operation occur during daytime ground wave reception with average ranges around 1000 Km (about 600 miles). The positioning accuracy under these conditions is within 3 Km (about 1.5 miles) over most of the area serviced. Use of the sky wave propagation of the signal extends the range to about 2400 Km (1400 miles) but the location accuracy degrades to an uncertainty in position of approximately 10 Km (6 miles). Much greater accuracy is achieved by Loran-C operating at 100 KHz. At this frequency ground wave propagation range extends beyond 2000 Km (1200 miles) and sky wave reception is useful out to 5000 Km (3000 miles). The improvement in accuracy obtainable with Loran-C is due to differences in pulse rates emitted by the elements of the Loran-C Master/ Slave chain of transmitters. Proper reception requires a more sophisticated receiver than for either standard Loran or Omega. Signal phase identification in the Loran-C receiver will yield position location with an error of less than 200 meters over the complete ground wave range and accuracies of 100 meters or less at ranges of less than 1000 Km from the transmitters. As in the case of Omega, the Loran receiver detects the time interval between the times of arrival of signals from two separate transmitters. These data yield the receiver's location on a hyperbolic line of position. A second, independent line of position, obtained from two other transmitters (or one of the original two plus a third) provides an intersection which fixes the receiver's location in two dimensions.

In all of these systems, even though time of day is not required by the receiver, it is imperative that all the transmitters maintain a predetermined, known synchronization between pairs of signals emitted by the system, and the time-base in the receiver must be good enough to provide an accurate value for the time interval between the arrival of the first and second signals of a pair.

If we can provide a navigator with a clock capable of maintaining precise time within close tolerances to a master clock for the duration of his travels, then position can be found by measuring the time required for signal propagation from the transmitter to the receiver. In this case, there is a known time of day for transmission of a navigation signal. The time delay in signal arrival at the receiver places the user somewhere on a circle about the transmitter site. A similar determination based on a separate transmitter will yield two possible positions (the two points of intersection of two circles) for the navigator. Some approximate knowledge of position or a third position fix will locate unequivocally the platform carrying the receiver in two dimensions. For three-dimensional uncertainty, location is achieved by replacing the circles in the above discussion with spheres and obtaining signals from enough transmitters to unambiguously fix position. In the synchronized time-of-day clock application, the frequency standard is subject to requirements similar to those for Omega and Loran use. In all cases, the receiver must be able to measure small time intervals with great accuracy. In the Omega and Loran cases, a degradation of synchronization between transmitting stations will result in serious navigation errors even if the navigator's time interval counter is perfect. An error of 10 μs, for example, in the expected time interval between emission of the pulses from master and slave transmitters can lead to location errors of about 3 Km. In the case where the navigation system relies on synchronized time of day between receiver and transmitter, it is important that the time discrepancy between the two clocks be kept below a level which sets the maximum acceptable positioning error.

Satellites offer advantages over ground stations as navigation signal sources because their useful transmissions are less subject to the sky wave distortion accompanying land-based signals. The Transit satellite navigation system offers the possibility of position location based on signals from a single source (1,4). The technique relies on the Doppler effect which, in this case, would produce measured frequencies higher than, equal to, and less than the transmitted frequency as the satellite approached, passed overhead, and receded, respectively. A precise frequency standard is used in the receiver equipment which measures the Doppler profile of the Transit signal. Since the location of the satellite is known accurately from extensive independent tracking data, a computer can calculate the Doppler frequency shifts with time for any position. The user, starting with an initial estimate of his location, computes his expected Doppler profile. A software package compares the recorded and calculated profiles and continuously adjusts the position of the receiver to obtain a best fit between the theoretical and observed Doppler frequencies. The Global Positioning System (GPS) offers state-of-the-art navigation and time dissemination capabilities on a global coverage basis. Originally conceived as a 24 satellite configuration, present plans visualize 18 satellites which would be able to provide position location under all conditions with an accuracy of about 10 meters. In this system, the location of each satellite is uploaded to the satellite periodically as a result of careful tracking by the ground control segment. The satellites, the space segment of the system, each with its own precision frequency standard, broadcast navigation and time signals to the third element of the system, the user segment. The user is any platform with a GPS receiver capable of determining position and time from the satellite transmission.

These are the major applications of frequency standards in navigation systems and they serve the position location requirements of most commercial and military traffic. Decca, a commercially-operated short-range radionavigation system is available in limited areas, principally in Europe. The specifications for the oscillators and clocks in navigation systems are developed by the same set of constraints as those which are present in communication and identification systems. Therefore a discussion of oscillator selection as a function of range, platform, environment, etc. is deferred to the section on choice of frequency standards.

Precise Time for Communication and Identification (C/ID)

Because the identification function is a somewhat specialized case of communication, it is convenient to address them together. The frequency standard offers two very important attributes to the C/ID system. First, a precise control of frequency, coupled with adequate user synchronization, provides a multiplex capability which enhances the message-carrying power of modern digital data and voice transmission systems. In the second place, the use of frequency standards can provide a level of information security and electronic anti-jam capability not otherwise available in real-time radio transmission.

Two common realizations of the multiplex feature involving precise clocks are known as Time Division Multiple Access (TDMA) and Frequency Division Multiplex (FDM) systems. In the former, a single transmission line is shared in time by many pairs of senders and receivers of information. Each transmitter operates on a separate channel which is sequentially sampled by an accurate time-phased selector switch. Thus many users are continually sampled for very short periods of time. A synchronized selector at the receive end of the line ensures that communications reach the intended receiver. For operating simplicity, all channels are sampled for equal time periods and extensive buffers are used for "bit-stuffing" and overflow storage to accommodate messages of variable length. In such a communication system, precise time interval is needed to maintain bit-stream integrity within specified limits and synchronization between user clocks is a necessity to ensure that channel coordination is satisfactory for extended periods of use.

In the FDM system, several users are allocated separate frequencies which are transmitted simultaneously over the communication link. A precise control of frequency is needed so that each message is routed to the intended recipient and so that channel cross-talk is minimized. Many systems combine time- and frequency-multiplexing techniques simultaneously with the result that both ends of the transmission medium require clocks that are synchronized precisely in time as well as in frequency. The phase coherence of such systems is often maintained by periodic repetition of a synchronizing pulse to keep performance within specification.

In military and commercial communication systems, spread spectrum techniques are used to obtain the processing gain obtainable by the modulation-demodulation process (5). Adequate intrasystem synchronization is a requirement for the application of direct sequence, frequency-hopping or hybrid methods. The cumulative bit-per-day drift rate of any element of such a system can be obtained from consideration of the oscillator stability and the transmitter code clock rate. For example, a system operating at one megabit per second which relies on an oscillator with a frequency stability of 1×10^{-8} will, in a worst case, accumulate a drift of 10^3 bits at the end of 10^5 seconds (27.8 hours). Extensive software techniques such as preambles are used frequently to guarantee timing latch-up and optimum synchronization when a message is to be sent.

Some examples of navigation and communication systems requiring precise time and time interval (PTTI) technology are the GPS, HAVE QUICK and JTIDS programs (6). As referenced above, the GPS system will provide very accurate position location and time, world-wide, on a continual basis. The satellites carry rubidium and cesium standards. It is possible that future space vehicles will have an on-board hydrogen maser as an ultra-stable oscillator. The correct time and satellite position is uploaded periodically to the satellites by the ground control segment. The users, airborne or ground mobile units, will probably rely on carefully-maintained quartz oscillators or rubidium standards. HAVE QUICK is a secure anti-jam voice communication program which relies on a frequency-hopping sequence to ensure system privacy. Time is obtained from the Transit satellite system and specifications for frequency stability have dictated the use of rubidium standards. JTIDS stands for Joint Tactical Information Distribution System. It is a secure, jam-resistant digital communication system which uses a TDMA architecture to provide communication, position location and identification.

The operating speeds of modern aircraft have generated a need for a recognition capability which can provide rapid, accurate identification. For this discussion, we refer to an active type of system in which one platform (aircraft or missile site, for example) actively interrogates an approaching aircraft. This ID system usually involves the transmission of an encrypted request for a coded password. A transponder in the queried aircraft recognizes the question and delivers the appropriate answer within the allocated time. A precision oscillator is needed in such a system to maintain the correct digital bit-stream relationships during the question and answer (Q/A) dialogue. However, to avoid the possible compromise of the dialogue by spurious repetition of the question or answer, it is desirable to change the encrypted Q/A sequence as frequently as possible (7). The time period during which a specific password is useful is known as the code validity interval (CVI). System time must be maintained within very close tolerances among all users to ensure that all friendly forces are inside the same CVI simultaneously and that a transition from CVI_n to $CVI_{(n+1)}$ etc. is executed with a high degree of synchronization. The length of the CVI can be estimated from frequency stability of the oscillator and the desired time interval between successive recalibrations of the standard. For example, an oscillator with a frequency stability of $1x10^{-7}$, using a CVI of 10 milliseconds would, in the worst case, allow the ID system to slip outside the CVI in 10^5 seconds. However, if another vehicle had an oscillator accumulating a time error of equal magnitude but opposite sense, then these two units would slip out of CVI overlap with respect to each other in $5x10^4$ seconds or just less than 14 hours. From this type of analysis we can conclude that if we desired a full 10^5 seconds of operating time between recalibration, doubling oscillator stability to $5x10^{-8}$ would lead to zero CVI overlap between oscillators drifting in opposite directions for a 10 ms CVI. Doubling stability again would lead to an overlap of 50% of the CVI at the end of 10^5 seconds while increasing oscillator stability to $1x10^{-8}$ would yield a useful CVI of 80% or 8 ms.

Frequency Standard Selection

The choice of standard for any of the NCI functions discussed above is limited principally by the precision required for maintaining the frequency or time and the environmental conditions in which the unit must operate. These conditions pertain to the physical stability of the platform and the range over which the platform must operate. In terms of a tactical scenario, the distances over which systems must operate fall into three categories; - long, medium and short-range. For the long range category, we presume that operating distances are approximately 100 to 1000 Km. Typical systems in this category are long-range surveillance aircraft and master ground-control stations. The intermediate operation range lies between 5 and 100 Km, with fighter and reconnaissance aircraft and helicopters having the most common platforms. Mobile ground vehicles such as trucks and tanks, and manpack units, make up the short range category with an operating distance of up to 10 Km. The relative number of oscillators needed for each category is generally inversely proportional to the distance involved. We may estimate that there would be approximately 100 short-range platforms for each medium range unit; and 100 medium-range units for each long-range system. Typical figures are roughly 100,000, 1000, and 10 respectively. The operating environment for the time base is also related to the type of platform and the distance over which the NCI function is required. For example, we may expect that a long-range platform such as a large surveillance aircraft would offer a relatively benign environment with only moderate variation in temperature and pressure, would have adequate space for a large time-base such as a cesium standard and would provide continuous power to the NCI systems for the total mission duration. A medium-range platform such as a fighter aircraft, on the other hand, would be more cramped for space, power would be available continually, but substantial vibration and g-force stress would be experienced. In addition, the oscillator would undergo rapid excursions in operating temperature and pressure. Depending on the kind of aircraft and mission, fast warm-up could be an important performance specification. For use in a question/answer identification system or a more general communication or navigation system, warm-up time must be short enough to ensure that all clocks are synchronized to system time before any NCI activity is needed. A rugged rubidium unit or a fast warm-up, high-performance quartz oscillator should fulfill the requirements for the medium-range platform. For the short-range ground-based units, vibration, shock and extremes of humidity and temperature will be common elements in the operating environment. Because the number of oscillators needed will run to many tens of thousands, it is likely that quartz technology will see widespread application for economic reasons alone. However, quartz oscillators do have size and weight parameters and power requirements which make them the most promising candidate for a manpack or mobile ground unit such as a jeep or tank.

There is a trade-off which must be considered in the mode of operation of the oscillator: that is whether or not to anticipate maintaining power for an extended period; - for example, a few days. If we wish to keep continuous power up, then the unit must operate at a power level low enough to make battery weight acceptable, and ageing must be such that the frequency drift does not interfere with system synchronization during the mission. If we operate the oscillator only intermittently, we avoid the power supply and ageing problems to a large extent, but we must contend with the warm-up time and retrace problems. In this case, the unit must provide a recovery to a narrow band about nominal frequency fast enough so that the NCI system can be used as rapidly as required. Frequency recalibration and resynchronization may have to be considered for successful operation over extended periods in either situation.

Some Considerations for Near-Term Financial and Technical Benefits

Economics will play an important role in acquiring frequency standards for systems now entering the design phase. Military quality standards cost about $20,000, $8,000 and $2,000 (clock option excluded) for cesium, rubidium and precision quartz technology respectively. Development of NCI systems to date has been a succession of independent, unrelated efforts which have resulted in a large number of incompatible units. This incompatibility is due partly to frequency and performance specifications, but is more significant from the point of view of dimensions, pin configuration and other physical and mechanical characteristics (8). It is highly likely that a sophisticated fighter aircraft will have three to six different NCI systems on board. Each of these systems could have its own independent time-base, entirely non-interoperable with any of the others, and purchased in relatively small quantitites. The possibility of developing a common oscillator, or set of oscillators, to fulfill the timing needs of various NCI systems promises substantial cost reduction in oscillator acquisition. Engineers are often reluctant to rely on a time-base which is not dedicated to their particular system. However, a common oscillator, plus one or even two back-up units are a les costly proposition than several independent stand alone models. Furthermore, economies of scale in production can be realized by steady-state rather than batch procurement, with accompanying benefits in quality control and reliability.

Many of the papers in these proceedings describe research work on the frequency standards of the future. However nearer term technical improvements are also discussed both here and in other reports. The latter category of technical paper promises performance improvements for NCI standards in the future. Among these advances are new techniques for improving the quality of cultured quartz (9) the SC-cut for a smoother frequency/temperature characteristic (10,11) and continuing development activity on the BVA (12), miniature high-frequency (13) and flatpack resonators (14). A shift to hybrid or integrated circuit application to oscillator electronics, and new efforts in chip-scale microprocessor control of temperature compensation can lower labor costs and increase reliability while simultaneously reducing volume, weight and power demand. Work is now in progress to decrease substantially the size and improve the operating characteristics of rubidium standards (15). New efforts in beam tube technology and optical state selection/detection (16) may broaden significantly the applicability of cesium standards for NCI use. Initiatives in the industrialization of the hydrogen maser may move this device from its present status as a custom "home-built" unit to a true off-the-shelf type of standard.

The most exciting prospect for this community is the obvious fact that the present surge in demand for sophisticated digital communication, both government and commercial, promises continuous need and support for new advances in all aspects of time and frequency technology for the foreseeable future.

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