COMMON TIME REFERENCE TECHNOLOGY FOR SYSTEMS INTER-OPERABILITY

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Abstract

The Global Positioning System has become the primary and most accurate means of disseminating time and frequency information. A growing and diverse mix of military positioning, communication, sensor, and data processing systems are using precise time and frequency from GPS. The precise accuracies required for their operation are also becoming more stringent. A new system architecture for providing a Common Time Reference to the operating forces and their related subsystems is being developed. This architecture is to provide a robust enhancement to implementations of GPS time and frequency subsystems. Through its implementation, inter-operability between systems is enabled by providing a Common Time Reference and the means for systems to operate synchronously as a foundation for common interfaces and data exchange.

The Common Time Reference approach and its relationship to present GPS time and frequency usage will be described to show the concept and approach of this architecture. A robust architecture utilizing distributed time standards and existing standards within individual systems is to provide new capabilities for existing fielded systems without the impact of requiring major retrofit. This combination of enabling existing and new resources to be utilized in a common reference will reduce the sensitivity to GPS anomalies and lack of continuous contact for precise updating. These systems would then be interconnected at the fundamental level of internal time and frequency generation, which would provide an inherent basis for functional inter-operability. The elements necessary for implementation of this architecture with generic systems will be discussed. Technical developments necessary for implementation of the concept and the impact on inter-operability will be discussed.

INTRODUCTION

The Global Positioning System (GPS) has become the primary dissemination system for Precise Time and Frequency (PT&F) for inter-operability of Naval and Department of Defense (DoD) systems. The move toward joint, diverse inter-operating systems that can gather raw data, process, communicate, and place weapons on target through a continuous stream of information moving from sensors to weapons carriers requires a level of synchronization not possible before GPS. This flow of information requires mobile platforms in the field, oceans, and sky to receive, maintain, and distribute PT&F data previously only available at major timing centers. Consequently, PT&F precision and accuracy are emerging in the utility to disseminate the reference time scale and maintain it throughout the operating forces. This utility and increasing dependence on GPS supplied PT&F is complicated by the vulnerability of GPS to electronic countermeasures.

The consideration of the vulnerability of GPS and its interaction with the various systems that use or need this capability has led to the development of a Common Time Reference (CTR)

Technical Architecture using Distributed Time Standards (DTS) to form a complementary capability working with GPS. The many systems using GPS previously often used precise atomic clocks and extensive supporting systems, which are being displaced by GPS timing receivers disciplining an internal oscillator. These receiver oscillators can be of low quality and still output the precise time provided from the spaceborne atomic clocks of the GPS system. As the use of GPS-disciplined, low quality clocks/oscillators increases, so does the dependence upon GPS as the time source. The increased use of GPS has created the demand for a profusion of receivers. To reduce the proliferation of GPS receivers, GPS-derived time signals are being consolidated and signals distributed to satisfy existing and new systems requirements. This situation is placing greater dependence upon continuous GPS contact.

Developments are being investigated to supply increased PT&F capabilities and reduce dependence upon continuous GPS contact by utilizing existing resources and unifying systems and interfaces. By providing the capability to maintain a coordinated local CTR within the operating forces, individual systems may approach the accuracy of that performed at timing centers. This complementary capability would decrease reliance upon GPS as a direct, continuous source of PT&F and provide the infrastructure for synchronizing the systems in the operating forces. A synchronous systems infrastructure requires accurate coordination and interchange of timing information between systems in order to achieve a network-centric environment for future military operations.

NETWORK-CENTRIC WARFARE

A concept for operating diverse military forces in localized theater areas is known as Network-Centric Warfare [1]. This concept relies upon inter-operable systems operating with closely coordinated precision across warfare areas, services, and weapons systems. Illustrated in Figure 1, joint forces in theater area operation require participating elements to inter-operate with

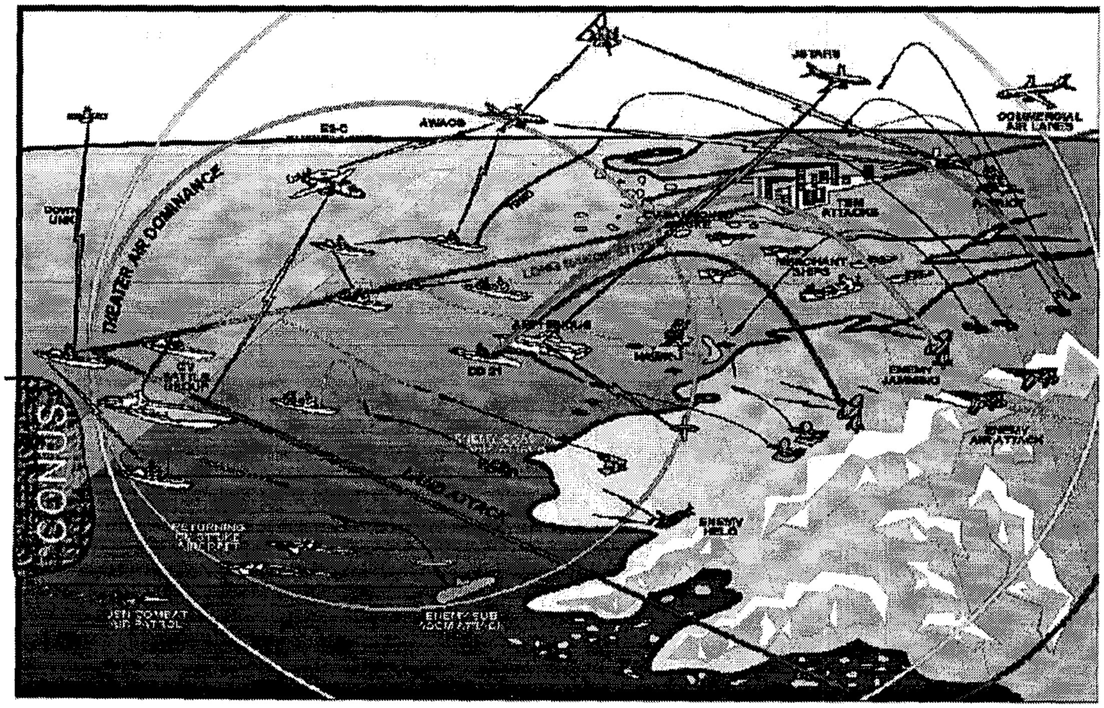


Figure 1. Network-Centric Theater Area Operation

a variety of centrally controlled, cooperative levels of deployment, surveillance, defensive, and offensive roles. Communications and data transfer are central to cooperative inter-operation. An example of this inter-operation is the need to dominate the airspace over the operating theater, which first requires a precise knowledge of everything within that airspace.

THEATER AIR SURVEILLANCE

To provide protection and enable air operations, the theater airspace must be controlled completely and continuously. For this to be possible, the operating forces must detect, identify, and monitor all aircraft within the theater. Data collection and transfer from the various sensors, platforms, and systems must be accurately referenced to common standards. The common positioning reference has become the World Geodetic System 84, now a global universal standard complementary with the International Terrestrial Reference System. The CTR is Universal Coordinated Time as maintained by the U.S. Naval Observatory, UTC (USNO) [2], which is a major contributor to and referenced with International Universal Coordinated Time.

An example of the possible joint surveillance forces in theater airspace is illustrated in Figure 2. In this example, surveillance and tracking functions of the different Naval and Air forces deployed for detecting and tracking hostile air forces or missiles are shown tracking an unknown aircraft. The times of observation by the different units are time-tagged with their local clock. Denoted T_{Ship}, T_{Air}, T_{E2}, and T_{Awacs}, the times of the radar or sensor measurement are measured and relayed to the ship in the case of the Naval Task Group.

These data are then processed onboard the ship for ship defense and formulating tactical response, as well as being relayed to the Theater Command and Control Center for inclusion in the overall surveillance picture. The data collected by the forces in the area would then be merged and processed to form a common picture. The common picture formed at the command center with these data from joint and coalition forces would need to be redistributed or identical to the ones formed by contributing task groups. Each step in this process may require updating the time-tagged measurements or processed results.

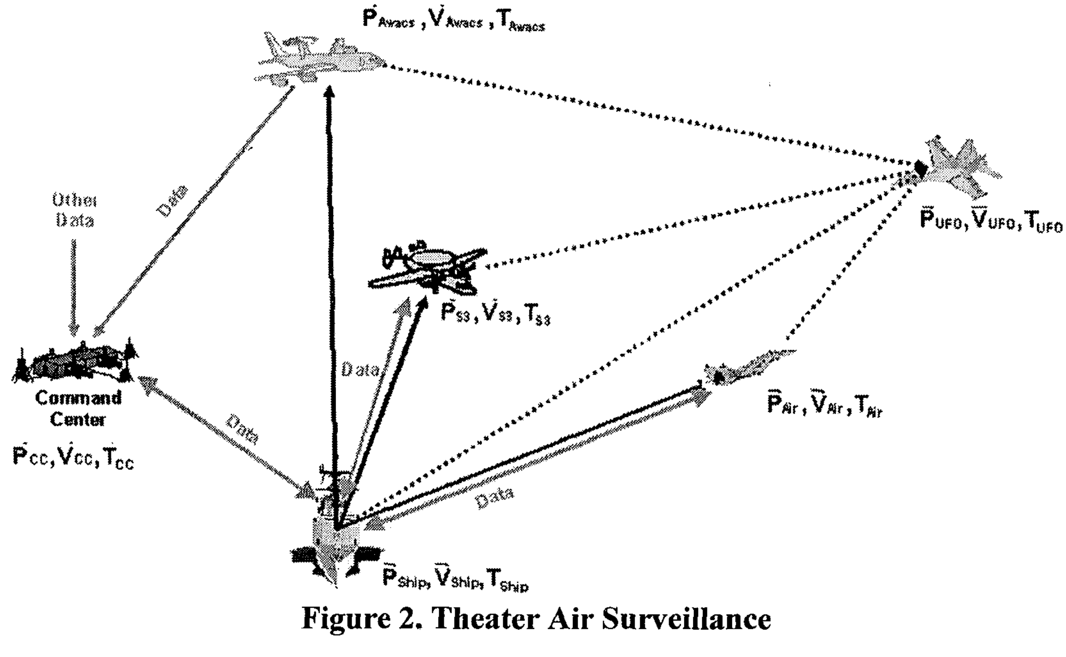


Figure 2. Theater Air Surveillance

So it can be seen in this operation, time has multiple influences from determining the time tags themselves to timing the transmission of the data messages through the various links. Processing of data is also dependent on the time and frequency capabilities of the various systems, which may be configured to be independent of the primary data being transferred. The integrity and accuracy of the time-tagged data passing through these systems is then a function of the systems infrastructure supporting its processing or transmission. The systems' infrastructure must then be configured for accurate synchronization that can be maintained, both internally and externally, to provide the accurate inter-operability necessary.

Timing in these surveillance units is generated from their local clock. How these clocks are used varies with the specific application, but they can be represented by the time maintained by the unit's local clock for sensor data. A simulated comparison of the different unit's local clocks compared to a common time is shown in Figure 3.

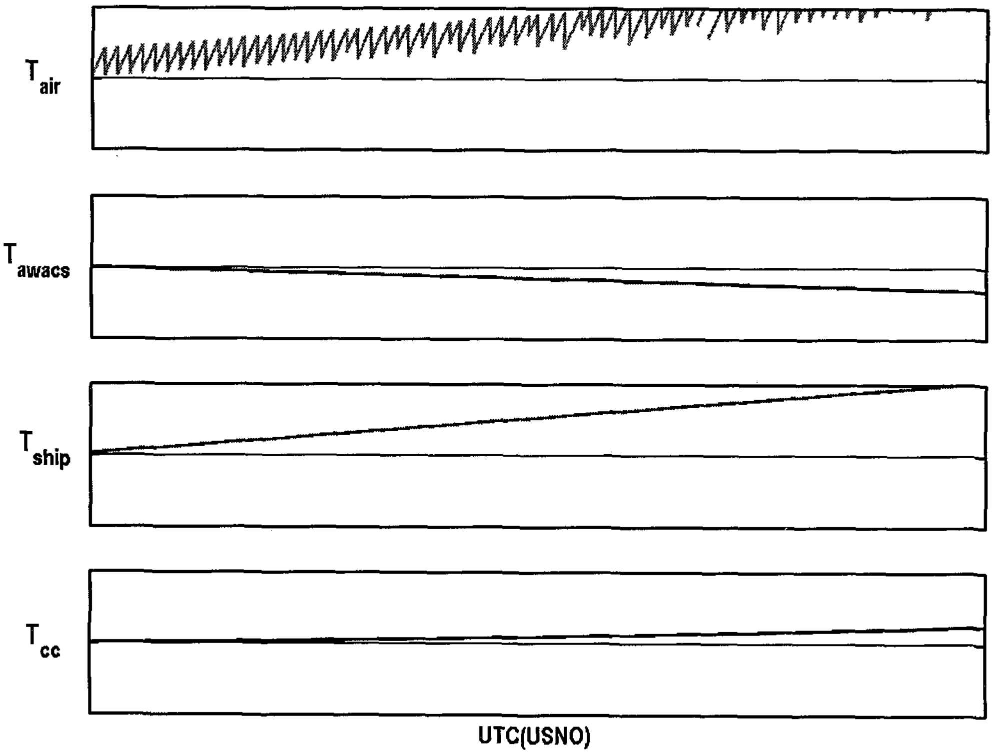


Figure 3. Unit Time Tag References

Each unit's time is represented by the clock Equation [3],

$$T(t) = T_0 + Rt + \frac{A}{2}t^2 + \int_0^t E(t)dt + t\sigma(t)$$

T_0 is the initial time setting,
R is the frequency or rate of time accumulation between time settings,
A is the frequency drift or aging.

These terms constitute the basic systematic performance of the clocks that may be modeled and monitored by each system to maintain synchronization. The last two terms represent those performance parameters more difficult to control. Environmental effects, denoted as $\int_0^t E(t)dt$, will integrate over operating time and environmental changes. Most notable among those effects are temperature effects. The preponderance of clocks throughout the systems are quartz oscillators of different qualities that are specified for their environments. However, the oscillator's performance within those limits or compensation for cumulative environmental effects are typically not monitored or accurately known in operation. The random noise component of performance, $t \cdot \sigma(t)$, determines the precision and ultimate accuracy possible with the specific clock involved with all other effects removed or compensated. The noise component is described as the product of the frequency stability, estimated by the Allan deviation and elapsed time from initialization or update [4].

The final performance of each system's timekeeping is then determined by the clocks used and methods to maintain them in synchronization. A variety of applications and techniques for maintaining synchronization within each system's overall design is used. The implications of this variety of techniques and methods are discussed in the following sections.

TIME UTILIZATION WITHIN SYSTEMS

Most DoD systems deployed in operational use today were designed 10 to 20 years ago. In designing these systems and determining PT&F requirements, the ability to maintain clocks remotely on board ships, for example, was very difficult. The precise means of time dissemination that were available had limited coverage and capabilities. Consequently, most systems were designed around local synchronization and relative operation that they would be independent of external inputs. Systems so designed would perform very well under independent, stand-alone conditions. Absolute common time was necessary for coordinating worldwide operation, but its accuracy did not impact operation of these relative systems. Therefore, absolute time was not viewed as a major operational issue and consequently not a system's requirement. The relationship in today's interactive systems has changed significantly.

Relative Networks

Relative time systems operate over a local area with a local network master time. Clocks and oscillators used in these networks needed precision in making time interval (frequency) measurements and relative time synchronization. Short periods of free-running performance are used between resynchronization with other local system elements [5]. Long-term free-running performance is necessary between widely dispersed strategic or worldwide systems, such as secure communications systems. For tactical systems within a theater of operations, quartz crystal oscillators, such as Temperature Compensated Crystal Oscillators (TCXOs) and more stable Ovenized Crystal Oscillators (OCXOs), are quite capable under these conditions [6]. Use in a relative tactical communication system is illustrated in Figure 4.

The Net Master controls system synchronization and participation of the user aircraft in the net. User clocks are set in synchronization by special acquisition preambles for net entry monitored in normal system operation and periodically updated through special communication signals. These updates would typically update the initial time difference of the clock in the user terminal, T_0, and therefore maintain it within the system signal tracking and reception limits. This update technique is simulated in the data plotted in Figure 5. Changing the time offset introduces time steps small enough so that they do not seriously affect system operation and the integrity of the timing information. Consequently, if the Net Master Clock were compared to UTC (USNO), as in the bottom plot of Figure 5, it could be of almost any offset value and rate; the relative net would still work perfectly.

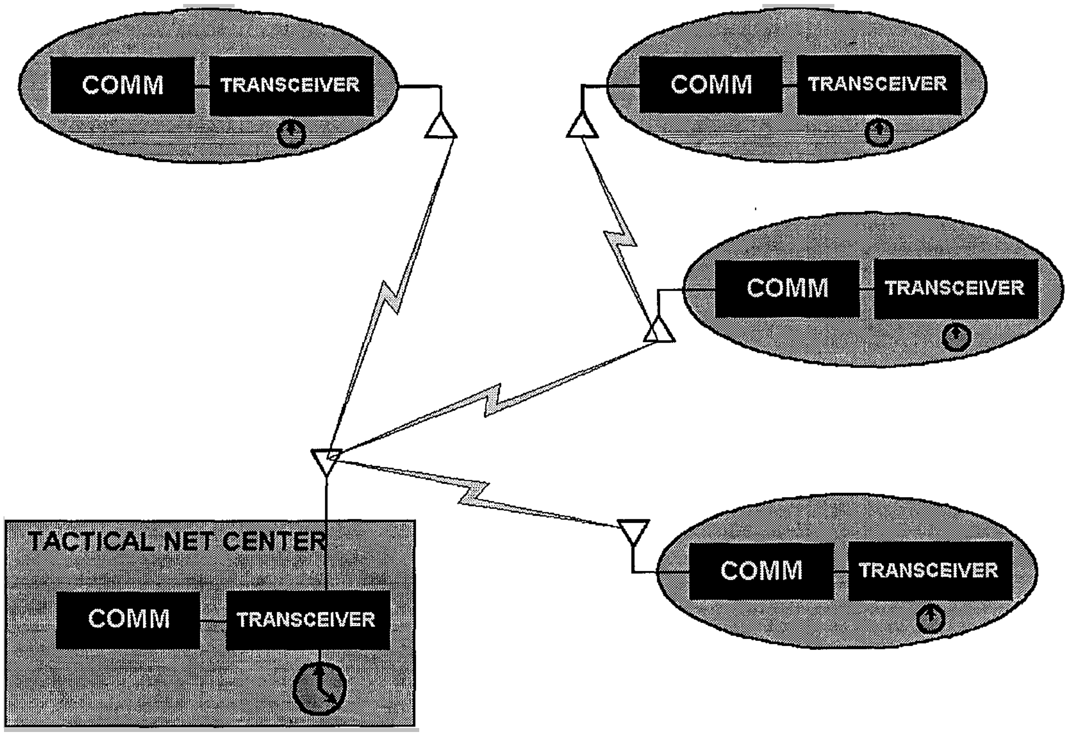
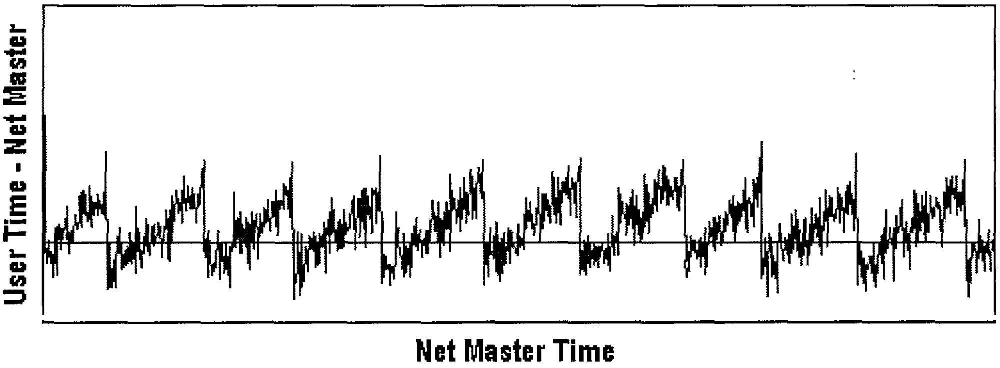


Figure 4, Tactical Communications Network



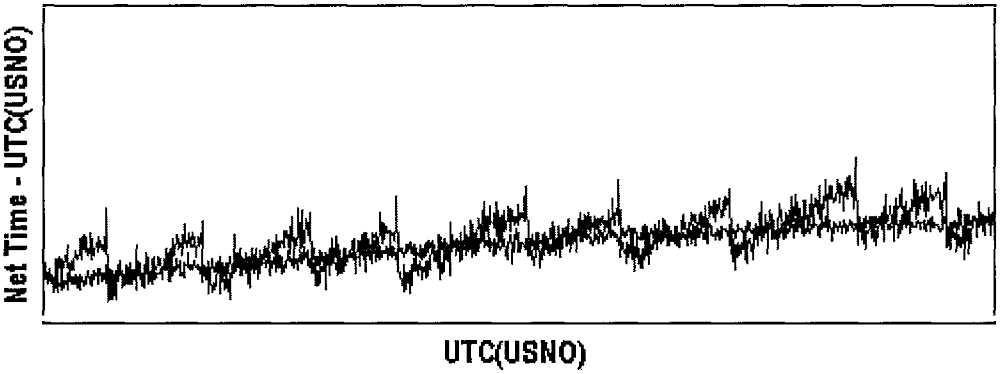


Figure 5. Network User Time Updates to Net Master

Referencing a relative net time to a remote absolute time scale has been quite difficult and inaccurate in the past. It is also unnecessary for independent operation. In today's environment of supporting joint operations, such as a common air picture with other systems or multiple relative networks, synchronization for data correlation becomes significant.

Clock synchronization within these relative networks was based on a hierarchy of accurate clocks. Clocks are configured in a hierarchy within the system design, from the most accurate to the least accurate. This system configuration arranges the more precise and accurate ones to update the lesser ones in a fixed arrangement to keep them all in synchronization. Performance accuracy is implicit within the hierarchy. Global absolute time dissemination systems were similarly arranged. For telecommunication networks in continuous operation, the fixed hierarchy is known as stratum levels [7]. Stratum 1 was the most accurate and stable of clocks, typically a cesium-beam standard. It would then maintain or update Stratum 2 level clocks, and so forth. This arrangement was economical, since the better clocks were also the most expensive. The interfaces and connecting links between clocks in these hierarchies were also configured to maintain the accuracy and precision of updating clocks down in the hierarchy. With multiple systems operating interactively, a hierarchy is almost impossible to configure or maintain. A new approach to synchronization to a common global standard is required.

Absolute Common Time

Absolute common time for DoD systems is the time scale known as Coordinated Universal Time (UTC) as maintained by the U.S. Naval Observatory, designated UTC (USNO). Use of a UTC time scale presents some problems for the military user, in that it is not uniform. Leap seconds are introduced to keep UTC within 0.9 seconds of solar time corrected for nonuniform earth rotation, the UT1 time scale, which is needed for celestial navigation and inertial systems [8]. A problem has been the distribution of leap second information to the military user, so the time step may be introduced at the proper moment. GPS does provide leap second information within this navigation message, so that GPS receivers may compensate for this change automatically. This provides a means of distributing the occurrence and direction (+ or -) of the leap second. Another, more significant problem has been the ability of existing systems to accept or correct for leap seconds. Most of these legacy systems must be manually reset or corrected. This manual entry problem is still a significant issue on the use of UTC as a common time within the existing systems infrastructure.

For allied or coalition military operations, such as NATO, an absolute common time references designation has been partially addressed in that NATO common time is required to be UTC [9]. This designation usually indicates the final international resolved UTC time scale, which is a postprocessed scale after collecting considerable data internationally and computing an accurate, stable, long-term reference. However, for military purposes, real-time coordination and operations requires a real-time physical clock as a reference. UTC sources differ in accuracy and availability from nation to nation. Consequently, a common time reference for NATO and Allied operations will be resolved for those operations.

Multiple User Systems

As systems were required to be more interactive and operate as part of a larger system or group of systems, the implementation of clocks and required synchronization within these systems becomes more difficult to clearly define. A generic ship and aircraft system is shown in Figure 6. The clock symbols show some of the clocks contained in these systems, since virtually all electronic systems contain clocks and oscillators. The overall system time requirements depend not only on the clocks used, but also on how they are used. Clocks control the time of the system elements, but the manner in which they are applied controls the timing of the system.

Within the same platform, systems are still predominately organized as relative, self-contained systems. A radar system and weapons system employs its own internal time for operation. Moving data processed with one internal time to another determines the relations between the clocks and sets the timing paths. "Timing" is then more accurately defined as the ability of information to move through the systems. Limits on timing of the multiple systems to pass information are determined by instrument delays, uncalibrated transmission delays (latencies) between units, the interfaces between the systems, and information processing delays. The interaction of these elements, which would seem to play a minor role in system operation, has major effects in overall inter-operability.

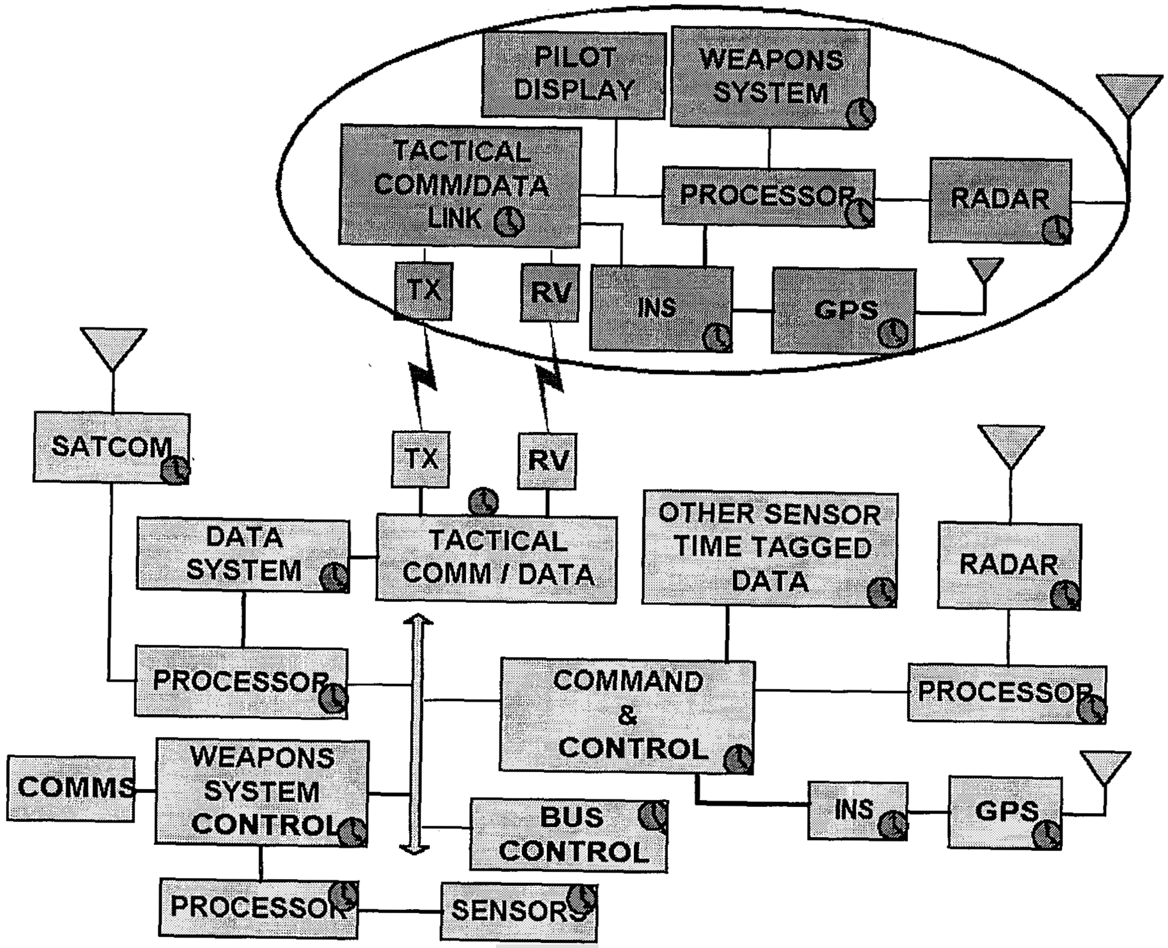


Figure 6. Generic Ship and Aircraft Systems

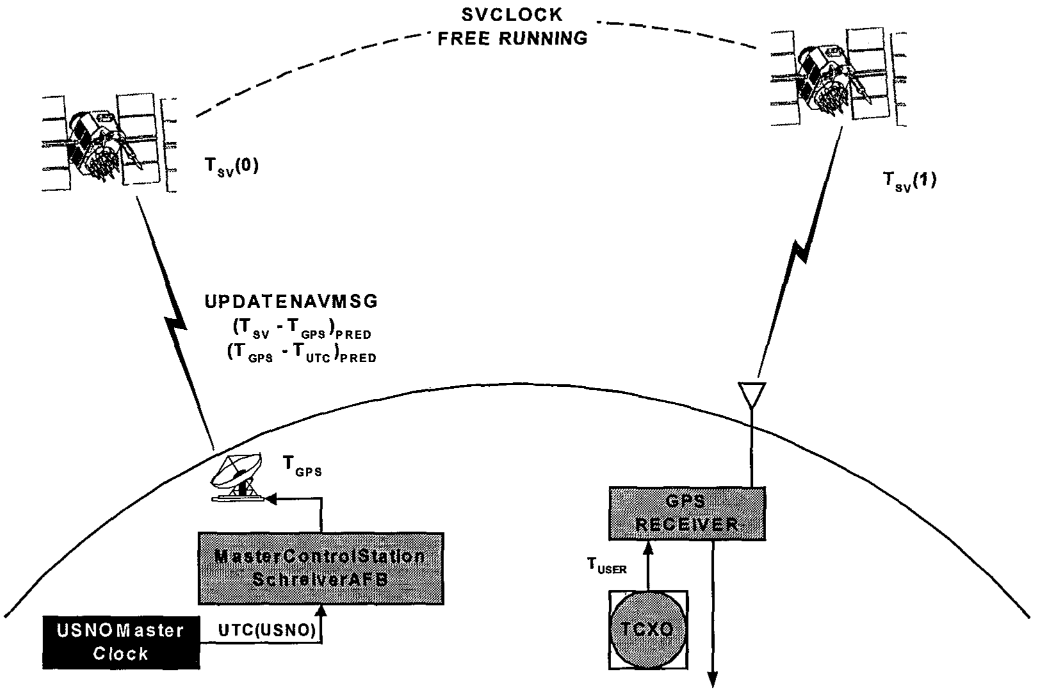
Given the profusion of the clock applications and time utilization within systems compounded by interaction with other systems, it is not surprising that timing requirements are difficult to define and specify. System level timing dependency and usage has been categorized to attempt to clarify the application within a specific system. These categories and limitations bearing on the time accuracy or precision needed in the category are as follows:

1. Positional Reference Time: Time tagging observations of platform positions or sensor measurements relating to positional information. The velocities and dynamics of the particular vehicle's motion determine the associated accuracies and precision limits and requirements.

2. Time Interval (Δt): Measurements of Δt for RF or optical measurements to determine range between objects or distance based on time of propagation of the signal at the speed of light. The associated accuracies and precision required are more stringent.
3. Communication Signal Synchronization: Data transfer links ranging from the local systems to synchronizing systems over global distances require both measurement of intervals and longer-term synchronization to maintain signal lock. Acquisition and demodulation of signal waveforms, bandwidths involved, modulation rates, and types determine time and timing requirements. The dynamics of these systems are limits relative to the speed of light.
4. Data Processing: Calculation of information and transmission through processing nodes and networks require timing and clocks. Processing delays for the calculations to take place dominate timing limits. Even asynchronous data transfer needs timing and set limits.

GPS TIME DISSEMINATION

GPS provides the primary worldwide, highly accurate capability for time dissemination to diverse remote units of the DoD. Different techniques for time dissemination are used within the scientific and timekeeping community, such as common-view time transfer that can intercompare clocks over intercontinental distances with nanosecond precision [10]. The DoD user relies primarily upon passive time dissemination as a product of positioning and navigation, as illustrated in Figure 7.



$$T_{GPS} = T_{USER} + d[T_{GPS} - T_{USER}] + CAL_{USER}$$

$$UTC(USNO) = T_{USER} - [T_{SV}(1) + dT_{GPS} + dT_{UTC}]$$

Figure 7. GPS Time Dissemination

This capability is made possible as a result of the highly synchronous nature of "GPS Time" [11]. GPS Time is the basis for accurate GPS measurements. It is continuously generated by the system Kalman filter at 15-min intervals from the constant monitoring of the atomic clocks in the satellites and monitor stations, as a composite, or weighted average of all these highly stable atomic clocks. The offset and rate of GPS Time from UTC (USNO) are determined from the constant monitored by USNO and correction terms included in the NAVSTAR satellite navigation message. The user can then correct GPS Time resulting from his navigation solution to an accurate time in UTC (USNO). To use this accurate time, the implementation of the receiver and instrumentation must be configured to output precise timing signals and data. The distribution system or circuitry being driven by these outputs must also be capable of maintaining the precision. GPS can then provide an accurate reference time to units across an operational theater and synchronize the variety of platforms and systems engaged.

With GPS capability and instrumentation for civilian time applications becoming so inexpensive, small civilian receivers have been integrated into a variety of timing equipment to discipline clocks primarily for telecommunications. These commercial integrated time subsystems can provide atomic clock level performance, so they are being used to replace more expensive clocks and are available off the shelf. Newer telecommunication and data processing equipment for military systems, that now emphasize commercial best practices and off-the-shelf acquisition, sometimes contain these embedded GPS receivers. These embedded civilian receivers then introduce hidden vulnerabilities into military systems. With accurate UTC (USNO) time now generally available to systems worldwide, legacy systems designed around relative time concepts may now utilize an accurate common absolute time and complement a systems-wide synchronized architecture.

CTR TECHNICAL ARCHITECTURE

The general view of the generation, dissemination, and utilization of time in military systems can be as shown in Figure 8. UTC (USNO) is the main element of Absolute CTR that was established as the reference time for use with all U.S. military systems.

The primary time dissemination system in the second element is GPS. By incorporating absolute time as the reference for local and tactical systems, they can then provide alternative time dissemination capability. A new implementation of Two-Way Satellite Time and Frequency Transfer (TWSTFT) has been developed for use with communications satellites [12]. TWSTFT can disseminate time with nanosecond accuracy globally; however, the technique is a point-to-point capability, vice the generally available broadcast capability of GPS. However, TWSTFT and the capability of tactical area relative systems, such as the Joint Tactical Information Distribution System (JTIDS), could be incorporated into an overall CTR architecture to develop an assured ability to synchronize systems to the CTR.

The final major block of the architecture contains the systems and their user infrastructure. The system-user infrastructure shown in Figure 6 can be represented as a distribution of clocks and oscillators.

This representative view, shown in Figure 9, illustrates the complete connection from the absolute reference, GPS, and the system clocks. The connecting links between the clock symbols represent their time comparison relationship, not necessarily data links or system operational data links. As discussed in an earlier section, relative system links may already provide the means to intercompare the clocks. GPS shown in the middle of the diagram represents dissemination of time by connecting directly to the systems. The other represents an embedded GPS receiver.

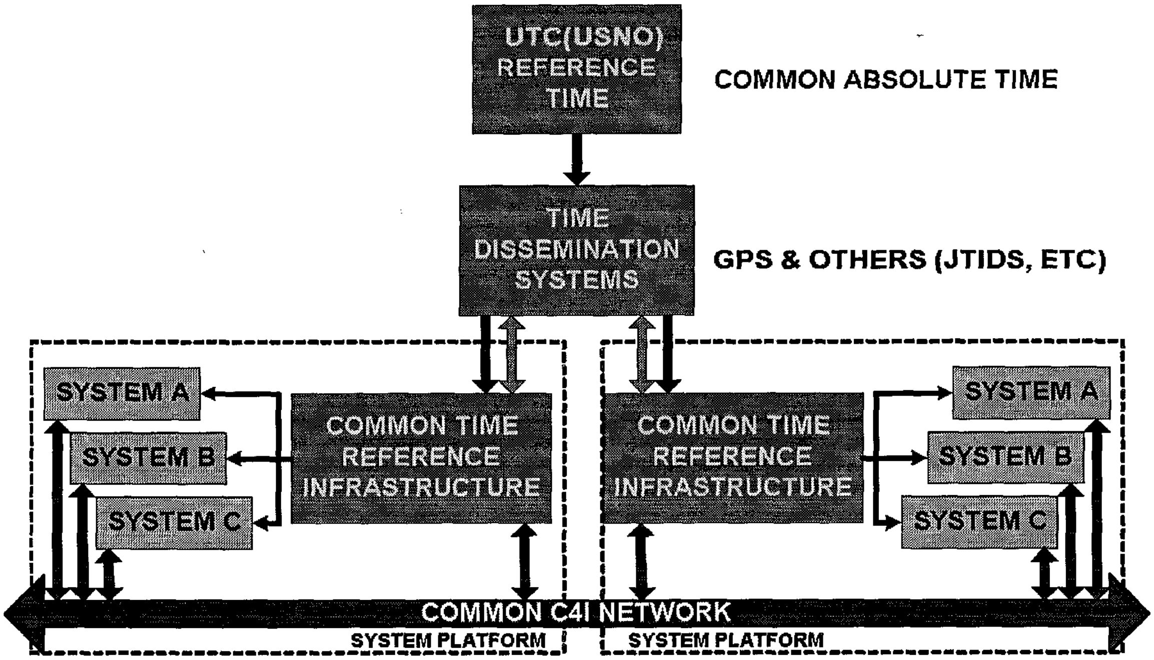


Figure 8. CTR Overall View

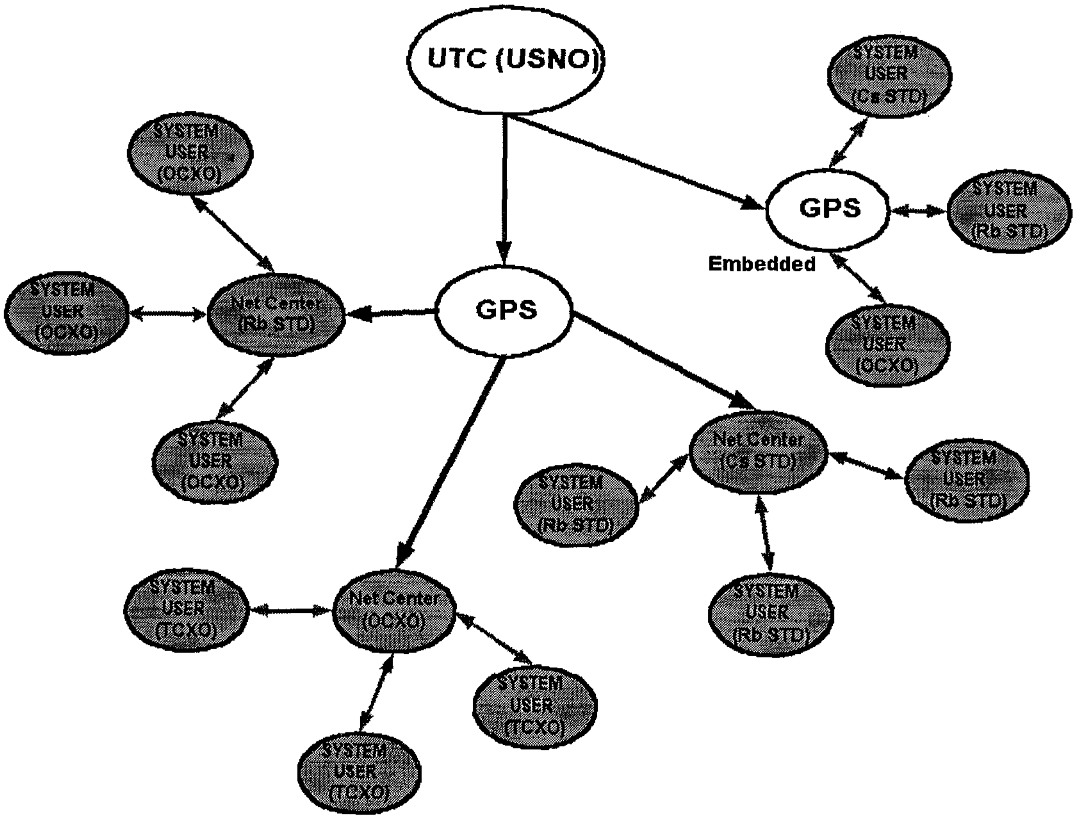


Figure 9. System-User Infrastructure of Clocks

group of clocks would then be combined with comparison, interfacing, and management equipment capable of maintaining an independent local CTR. This local CTR, shown by the markers, would then be maintained in synchronism with the absolute CTR via the time dissemination element. This element could consist of GPS receivers and other means, such as TWSTFT or through a local comparison through JTIDS to Task Group participants. The dissemination systems, including alternatives, would be active participants in the composite time group maintaining time throughout the systems infrastructure and other task group elements.

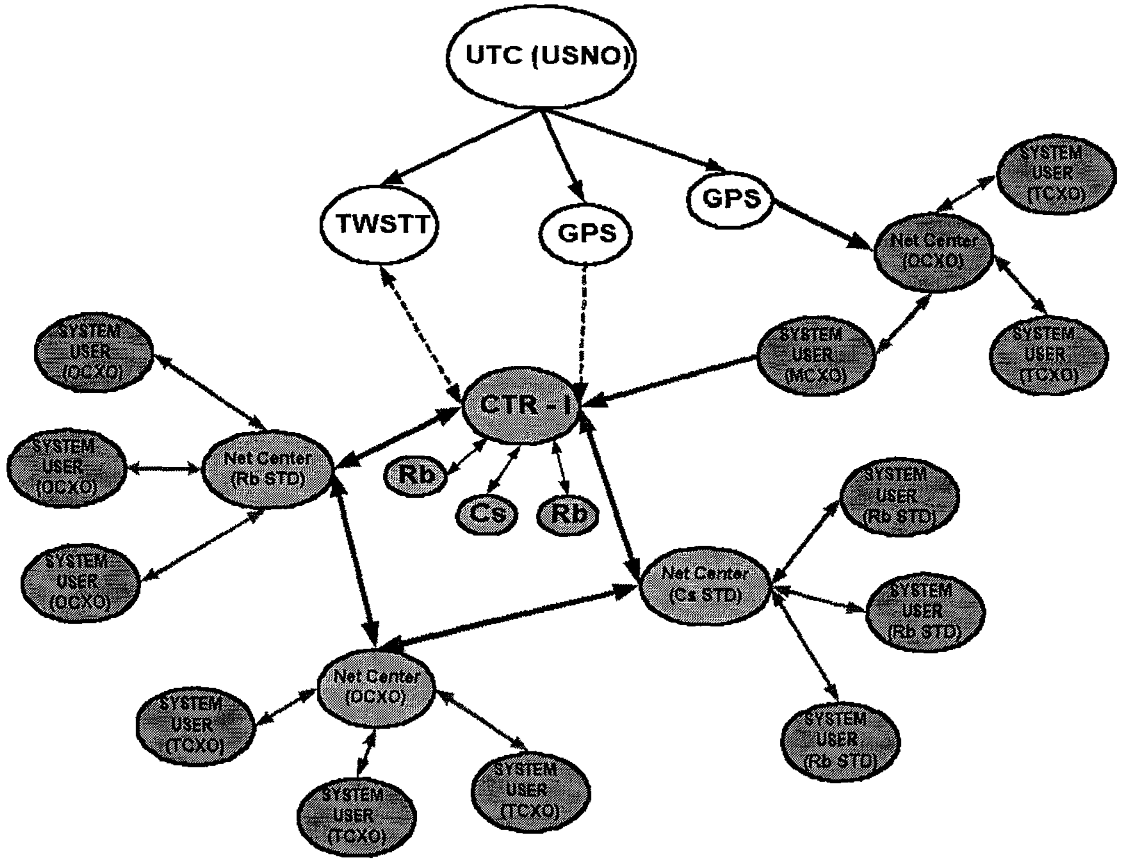


Figure 10. CTR Approach Combining Existing Clocks

CTR TECHNOLOGY ELEMENTS

The CTR functional infrastructure incorporating existing clock assets is shown in Figure 11. This functional diagram shows the elements of the architecture necessary for generation, comparison, maintenance, and distribution of the CTR within the platform and systems.

Central to the CTR infrastructure are the GPS receivers, which have been deployed on most Naval Ships and are being deployed on aircraft, ground forces, weapons, and fixed sites of all services. The preponderance of these receivers is intended for positioning and navigation purposes. Receivers for supporting time are in use, many of which, as discussed earlier, being embedded within system components. Submarines have a dedicated system to distribute time to clocks on board [13], and the Block 3 Upgrade to the Navigation Sensor System Interface onboard combatants includes a time distribution function [14].

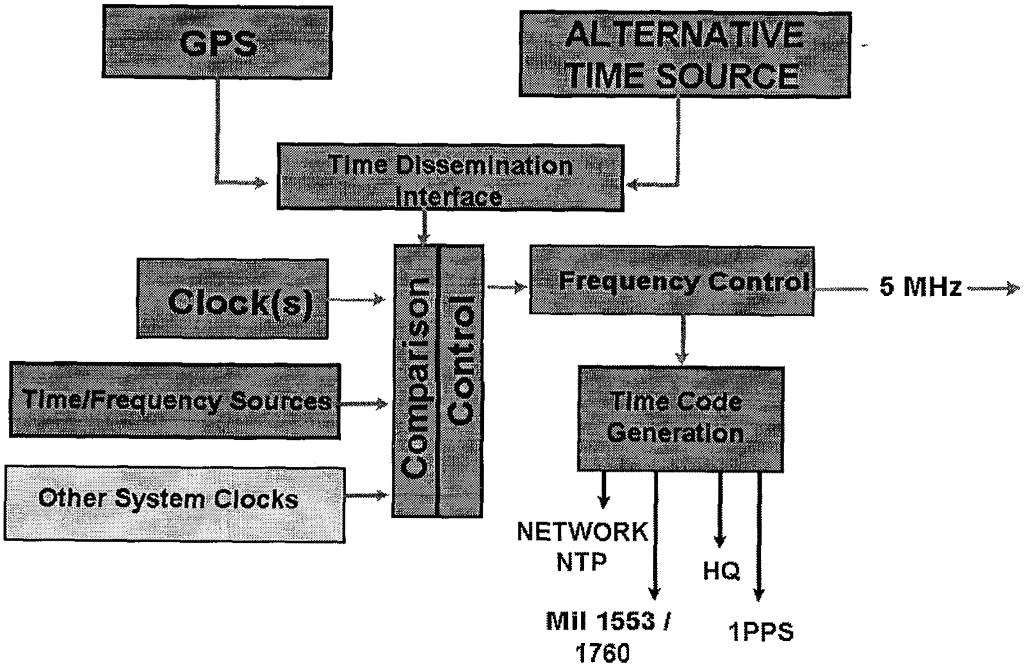


Figure 11. CTR Functional Infrastructure

Most GPS installations reflect time as a product of navigation and modifications currently being investigated are focusing on more deeply integrated navigation systems for increased positioning accuracy or resistance to electronic countermeasures. Time interfaces either rely on the GPS Precise Time and Time Interval Interface GPS-ICD-060 [15], which actually provides three different interfaces made up of older interface standards, or other instrumentation standards. Other GPS Interface Control Documents, such as GPS-ICD-153, address some time interfacing aspects as well, but not as a general capability. Time interfaces developed for instrumentation, such as the IRIG Time interfaces [16], the Mil Std-188-115 [17] and DOD-STD-1399 [18], are used. Most of the military interfaces have been derived from unique systems interfaces devised for relative system operations. These were subsequently adopted by developing systems or to instrument special capabilities that have spread to other applications. A good example is the Havequick interface. JTIDS is another with a unique interface. They are used for point-to-point distribution.

To effectively provide a robust time interface with sufficient performance for the primary dissemination system, GPS, and possible alternatives, consideration of an optimum interface or set of interfaces should be developed. Prior efforts to establish a single standardized interface, such as the STANAG 4430, Precise and Time and Frequency Interface for Military Electronics Systems [19], to replace the multiplicity of interfaces used has meet with very limited success. How successful any new standard would be depends upon the extent the CTR infrastructure would be implemented. Nevertheless, a standardized interface would enable implementation of a synchronous infrastructure and reduce the multiplicity and maintenance of the many legacy interfaces.

Precise Clocks

Precise Clocks are typically the first subject raised in any discussion of PT&F and are a major consideration to for military applications. However, the CTR approach is structured to take advantage of existing precise clocks already distributed throughout military systems. Supplemental clocks resulting from efforts into new technology clocks can play a role in implementing the capability. The actual mix of clocks available on subject platforms may require supplement to form an accurate composite time group sufficient to met the needs of the systems they serve. New technology efforts may supply this supplement, though they are mainly focused on increased capability for very difficult problem areas in maintaining time, such as small field radios, handheld units, and those for weapons [20].

A consideration in the use of new clock technology is the general decline in the availability of high performance or unique clocks and oscillators. The telecommunication market has created a large demand for low cost and, often, lower quality oscillators. Accuracy is provided by inexpensive GPS receivers in higher performance applications. Consequently, development of precise clocks both crystal-driven and atomic is being conducted by service R&D agencies. Small rubidium clocks, of lesser performance than previously generally available units, are also being utilized in the telecommunications market. For larger platforms, these small rubidium units may be a viable supplementary capability for some uses.

Intercomparison Subsystems

The key component technology that the CTR infrastructure requires is the ability to intercompare the clocks within and between the systems. Unless the actual clock performance can be measured in situ, the ability to maintain a synchronous infrastructure accurate to a CTR will be very difficult to achieve. Combining clocks to a common composite time maintained closely to the absolute CTR will require specific continuous knowledge of the participating clock performances.

Measuring actual clock performance in the environment it has to operate in, will determine the clock performance effects of clock sensitivities [21,22] and the subsequent effect on the system. From the clock equation introduced earlier, the environmental induced error,

$$\int_0^t E(t)dt + t\sigma(t)$$

integrates over the duration of the environmental changes and is a function of many different factors. The most significant environmental factors are temperature, vibration, and variable magnetic fields [23]. These factors can have significant effects on quartz crystal oscillators. Actual performance between similar clocks can also have variable values of frequency offset, R, and frequency aging, A, terms. These effects are within what would be considered normal operating limits and not abnormal. Complete clock failure resulting in loss of signal is not as common as abnormal jumps in frequency, phase, or aging terms, leading to anomalous performance. This anomalous behavior is difficult to identify without actual measurements and can have serious performance results. The more deterministic terms of clock performance having been established, the random noise component, characteristic of the clock establishes its basic behavior. This term is expressed in the time domain as the square root of the Allan variance, or Allan deviation, and is shown in Figure 12 for the major different clock types. This component determines the ultimate stability of the clock signal and the ability to determine and predict performance. This term may change over the life of the unit, reflects environmental effects, and varies between similar units, even the same type unit manufactured by the same manufacturer. Characterization of the clocks in under operating conditions is key to management of synchronization and is, in turn, highly dependent on the ability to compare clocks.

Whatever intercomparison technique is used [4,24,25], they can serve other possible uses. Automated precision comparison techniques can be used to monitor calibration of both clocks and distribution systems. They may also identify degrading performance and establish an accurate perturbation free means of switching clocks. The most significant use is to establish a basis for forming a composite time from the participating clocks.

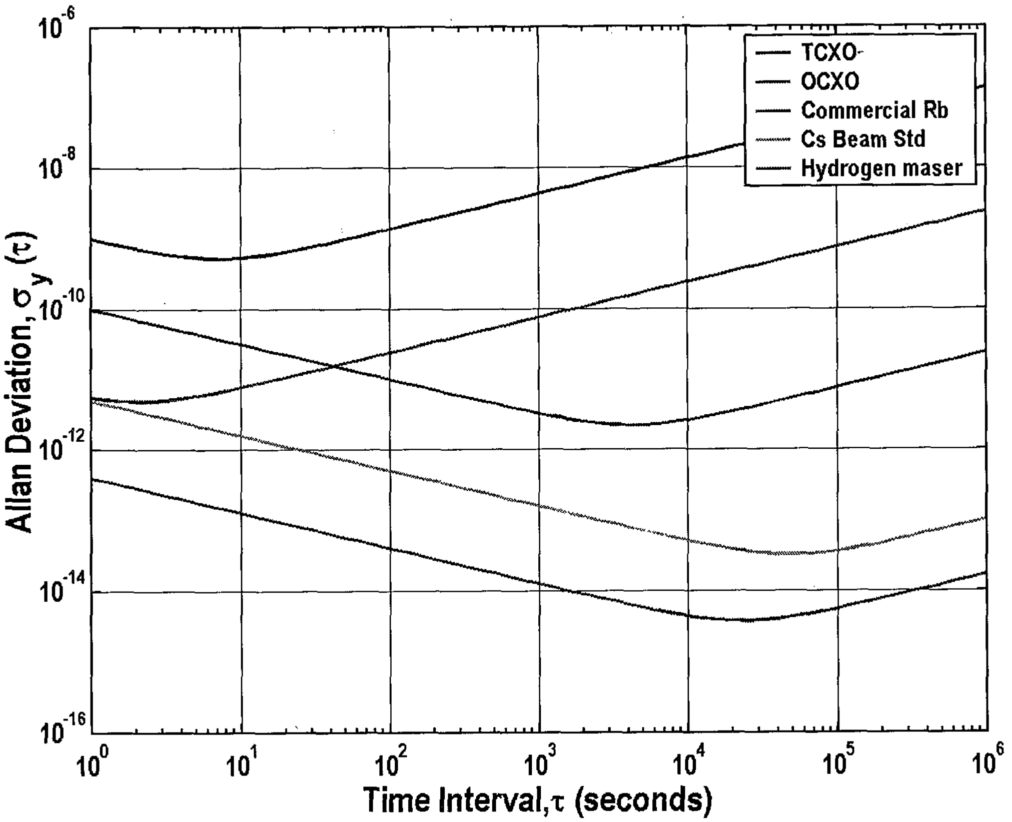


Figure 12. Allan Deviation of the Major Clock Types

Distribution Media

Connecting the CTR infrastructure within the systems will require distribution systems and different media. Implementation of signal distribution along with the need to provide clock signals for intercomparison could result in an overly complex and expensive distribution system for large platforms. Specific implementation of this architecture within the existing systems will need to be tailored to the specific unit.

The technique for distribution consists of various types of cabling and communications media [26]. Calibration of the media and interconnections will be a significant implementation issue. Calibration of fixed media, such as dedicated cabling, will not be as significant a problem as digital data and computer networks, which could be especially difficult. These networks are basically asynchronous, involving processing delays and network switching that can be unpredictable. Techniques for time comparison and synchronization with these networks have been developed, such as the Network Time Protocol (NTP), to provide a means of synchronizing computers through IP networks [27]. Within the limits of the network, NTP can maintain time within computer systems synchronized to millisecond levels. SONET systems offer the potential of providing a synchronous means of more accurate time distribution over digital networks [28].

Distribution media that present unique problems are Electronic Transfer Devices. These devices can be categorized with handheld radios and GPS receivers as far as the technical problems involved. Used for updating avionics prior to takeoff and physical transfer of data between equipment, the ability to maintain accurate time over the intervals necessary is highly dependent on the internal oscillators. Interfacing them into the CTR infrastructure is another consideration that must be addressed.

Composite Time Generation

The formation of a composite time from the existing system clocks will be possible with continuous precision comparisons. The resulting performance of the composite time would be dependent upon the actual clocks involved. Composite time is a form of a "Clock Ensemble" [4,29]. Clock Ensembles are used to generate time scales in major timing centers, such as USNO, to establish the most accurate time scale possible. This technique involves comparing the output of a large number of identical clocks of known characteristics and applying an ensembling algorithm to form a stable, predictable time more stable than the individual clocks. Similarities of the clocks are used to model and tune their operation, and the final determining factor is the number of clocks for stability improvement. For CTR composite time [30], the number and similarity of units to be used cannot be assured within the system clocks available. Consequently, ensembling for increased performance is not a specific objective, but would take advantage of the other major benefit of ensembling, which is to be insensitive to clock failure. This benefit will increase the overall reliability of the timing system. Forming a mean time that is necessary for synchronization could be adapted to a group composite.

The random noise characteristics of the major clock types that affect establishing a mean composite time are shown in Figure 12. Ensembling the specific clocks shown in Figure 12 would result in one or another clock dominating performance at different ranges of averaging times. The approach to forming a composite from a mixed clock group would be dependent upon specific algorithm to be applied, the physical interconnection and establishing local clocks for comparison reference, and maintenance of the resulting composite. An approach is diagrammed in Figure 13. This diagram shows a core group of clocks associated with CTR control and management. These core clocks would provide the reference for intercomparison, maintaining the mean time, and generating a physical signal representing the mean time, if necessary.

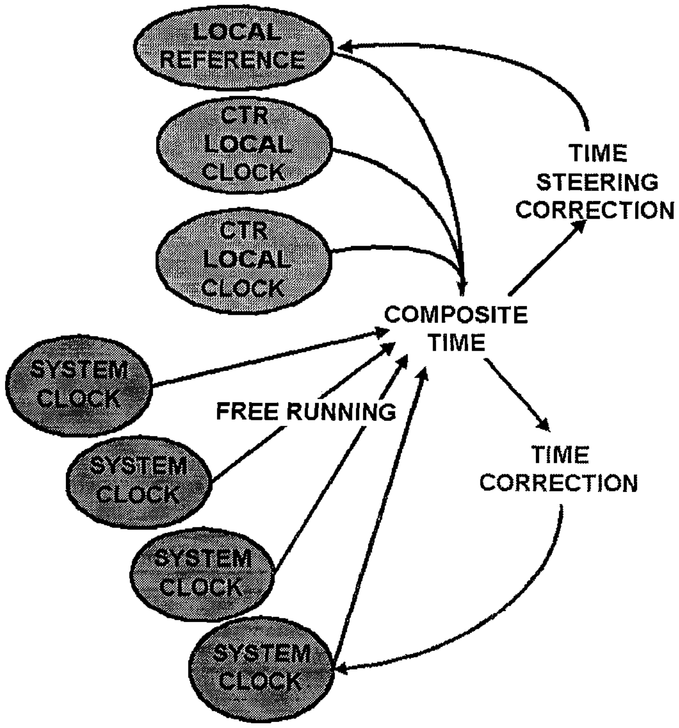


Figure 13. Composite Time Generation Approach

The actual composite time could be kept in the form of a "Paper Clock." In this case, there isn't an actual physical signal generated, but only correction terms to be applied to other clock signals to bring them onto a common time. Examples of this type of Paper Clock operation are the international UTC time scale and GPS Time. In both of these cases, a physical signal is not derived in the process of determining the time scale, as in the case of UTC, and for GPS the Master Control Station produces corrections that are applied with the free-running clocks in the system's satellites. However, these cases also result in large numbers of time users generating physical signals synchronized to the Paper Clock time. Generation of an actual physical signal, as is necessary for some communication systems, could then require a physical distribution system to provide this signal to the user systems.

TESTBED DEVELOPMENT

To investigate and determine the technologies necessary for CTR implementation, a Technology Demonstration Testbed (TDT) is being developed. This Testbed will be configured in the Laboratory to simulate with hardware and software the implementation necess ary for the generic platform's infrastructure. The various technology areas discussed above will be analytically and experimentally investigated for demonstration with the TDT. The elements of this TDT will be used to design and develop a prototype installation for actual field-testing in follow-on efforts.

Requirements Definition

To determine the utility of this concept, the compilation and more detailed knowledge of the various systems timing needs and requirements are necessary. The systems needs and requirements must be better defined and clarified, since system's designers have built their systems on old basic assumptions about time and frequency availability and usage. These requirements are difficult to obtain and limited sets have been generated. A more comprehensive database is being collected throughout this effort. An approach to clarifying these requirements is to specifically test the existing systems capabilities in time generation and maintenance.

Legacy System Testing

A number of efforts are underway to develop inter-operable systems and alternatives to GPS, such as the JTIDS/GPS integration effort to ensure the compatibility of these two systems to support GPS acquisition. Coordination with these other efforts could take the form of participation in related testing. For example, the Ballistic Missile Defense Office is sponsoring calibrated testing of JTIDS implementation with the Aegis weapons system for missile detection and tracking. Part of that test could be used to determine time-transfer capability of the integrated system. If the test is configured for appropriate timing measurements, coordination and analysis of that test could provide data on time and its performance in these systems. Coordination of these testing efforts can provide extremely valuable data on system timing performance and common needs. Other spcific tests are also being planned.

Laboratory Demonstration Testbed

From the concept of distributed time standards, and the results of identifying of timing requirements combined with data collected from system testing efforts, a Technology Demonstration Testbed (TDT) is being configured. This TDT will simulate, with hardware and software in the Laboratory, the implementation of a common time reference infrastructure in generic platforms. The various technology areas discussed above will be analytically and experimentally investigated for demonstration with the TDT. The elements of this TDT will be validated to the point that the results could be used to design and develop a prototype installation for actual field-testing.

SUMMARY

GPS has had a major impact on the capability to determine position and navigate military platforms and systems. The impact of providing Time is just beginning to be recognized and may have an even more significant extension of military capability and operations. To take advantage of having precise time and synchronization of remote and dispersed forces with an absolute common reference, a systems infrastructure incorporating legacy systems is being developed. This infrastructure "System of Systems" approach can incorporate the old with the new. The resulting military capability will achieve inter-operability at the most basic level, Time.

The challenges to effecting a Systems approach to a CTR are more than just technical. Since they cross system and program boundaries, implementation will be programmatically difficult. To establish benefits and effectiveness, new methods for demonstration and test under operational conditions will be necessary.

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Questions and Answers

THOMAS CLARK (NASA Goddard Space Flight Center): Both what you and Chris [Gregerson] have said has been very interesting. If we compare them with the material that was presented last night at our after-soup talk, I counted up the fact that the train systems, where the common time reference and time dissemination ended up evolving to the conductors on the trains, accounted for 45 losses of life in the 1800s. You cited the Scud missile accounting for 28, so these things are real problems and they are not new.

It strikes me that while the DoD may be taking the lead on this that the problem is not unique to the DoD. Those of you who fly out today, the time reference on the commercial airliner that you fly out on will be the dash clock that the pilot has, which he sets from his wristwatch. There is no time code written on to the flight data recorders, so the reconstruction of problems like Alaska 262 and the event chain to even do any diagnostic is rendered much more difficult by the lack of any precise time available on the aircraft. That need for precise time in the civilian airline community also extends to things like ground control. When your plane is taxiing today, since the time reference exists only in the pilot's mind for the aircraft, that is not in any way conveyed to the ground control system at the airport. It has very little correlation with the time system that used by the navigators back on the ground that are telling the airplane where to go.

That's just one example. I wonder, in all of your deliberations within DoD, if the need for the same type of study by the civilian community and, in reality, the need for some inter-operability between the military and the DoD is being considered. Because it is not just your problem, it's everyone in the audience's problem when you fly out of Dulles Airport this afternoon. This comment, followed by a question: are you talking to anyone outside of DoD? That's really my question, Ron.

RONALD BEARD: Actually, yes. I think that is a very large consideration in the WAAS system and inter-operability. The military aircraft have to fly to a civilian air station in order to get where they are going, so they need to be inter-operable with them, and the airlines are also very concerned about this inter-operability and that sort of thing. I defer a lot of that to Bill Klepczynski, who is involved in that sort of thing.

WILLIAM KLEPCZYNSKI (Innovative Solutions International): Thank you. There is within the satellite-based augmentation systems a working group called the Inter-operability Working Group. One of the issues that we work on is how do we synchronize the different augmentation systems like EGNOS, WAAS, and MSAS. That issue is being discussed now, and a working plan is being established now. I think on December 12th or so, the EGNOS people are going to be working on it.