MILITARY APPLICATIONS OF TIME AND FREQUENCY

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Abstract

The introduction of the NAVSTAR Global Positioning System (GPS) to the military community is having an lesser known, but highly significant, impact on those systems requiring dissemination of precise time and frequency. Precise time/frequency and their uses could have a wider ranging influence on military electronic systems than the positioning/navigation aspects. The implications are not as well known or recognized. Time and Frequency (T/F) are a fundamental function needed by all military electronic equipment. From generation of frequencies for communications to remote sensing of geophysical quantities with time-tagged data requires oscillators, T/F standards, and/or clocks. The application and requirements for these standards and their maintenance of them onto a common timescale is a specialist's area often overlooked in the development and deployment of these systems, only to be addressed later as a operational problem area. The wide spectrum of applications and uses for timing devices within military systems can be categorized into different system types: (1) navigation, (2) communications, (3) identification, (4) remote sensing, (5) intelligence, and (6) weapons.

In addition to using T/F devices and technology, military electronic systems are on diverse platforms, which operate most effectively in a highly coordinated, interactive environment. This requires all units and elements of the operating forces to be referenced to the same time. U.S. military systems are required to be referenced to Universal Coordinated Time (UTC) maintained by the U.S. Naval Observatory (USNO), designated UTC(USNO). From this central reference, time is disseminated through various existing military and scientific systems. Navigation systems are the most immediate and well-known users of T/F, and from this fact are the primary systems used for T/F dissemination. Heretofore, a single system has not had the capability of widely disseminating precise time; consequently, many different systems with different capabilities have been used. Today the NAVSTAR GPS provides a general purpose, highly precise means of disseminating time and has been used operationally since the first technology satellites of the system were launched.

This paper summarizes the areas and application of precise time and frequency uses in military systems with specific examples.

INTRODUCTION

The Precise Time and Frequency (PT&F) utilization within military forces encompasses four major areas: (1) timescale generation and coordination, (2) dissemination systems for PT&F, (3) distribution system within platforms and for local areas, and (4) users in platforms and systems. As used in this paper, the term "user platform" includes ships, submarines, aircraft, land mobile units, and fixed-site installation (e.g. airfields). Within the overall generation, dissemination, distribution, and use of PT&F, a variety of interfaces exist for the transfer or use of PT&F. A standardized interface to determine a common interface between military equipment or systems would provide increased interoperability. The use within the overall context of PT&F, as well as specific examples for equipment, will be discussed in this paper.

US DoD TIMESCALE

The timescale adopted for military systems is Coordinated Universal Time (UTC). UTC is founded on the SI second defined on the period of the frequency between two hyperfine levels of the ground state of the cesium atom. Thus, a cesium-beam standard can be considered as a primary frequency standard, and is used extensively in military systems. Coordinated Universal Time (UTC) was adopted with the advent of atomic time (AT); UTC is the approximation of UT generated by atomic clocks, and since it is approximate, corrections known as "leap seconds" are introduced periodically to keep UT1 and UTC to within 0.9 seconds of one another. International Atomic Time (TAI) is a continuous timescale generated by atomic clocks located in timing centers distributed around the world and coordinated by the International Bureau of Weights and Measures (BIPM), located near Paris, France.

UTC and TAI differ by an integer number of seconds; the rates are the same. UTC itself is a composite of the measurements made at numerous time observatories and centers around the world. It is the basis of legal and scientific measurements maintained by local or national timing centers as the output of their physical clocks, as distinguished from the international value determined as a "paper" or theoretical timescale. The local or national time is identified as UTC(XYZ), where XYZ is the center generating and coordinating the timescale. This quasi-uniform and universal timescale presents particular problems for the military user, in that it is not continuously uniform. The introduction of leap seconds to keep UTC allows the timescale to be used as an approximation to UT1 only for those users with a time accuracy requirement of about $\pm$ 0.9 seconds. Alignment of inertial systems, for example, requires knowledge of UT1. Aside from introducing significant jumps in the timescale periodically, the dissemination of the time and value of the leap-second occurrence has posed significant problems for the operating forces.

ALLIED/NATO REFERENCES

For U.S. Allied or NATO operations, the availability of a common timescale poses additional problems. Each participating member nation or ally has, or refers to, an observatory or laboratory that is charged with the establishment and maintenance of their national UTC timescale. These master references are coordinated internationally, and the international UTC timescale forms the basis of timekeeping and time-interval measurements for NATO military forces. Via primary and backup dissemination systems, each equipment/system onboard the various user platforms are provided with time and frequency signals which are directly traceable to the nation's master UTC reference. The accuracy and availability of UTC reference sources differ from nation to nation. The maintainance ot UTC is coordinated, but the individual nation's sources and availability for military bases and systems may well have widely varying values. For joint or NATO operations with mixed forces, the capability to be synchronized can be a significant problem. The addition of leap seconds and the communication to operating forces compound the problem.

DISSEMINATION SYSTEMS

Time-dissemination systems are typically military systems developed for navigation and communications and often have their own time basis or timescale. In the case of GPS, the system internal synchronization time basis is determined and known as "GPS Time." This is the time determined by the ground tracking system for maintaining the operation of GPS. GPS time's continuous nature is needed by the system to synchronize the satellites for navigational operation and consistency. The known relation of GPS Time to UTC(USNO) makes GPS a global, continuously available, general-purpose time-dissemination system with much greater precision than previous global systems.

From the time reference through the dissemination system, a platform or user requiring precise time or frequency is at the bottom of a timing hierarchy that gives it traceability to the adopted timescale. In practice, the timescale must be associated with a physical clock, although the true timescale may be a "paper" clock or internal system time base. Figure 1 illustrates this representative timing hierarchy. There may be other routes to traceability, and the hierarchy may even change during a mission. If, for example, the dissemination system were GPS and the platform were an aircraft whose platform clock is not operating until just before a mission, time would be obtained initially from the site clock, which operates continuously. Then, if GPS were using its Selective-Availability/Anti-Spoof (SA/AS) mode, precise time would be needed to acquire its code quickly. However, the platform clock would not be accurate enough for direct access to GPS and might later be updated by it.

Figure 1 also illustrates the overall PT&F resources and systems within the timing heirarchy. There are many communication and navigation systems presently in use which have an inherent capability to disseminate PT&F signals on a non-interference basis with the systems' primary missions. While some of these systems have the capability to disseminate both time and frequency, e.g. GPS and LORAN-C, many systems can be used to disseminate either precise time or frequency. The U.S. Navy Navigation Satellite System (NNSS) or Transit, for example, has only a precise time dissemination capability, and current VLF broadcasts can be used only as a precise frequency reference.

In general, each clock in the hierarchy, depending on its mission, must operate autonomously for some period of time. For a hand-held clock that carries time from a site clock to mobile platforms, autonomy may prevail for only minutes or a few hours. For submarines, the clocks might run autonomously for some months. For survivability, a clock may need to operate autonomously for the time required to restore a failed link with the next higher clock, to establish a different hierarchy, or to finish the overall mission.

SYSTEM PT&F INTERFACES

PT&F interfaces are a secondary and important link in the timing heirarchy. These two-way interfaces between individual systems form a vital link in the dissemination and coordination of PT&F within platforms and between systems. The use within the equipment and the operational requirement the equipment is required to meet are usually tailored to the needs of individual systems, without consideration of the variety of systems on the platform. Consideration for an overall architecture needs to be developed to take advantage of developing universally synchronized military systems.

An important interface issue that needs consideration is that all systems, regardless of how they acquire the reference, should use the same basic timescale, UTC. By accepting it as the reference, inter- and intra-system interoperation can be supported. These interfaces are generally designed to communicate the time base that the system it serves uses. Traceability between system time bases to UTC can vary widely from one user system to another because of their different requirements and operating methods.

Interfacing of systems beyond use of a common timescale should be aided through a common platform-level timing facility, which could provide time, and perhaps frequency, signals to serve all the users. Beyond time maintenance, little other information would be of common interest. However, not all timing facilities can easily provide all the information needed. If a standard time code is to be used, other considerations are needed: the local distribution medium to be used; the time resolution to be supported by the code itself; the need for and ability to support information about leap seconds; the detail needed to resolve ambiguities of seconds, minutes, hours, days, days of years, and years of centuries; and Time Figures of Merit (TFOMs), if needed. The need to provide TFOMs might depend upon how the accuracy of the service is expected to vary. Users may elect to use TFOMs internally, whether or not the service provides them. Current interfacing time-code considerations have involved the adoption of a code that has provisions for all the information, most of which would be optional. It does place a burden on the users to maintain all the required information to support the interface itself, even though the user may not need the information himself.

TIME FIGURE OF MERIT (TFOM)

A Time Figure of Merit (TFOM) developed for use within a PT&F time code is intended to describe the accuracy of the time reference that is being supplied by the time code to a unit or system. If the TFOM is a credible index of accuracy, a user might assess the accuracy of the reference before accepting a time update from it. In order to accomplish this, the TFOMs would represent an accumulation of timing uncertainties through the chain of time dissemination and distribution operations from the primary reference, e.g., UTC(USNO), to the ultimate user. These uncertainties accrue from measurement errors and uncertain clock performance during periods between direct comparisons with the reference or from "flywheeling" to maintain the reference for continuous operation. The evolution of the errors is illustrated in Figure 2. This method requires that each node in the chain add its uncertainty to that of its reference. While some uncertainties might be considered random and a smaller TFOM might be justified, a more elaborate TFOM is needed to convey all the required information. Obviously, the TFOM can be kept small by keeping the number and uncertainty of measurements low and using better clocks and shorter periods of autonomous operation. The relationships of the timing errors and TFOM values should be managed by some fixed plan for the particular system involved to reduce the amount of information that may need to be transmitted and to ensure equal treatment of the errors as the values propagate through the system and its various nodes. Time management from reference to user can be managed in two principal catagories: fixed and fluid hierarchies.

FIXED TIMING HIERARCHIES

In a fixed timing hierarchy, an established chain of timing references is used, as in Figure 1. Normally, fixed chains are designed for a specified accuracy, so the end user can generally rely on the final time reference he receives as being within the system tolerance. There is generally little use for a TFOM in this situation, although an alarm may be used if there is a failure. An alarm received through the chain might be cause for a user to revert to independent timekeeping with the local clock or to use an available backup reference.

Most fixed hierarchies employ relatively short paths or few nodes to the ultimate UTC reference. The chain in many cases is simply an established time-dissemination service, such as GPS, and the local clock is occasionally or regularly updated via that service. However, the major dissemination services do not ordinarily provide TFOMs, because they have the resources to maintain advertised accuracy with high confidence. An alarm may be issued (e.g., by LORAN-C or GPS), however, if certain equipment is not performing properly. Some other dissemination services involve larger uncertainties than GPS. Although very-low-frequency, low-frequency, and high-frequency transmissions may be very accurate at the source, the error in estimating propagation time to the receiver may be in the order of a millisecond if not within line-of-sight or groundwave range. One-way transmissions from geostationary satellites may involve uncertainties of some tens of microseconds. All of these transmission errors may be considered measurement uncertainties, and appropriate TFOMs might be assigned if the errors can be measured or otherwise quantified. If the information to quantify exists at the node in question, the accuracy of the measurement is then known and could be used to upgrade the TFOM to the users; there is little or no need to transmit it in a time code.

Some fixed hierarchies contain distribution media, such as microwave links, fiber-optic cables, dedicated telephone lines, etc. Their contributions to time error generally consist of fixed delays, which may be compensated by two-way transmissions or simply taken into account by the user. Only the variability of the path would be of concern to the user. However, the range of variability usually is known to the user and cannot be determined by the sender. Therefore, inclusion of a TFOM in the transmitted signal would be of little interest, although an alarm might be useful if the system becomes defective.

FLUID HIERARCHIES

In a fluid hierarchy, part of the timing hierarchy is not fixed. Although the upper levels may be fixed, some at the lower level, especially aircraft and other mobile clocks, may be disconnected from the fixed chain for the length of a mission. To meet their accuracy requirements during these periods of autonomous operation, other links with other systems or equipment traceable to the primary reference are used. Updates then might be obtained from another clock within communication range whose TFOM was lower than their own. Thus, new sub-hierarchies are created, whose structure is based on an hierarchy of TFOMs.

Operation of a fluid hierarchy could depend critically upon the validity of the TFOMs. The TFOM of a platform clock would then be determined from the sum of the following: the uncertainty represented by the TFOM of the last clock used as a reference, the measurement uncertainty with which the last time update was made, and the added time uncertainty contributed by the platform clock since the last update. The second and third terms could cause each lower level of the hierarchy to declare a higher (poorer) TFOM than the previous one. The measurement uncertainty for each time transfer might be a specified number of milliseconds or microseconds, based on nominal values for the technique used. However, there is no good basis for self-determination of the third term if the platform has only one clock and no means to check it against a more accurate reference. "Semi-worst-case (SWC)" clock performance could be assumed since the last update, but the means to determine or calibrate the actual performance is needed to insure performance. SWC performance could assume that the clock has run at the manufacturer's maximum specified rate error since the last update, although experence has shown a significant variability in performance, especially in severe environmental conditions. Success of this operation depends strongly on availability of clocks with better

TFOMs at key distribution nodes. A squadron of aircraft from one location and using the same type of clock, for example, could not update each other, because their TFOMs would be identical.

For platforms using TCXOs or MCXOs, the SWC bound must include the effects of the entire environmental range. The SWC method of determining TFOMs can easily result in having one clock updated by a less accurate clock, although the maximum error is still generally limited by the SWC bound. Some TFOM increments in the more elaborate TFOM schemes are as small as about 10%, a trivial increment considering the coarseness of knowledge of the clock's actual rate. However, in a long daisy chain of updates, a sum of these small increments can reflect a substantial loss of accuracy which would be need to be accounted for. A defective clock under these conditions could badly contaminate the system if protective measures are not used.

THE NAVSTAR GLOBAL POSITIONING SYSTEM (GPS)

The NAVSTAR GPS is a navigation satellite system that provides continuous worldwide three-dimensional position, velocity, and time information to properly equipped systems. This system will be the primary dissemination system for U.S. and cooperating NATO forces. All user systems are synchronized to GPS system time for navigation, and the precise time output is UTC as maintained by the U.S. Naval Observatory (USNO). GPS system time is maintained by the Master Control Station (MCS) through the use of the cesium standards deployed throughout the GPS system and the Alternate Master Clock ensemble of atomic clocks co-located at the MCS by the USNO. The capability of GPS user equipment (UE) to disseminate UTC(USNO) worldwide is to an accuracy of approximately 100 nanoseconds.

GPS UE has several versions that are tailored for the specific user platforms, as described in the Interface Control Document (ICD) for the GPS program, GPS-ICD-060. The various models of GPS UE are assembled from several integral components designed to satisfy the requirements of the variety of user platforms. The receivers of the GPS air and sea UE are each equipped with a common Precise Time and Time Interval (PTTI) module specifically designed to exchange time-related information with other systems. A variety of user equipment for use specifically in PT&F systems has been developed. Most common are equipment for use with the Standard Positioning Service (SPS), but for military systems a few receivers utilizing the Precision Positioning Service (PPS) are also available.

LORAN-C

LORAN-C is a ground-based radio navigation system that broadcasts on a frequency of 100 kHz using a bandwidth from 90 to 110 kHz. At this low frequency, the radio waves follow the earth's curvature, are relatively undisturbed by the earth's ionosphere, and are very stable. The signals propagate in two forms, the "skywave" signals reflected from the ionosphere and the "groundwave" signals following the earth's surface. Groundwave signals provide the more accurate results and skywave somewhat less accurate.

The system consists of many synchronized chains or networks of stations. These stations provide groundwave coverage of most of the United States, Canada, Europe, the North Atlantic, the islands of the Central and West Pacific, the Philippines, and Japan. One station in each chain is designated as a Master Station, and the remaining stations are slave stations. The Master Station transmits groups of pulses that are received by the slave stations. The slave stations receive the master pulse groups and, at a later time, transmit similar groups of synchronized pulses.

On a user platform, the constant time difference between the reception of the master pulses and the corresponding slave pulses establish a line of position that is used for navigation. Signals from three separate LORAN transmissions are needed to determine a line of position. For PTFS applications only, a single LORAN station is needed if the user accurately knows their position. The LORAN-C system is synchronized by and compared to UTC(USNO) to maintain precise time throughout the system. Except for very long overland paths, LORAN-C groundwaves have a precision of 0.2 μs and an accuracy of 0.8 μs, with the published corrections applied. Cycle identification errors could add $\pm$ 10 μs to these figures. Efforts are now underway to keep the LORAN chains to within 100 ns of UTC(USNO).

DCF-77

DCF-77 is a low-frequency radio transmission system operated by the German government. This system transmits UTC as maintained by the Physikalisch Technische Bundesanstalt (PTB) in Braunschweig, Germany. The transmitter signals are amplitude-modulated BCD time code at a rate of 1 bit/s, with a 1 minute time frame. A user receiver can expect an time accuracy of 50 μs to 1 ms, depending upon propagation effects. Frequency measurements can be expected on the order of 5×10^{-13}.

PRECISE TIME REFERENCE STATIONS (PTRSs)

A PTRS is defined here as a remote station employing clocks and measurement systems to independently maintain precise time and frequency references for other users or calibration purposes. Often in these PTRSs the intent is to maintain a timescale synchronized to UTC. The clock systems used may be an ensemble of clocks, multiple clocks tied together with a data acquistion system to produce a combined or improved output, or highly stable high technology clock systems such as hydrogen masers. These clock systems are then compared to the UTC source by several independent time comparison techniques, such as GPS, LORAN-C, and/or Two-Way Satellite Time and Frequency Transfer systems.

A type of PTRS is used in the satellite communications networks of the Defense Satellite Communications System supporting syntonation of the stations and active timing comparison through the system. This employs a special modem to generate and receive precise timing pulses transmitted through the system. By this means very precise time or frequency comparisons can be made to support a spread-spectrum synchronous communications system. Other strategic communications systems employ similar means for maintaining overall system synchronization.

ELECTRONIC TRANSFER DEVICES (ETDs)–PORTABLE CLOCKS

A common means of precise time comparison and dissemination that was extensively used is portable-clock time transfer or so-called traveling clocks. These systems usually consisted of a portable cesium frequency standard that would operate on batteries, and was physically moved from one site to another for time comparison. Accuracies obtainable from this technique have been reported on the order of a few nanoseconds, and it was used for high-precision intercontinental time transfer. Use of this technique currently is limited to short distances for the most demanding requirements, but a analogous technique is being considered for new systems. This new technique is to use small self-contained Electronic Transfer Devices (ETDs) for short distances, within a limited time of operation, and for distributing between larger numbers of users, e.g. aircraft on a flight line getting ready for takeoff. These small self-contained ETDs are highly dependent upon the type and quality of oscillator used, since it determines the quality of time information available. Implementation of these devices has been been signficantly hampered by the oscillators required.

USER SYSTEMS/PLATFORMS

Tactical communications systems require PT&F for their operation. The frequency-hopping nature of the Havequick system requires that the participating units be synchronized, and to address this requirement the users are organized into local area nets. Each local area net is controlled by a net master located at a centralized ground site. The net master then distributes net time as the local time reference directly to the users or the users exchange time over the air among themselves to maintain their comunication capability. This relationship is shown generically in Figure 3. The net master (HQ Ground Equipment) maintains itself in time globally by some external means, such as through GPS or to a PTRS. Other tactical communications systems operate in a similar manner.

IFF systems, such as the Mark XII, the canceled Mark XV, and the proposed NATO Identification System (NIS), are currently query-respond-type systems. Operating in encrypted mode, the systems rely upon being highly synchronized. They are in principle very similar to tactical communications systems. These systems are also organized to operate in tactical area nets. The operation can then be described in terms of the generic diagram of Figure 3, and interchange of timing information is directly from the local area master or interchanges between units over the air. The definition of accuracy and a suitable interface for the interchange of timing information have been particular problems with the development of the systems. The Mark XV system implementation depended heavily upon the development of a hand-held ETD capable of updating aircraft on the flight line or carrier deck. This development was extremely difficult, given the quality of small oscillators, and was a major factor in the cancellation of the program.

These systems are good representatives of the fluid hierarchy timing systems and the dependence on a suitable PT&F interface that can meet the needs of PT&F information interchange.

PLATFORM DISTRIBUTION SYSTEMS

These systems are a means of providing a precise time and frequency reference at the platform level. These platform levels are typically airbases or ships which have a combination of user systems requiring PT&F resources. These platform-level systems would require survivability and redundancy to meet their military missions. They would be capable of providing PT&F signals for some period, and would not require continuous contact with the time-dissemination systems. The design of these systems combines the primary and backup dissemination systems with precise clocks capable of running independently. An example for airbase use is shown in Figure 4. This system can reduce the individual requirements of the participating user systems and, in turn, provide an increased level of accuracy at the base level.

In Figure 5 an example is shown of a shipboard distribution system. A system of this type would normally employ at least three reference standards. All the standards in the system would contribute to the time and frequency measurements and one is selected to be the master reference. The output of the master reference could be steered to reflect the combined results of the composite results and, thereby, provide an even more stable time and frequency reference. The distribution of the system could also refer to the physical isolation of the frequency standards from user equipment and from one another. The distribution system survivability and availability are enhanced by the components' physical separation and the ability of any standard in the system to become the overall system reference.

If a platform timing facility were to be provided, it must be decided whether or not the facility would accept time updates from any of its user systems. If TFOMs would be the basis for the facility to accept such updates, their meanings should also be standardized. This would be difficult. Systems use a wide variety of techniques for time transfers, and their criteria for estimating the degradation in timekeeping may also vary. Manufacturers' specifications are probably an insufficient guide to estimate uncertainty, because some are much more conservative than others. Other factors of importance are how often and accurately oscillators are calibrated in frequency, how well the systems are maintained, what the mean time is between (undetected) failure of clocks and measurement systems, and what overall management is used to assure accuracy. A conclusion that might be reached about accepting time updates from the users is that it should be an extraordinary measure that is resorted to only in an emergency.

SUMMARY

This brief paper has touched on a number of issues in the use of PT&F information by military forces. These issues have generally been overlooked in the development of individual systems because those developments rightly focus on the individual system's requirements. Coordination of PT&F for synchronized multi-service and multi-national forces requires that a systems approach be applied to PT&F. The implications of maintaining these services, especially in wartime, are deserving of closer study.

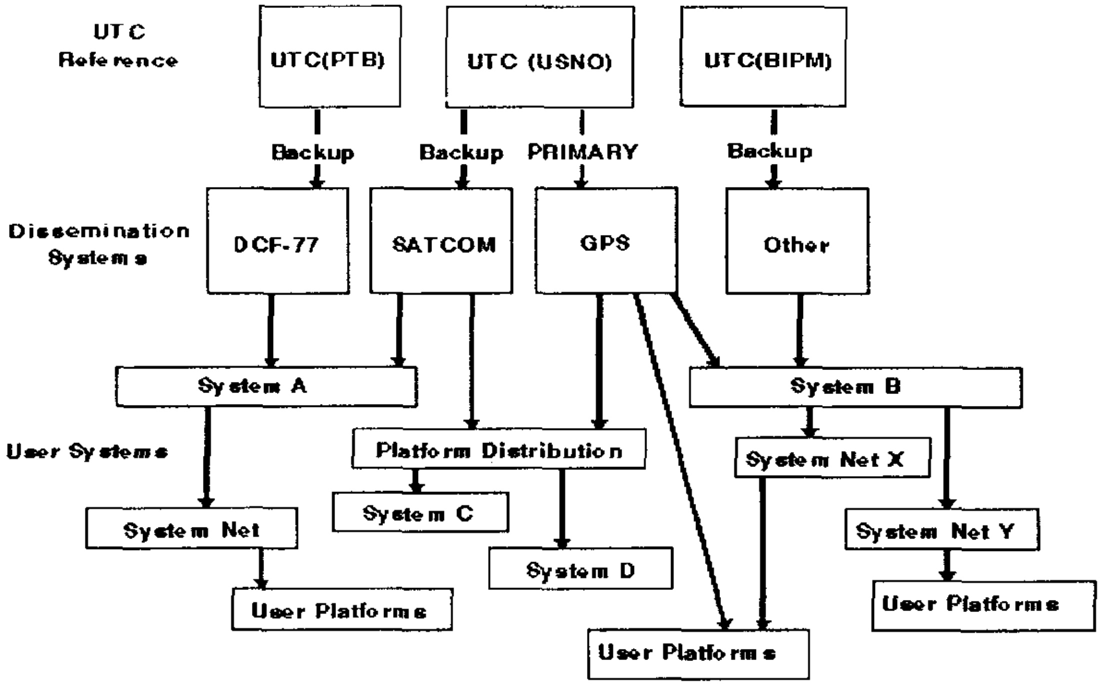

Figure 1, The Timing Heirarchy

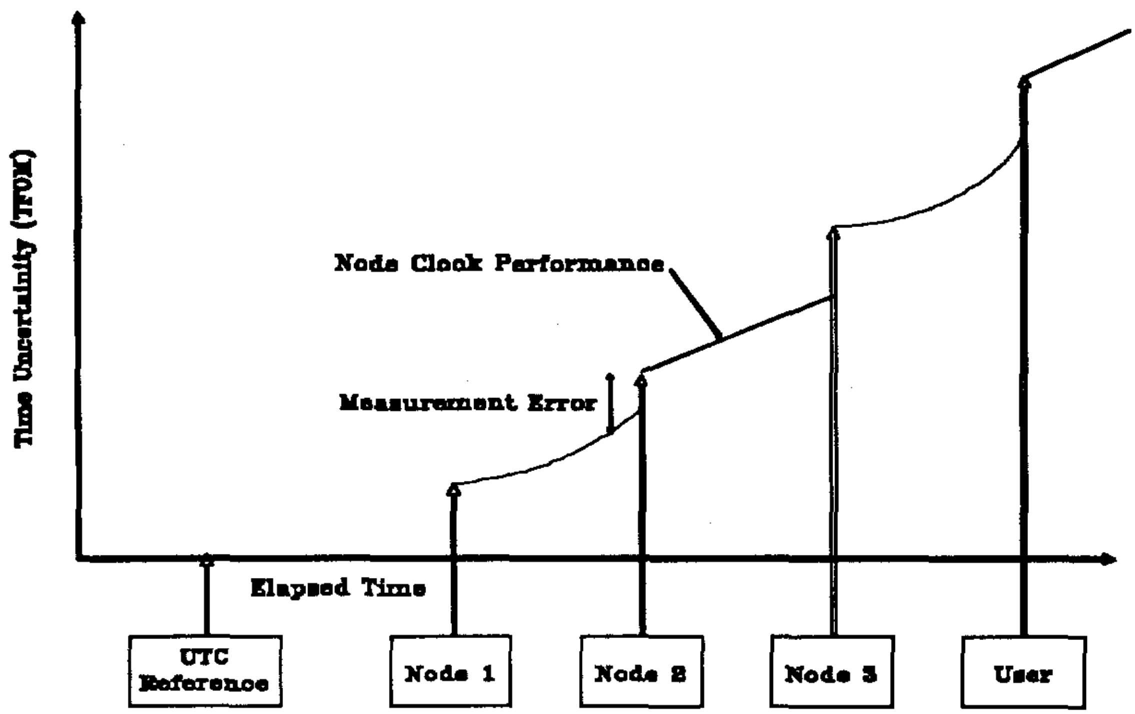

Figure 2, Time Figure of Merit

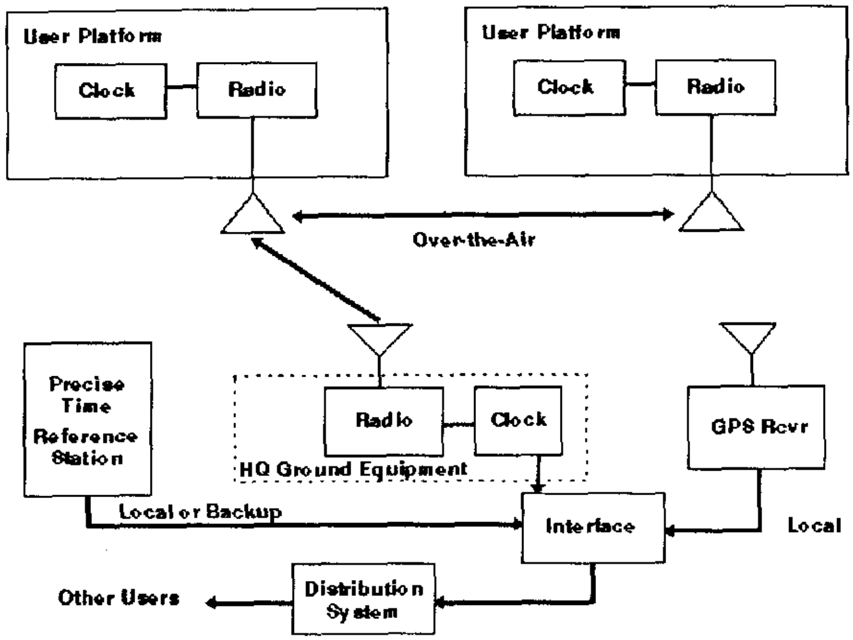

Figure 3, Generic User System

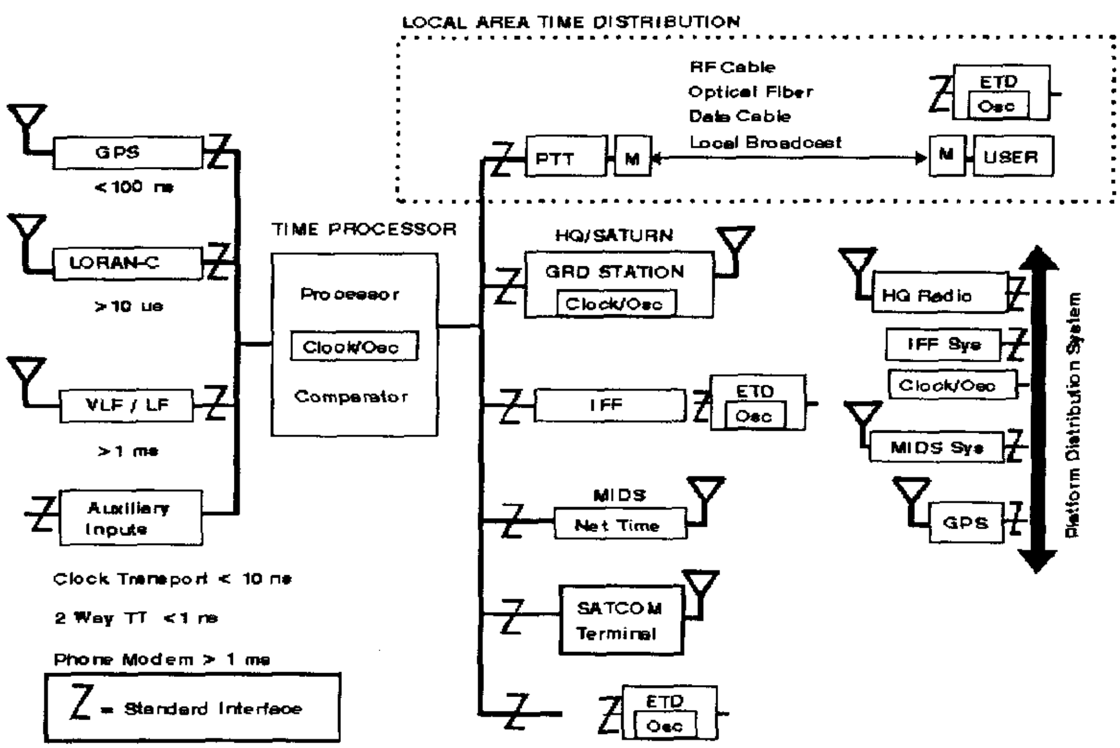

Figure 4, Example Airfield Distribution System

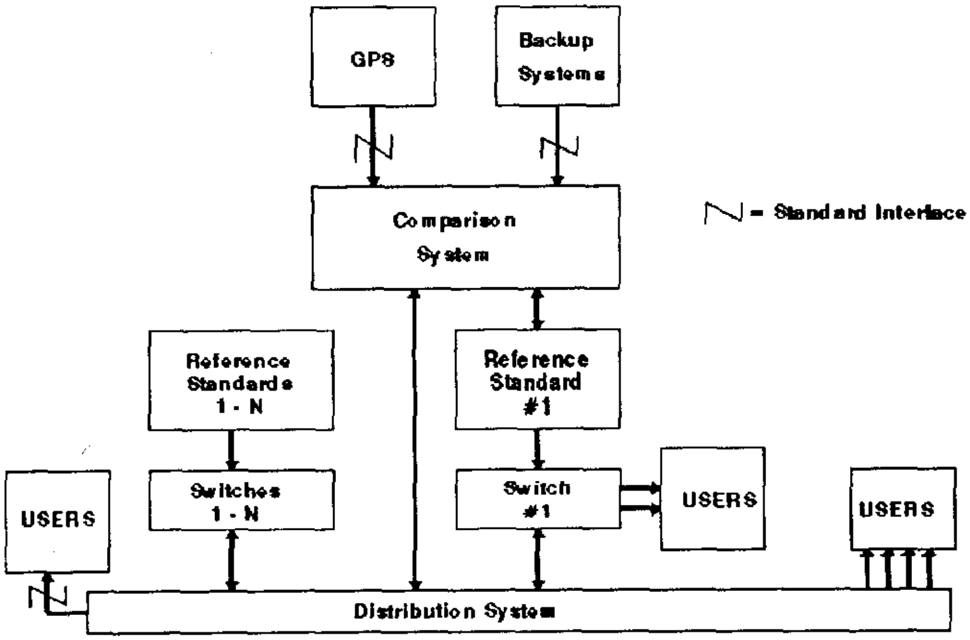

Figure 5, Example Shipboard Distribution System

Questions and Answers

GERNOT WINKLER (INNOVATIVE SOLUTIONS INT'L): In view of the fact that the subject is central to this conference, we should spend maybe three more minutes on that in a general way. The rule of time and specification for the needs for time are unique, not only because time is pervasive and goes into every operation which we know, but also because there is a great confusion about it. Many people who specify accuracy should be aware of why they are using clocks at all. You mentioned, for instance, the fact that in these communication satellites there is a clock. Well, yesterday we had a discussion about the systems, the coming improvements or additions to the Global Navigation System, as envisioned by the Europeans, which do not propose to put clocks into the satellites. I remember Dr. Busca's discussion where he said that clocks will simplify that. So the question of requirements is extremely complex.

In addition, I suggest distinguishing two concepts: a requirement in the sense of minimum tolerance or a requirement without which the system cannot operate or get into trouble. And between the benefits from doing better than that, you mentioned that we're going to upgrade requirements in the future. Well, if you want to do that, why not contract with incentives for operation which is better than the required minimum specifications?

The incentives are extremely important. And they are extremely important for another reason. Because today, our civilization, not only in this country but everywhere in civilization, suffers from what I call the "sufficiency syndrome." Once a requirement is set and people do accomplish the requirement, they feel that's sufficient. We don't need to do any better, because nobody has told us that we have to do better. You see, I'm coming back to these incentives, so these are very important additions.

In addition, there's another point. When you talk about requirements, in the military we have the concept of validated requirements. A command authority, possibly even at the highest levels in DoD for expensive systems, goes through a review; and a requirement is finally specified, because by specifying it, you commit your money. And that has an interesting side aspect because nobody who would have benefits from doing better than a specific requirement can get these requirements known because he will be hit immediately with the question, "Are you willing to pay for it?" So that's a very complicated thing. And I think in the requirement issue, because it is central to the conference, we ought to spend more time on these aspects. Thank you.

ROBERT VESSOT (SMITHSONIAN ASTROPHYSICAL OBSERVATORY): I'd like to comment on the need for short-term stability for possible multi-static radars and tracking systems where you need, in fact, in real time a measure of the position and velocity of that object so that you can do something about it. And I am despairing at the level of support that one can even imagine getting in the near future to keep a group of people alive and well in this direction, because I feel that if we are going to consider this as any form of our national defense system, this short-term stability and the ability to make these determinations of position and velocity depend on time, as Gernot has explained before.

JOHN VIG (ARL): I would like to comment on how we get requirements. Several years ago, my lab director, at a time we were short on money, which is not unusual, had a bright idea that we should have teams going out to do marketing. And I and a couple of colleagues decided to go see program managers. For example, we went to see the program manager of a radio system for the Special Operations Forces. I went in to see a Colonel, and I said, "Sir, we're here to help you. We want to find out what your requirements are so that we can develop a better oscillator for your system." I said, "Could you tell us a little bit about your requirements?" And the guy said, "Not only do I not know what clock we're using, I don't care what clock

And the guy said, "Not only do I not know what clock we're using, I don't care what clock we're using. What I specify is I want a radio for my guys to go into – and he named a country in the Middle East – and I want those guys to be able to stay there for awhile without being discovered. And when the time comes, I want them to be able to turn the radios on and be able to communicate without being discovered and then be extracted from the territory. Those are my requirements. What clock we use is totally up to the contractor." I said, "Okay, can I have the name of the program manager?" So I called the program manager at the contractor and the guy says, "I don't know what clock we're using nor do I care. That's up to Joe Schmoe at Building So-and-so."

It turned out to be a junior engineer who was making the decision as to what clock this system was going to use, which is a system on which the Special Operations Forces are depending. So it's very difficult for one to get the requirements from program officers. The program officers usually don't have the expertise and oftentimes they don't care what the requirements are for the clock or the timing system.

RONALD BEARD (NRL): Right, I think that's the point. It's a system level; a lot of these program managers don't even know they're using time in most cases. They don't care until they get out in the field, the guy plugs in the radio and he can't talk. And then after significant study, a lot of other effort, they find out that the oscillator is not remaining synchronized with the system on the other one; then there is a major problem.

CAPT. KENT FOSTER (USNO): [inaudible]

KEN PERRY (AEROSPACE CORP.): I guess some of what this is saying – this seems to be saying that it's up to us to understand the system requirements so that we can translate those into timing requirements; because, I think it's – I don't know if "unreasonable" is a proper word – but it's not going to happen that this junior engineer is going to understand timekeeping enough to be able to translate timekeeping abilities into requirements. So it's up to us to understand the system requirements and do the translating for the rest of the community.

RICHARD GRIFFIN (TEXAS INSTRUMENTS): A lot of the discussion of requirements is focused on requirements with respect to UTC. The areas we're interested in are more like stability for local between a small number of platforms, but where we need precision timing between platforms. We don't really care how we relate to UTC; we need to be able to have timing standards that we can have among a small number of units to coordinate specific activities, but at a very high precision. So we're concerned with the stability of the clock, not necessarily with its accuracy with respect to the UTC.

RONALD BEARD: That's part of the complexity of the situation, it's that many systems look at it that way. They require precise time for a particular application and radar or something like that.

GERNOT WINKLER: I would like to say that you are not alone. Every timing system has started with the same position, every one. I remember Omega, LORAN – not GPS – but certainly Transit, they all started with the idea that they were not interested in anybody else. And yet, they completely forgot that there are interfaces and that they can get tremendous benefits from making sure that these interfaces are part of the system right from the beginning.

RONALD BEARD: Part of the solution to your particular problem, without trying to be presumptive, may be getting time from another part of the platform that already has a highly stable clock, for example.

MARTIN BLOCH (FEI CORP.): In all of this discussion, there is one major problem which hasn't really been addressed; and one is to generate precise time or precise frequency at low phase noise. And the second, in my experience in 35 years in this industry, is that the environmental effect of maintaining this under real operational conditions is usually being ignored by those junior people. And the problem is not addressed until after the systems are built and then a lot of money and a lot of effort are poured in and really wasted on this.

So a part in 10 to the 15th sounds ideal when you are at NIST or at USNO, but a part in 10 to the 10th when you are on operational aircraft or in a helicopter or in a moving vehicle is a bear. And we have to find a better way of addressing it in early design of systems rather than fixing it. We can fix anything, but it's very expensive. And we haven't come up with a solution on how to do it yet. But maybe at next year's PTTI, we'll do better.

RONALD BEARD: I think part of the answer to the Captain's question is that this conference provides this kind of information and provides a forum for people to be able to understand the awareness of how this affects their systems. I don't know that we can come up with a particular solution *per se*.

JOHN VIG: One of the reasons that these problems get repeated over and over again is that we have a great deal of difficulty documenting what problems have occurred in the past. Usually when there's a problem, nobody wants to admit to it; it's swept under the rug and it's forgotten as quickly as possible rather than being documented so that people can learn from it. Is there any documentation of the GPS story, for example, as to how the clock development for GPS has progressed over the years and how much money has been spent?

GERNOT WINKLER: What do you expect if you have professors and leaders of all levels who say the past is of no interest to us? "We don't want to hear about the past!"

ROBERT VESSOT: Well, I am part of that past. And I think the issue that I see that is central to this whole discussion is this question of sufficiency. Once the specification is met, everybody says "Yes, amen, things are going to go on forever this way." The problem is that, when an advance was made in the ability to do timekeeping and frequency stability, I've never seen it happen that that advance hasn't been eagerly accepted and implemented. And I think that this is clearly the case now. And if we stop doing advanced research on clocks, we're headed for trouble.