Naval Research Laboratory

Washington, DC 20375-5320

NRL/FR/8150--04-10,079

Common Time Reference for Naval Systems

Ronald L. Beard
Joseph D. White

Space Systems Development Department
Naval Center for Space Technology

Edoardo Detoma

Honeywell Technology Solutions, Inc.
Columbia, MD

Patty DuPuis

Telenetics, Inc.
Alexandria, VA

October 12, 2004

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
October 12, 2004

2. REPORT TYPE
Formal

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Common Time Reference for Naval Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Ronald L. Beard, Joseph D. White, Edoardo Detoma,* and Patty DuPuis**

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
81-1356-M4

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/FR/8150--04-10,079

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 North Quincy St.
Arlington, Virginia 22217-5660

10. SPONSOR / MONITOR'S ACRONYM(S)
ONR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
* Honeywell Technology Solutions, Inc., Columbia, MD ** Telenetics, Inc., 804 South Columbus St., Alexandria, VA 22314

14. ABSTRACT

A Common Time Reference (CTR) is a critical factor in the development of new force capabilities, and perhaps the most difficult to achieve without dependence upon GPS. A technical architecture linking the systems on a common reference framework using their existing time and frequency standards was examined as the most effective approach to achieving interoperable systems. To build an inter-systems architecture within the existing system and platform infrastructure will require a fundamental change in adopting interoperable interfaces and more extensive management of the fabric of technical parameters. The foundation of this new architecture can be built upon the existing infrastructure distributed throughout the legacy and developing systems. The means of providing the elements for this architecture and supporting infrastructure is the objective of this report. The interconnection of assets provides the means for synchronization and coherent system operation.

15. SUBJECT TERMS
Common Time Reference (CTR) PTTI Time and Frequency Clocks Network-Centric Warfare

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Ronald Beard
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	UL	66	**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified			202-404-7054

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

CONTENTS

COMMON TIME REFERENCE FOR NAVAL SYSTEMS

INTRODUCTION

Time and frequency have been used throughout the Department of Defense (DOD) systems since the beginning of the electronic age. The ability to synchronize radios, radars, and other such systems on a global scale to very precise and accurate values was not possible until the introduction of the Global Positioning System (GPS). GPS has had a significant impact on military systems. The most noticeable is the introduction of general-purpose precision weaponry on a wide scale. The capability of precisely positioning objects and targets along with precision guidance of inexpensive weapons on a worldwide basis has revolutionized military engagements. GPS is the primary factor in the transition to joint precision systems for navigation and positioning for local and tactical engagements. Less well recognized is its role in providing precise time and frequency (PT&F) data for synchronization and communication. The GPS became the primary dissemination system for PT&F information for interoperability of Naval and DOD systems before it became operational as a navigation system.

The change in precise engagement to smaller forces using GPS guidance and positioning for precise strike, maneuvering, and operation has combined with the upsurge in computer capabilities toward fusing diverse warfighting units and systems into interoperable effective mission area forces. These forces, together with interoperating systems, gather raw data, process, communicate, and place weapons on target through a continuous stream of information moving from sensors to weapons carriers. This capability requires a level of synchronization not possible before GPS. The interoperable flow of information requires mobile platforms in the field and oceans to receive, maintain, and distribute data previously only possible at major land-based, co-located centers. Consequently, this interoperability is enabled by the ability to synchronize and precisely time events, remotely collected data, diverse communication signals, and streams of asynchronous data for processing.

The utility of the omnipresent GPS capability is increasing dependence of more systems to maintaining continuous contact with GPS. The nature of the GPS satellite downlink with its known signal structure and low power places it at extreme risk of being easily and inexpensively denied to our military users. Given the increasing dependency, U.S. forces could be severely jeopardized by the vulnerability of GPS to electronic countermeasures. The Naval Research Advisory Committee (NRAC) concluded after a study was conducted that such was the case, i.e., that our forces were at risk [1]. Among their recommendations was to revitalize Naval research into possible solutions in the areas germane to the vulnerability of GPS to electronic countermeasures.

The consideration of the vulnerability of GPS and its interaction with the various systems that use this capability has led to the need for a Common Time Reference (CTR). A technical architecture linking the systems on a common reference framework using the existing time and frequency standards in these systems and interoperable interfaces could form overall an inherently interoperable force capability. Many systems are already using GPS for PT&F applications so that existing PT&F standards are being displaced by GPS timing receivers that discipline internal oscillators that are in general of lower quality. As the use of GPS-disciplined, lower-quality clocks/oscillators increases, so does the dependence on GPS as the source of time and frequency. To avoid proliferation of GPS receivers, GPS-derived time signals

Manuscript approved July 16, 2003.

are being further distributed to satisfy existing and new requirements. Increased use of GPS for guidance and precise control of weapons systems is placing even greater dependence on GPS and continuous contact with its signals.

A CTR for Navy and Joint systems to establish a common time would require the interconnection of the assets using timing information [2]. The interconnection and synchronization of the various systems would then be the mechanism for a possible solution to denial of GPS that is being used for time or frequency.

OBJECTIVES OF COMMON TIME

For the timing information to be of value, a CTR would need to satisfy each individual system's requirements and would need to know or measure the source of the time being passed between systems and the quality of the time being transferred. To understand requirements associated with a CTR requires an understanding of the generation, maintenance, and types of time in use. These concepts and techniques are so fundamental to the principles and techniques of electronic systems that their use is often misunderstood in systems development. To provide a better understanding of this subject is a primary objective of this report. Their use for the synchronization of these same electronic systems that enables interoperability is the second.

The use of a CTR among Naval ships, aircraft, and systems would involve combining different techniques of precise time and frequency technology. This combination will result in:

1. distributed time and frequency references maintained to the common reference,
2. use of existing means to accurately disseminate/distribute the common reference with augmentation where needed,
3. establishing common interfaces for exchange of timing information between dissimilar systems,
4. incorporating subsystems to measure time and frequency signals precisely for correction of other systems PT&F sources and timekeeping systems, and
5. providing the means of reducing dependence upon GPS as the single systems for time and frequency dissemination.

To augment GPS receiving systems and duplicate their performance even in the short term, the clocks and oscillators used determine performance in the free running mode. This is currently referred to in GPS receiving as "flywheeling" through an outage. The receiver clocks would maintain some performance for a short period but still suffer significant degradation. To ensure GPS enhanced capabilities in any electronic environment, the optimum method for maintaining performance is to use techniques that can be independent or semi-autonomous. A common reference that is independent of required continuous GPS updates can be established by carefully combining all of the timing resources involved. Clock ensembling techniques can synchronize the contributing components and in the process enable them to "keep time" with these same components. The techniques required to provide common time and frequency could significantly increase resistance to GPS outages at the same time.

Interoperability

The increasing need for military forces to be able to share, distribute, and process information has been described as Network-Centric Warfare [3]. This concept calls for Joint and Allied Forces across warfare areas and weapons systems to be capable of seamless communication and information flow and of deploying highly accurate weapons delivered precisely on their designated targets. Joint forces engaged in such a theater of operations are illustrated in Fig. 1. These forces would be able to interoperate on various centrally coordinated levels of movement, surveillance, offensive missions and defensive roles. A CTR would enable these forces to precisely reference synchronization of sensors, communication and accurately time tag data for processing vital information. The data generated and exchanged by the mix of systems and services engaged in the particular military operation could provide a Common Operational Picture (COP) [4]. Figure 2 illustrates the source and types of data.

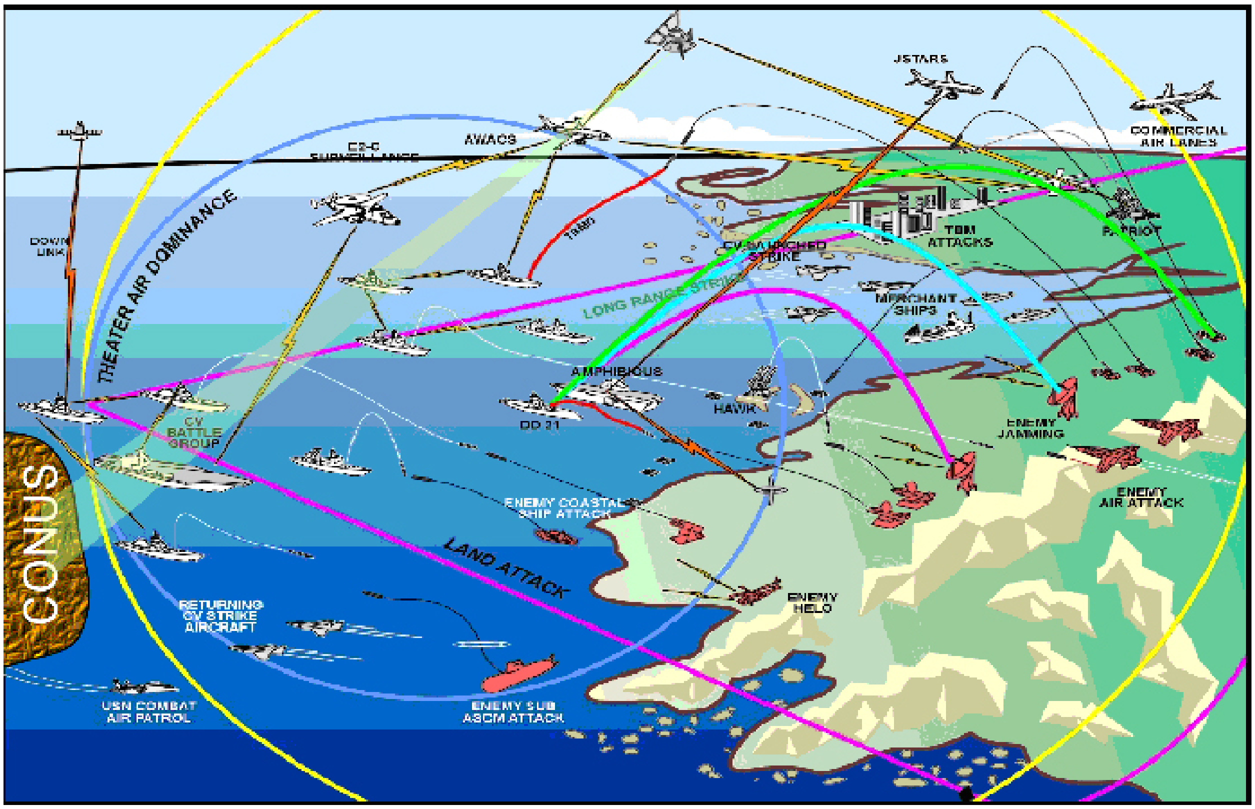

Fig. 1 — Schematic of theater of operations

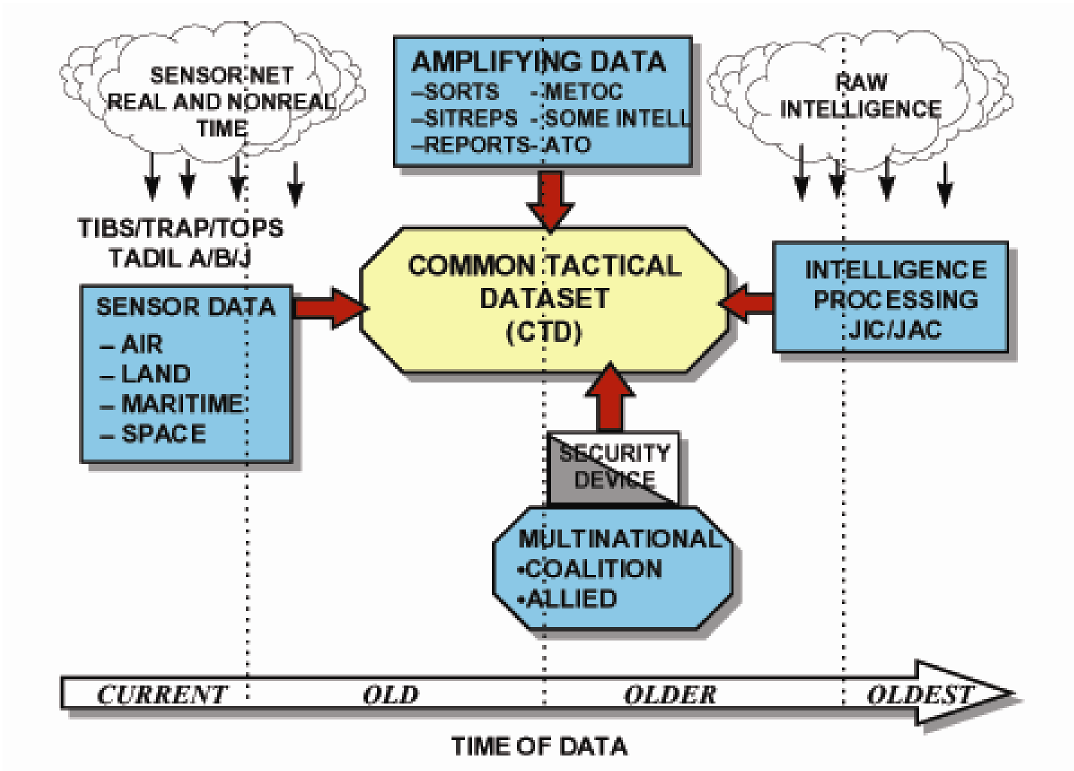

Fig. 2 — Common Operational Dataset from CJCSI 3151.01 10. Jun 97

The time of data arrow at the bottom of Fig. 2 could be interpreted as "real-time." Events occurring in and for the activities illustrated occur in relation to each other represented by the availability of data in the Common Tactical Dataset.

Figure 3 illustrates the interrelation of forces engaged in air defense in a theater of operations. To control the airspace over an operating theater, the ability to detect, identify, monitor, and intercept all aircraft within the airspace must be continuous and accurate. The various radars, platforms, and systems contributing to the surveillance picture need to be interoperable such that sensor data can be collected and transferred in real-time, accurately referenced to common geotemporal coordinates. Shown are surveillance assets of different forces whose data are collected; some units preprocess on board, while others transmit to processing centers or other ships (in the case of a Naval task group). These data are then processed and correlated to associate target tracks locally and relayed again to the Theater Command and Control Center for formulation of an overall theater surveillance picture. The time-of-occurrence of the events in this area are critically important to be accurate and available in a timely manner to the processing centers. The real-time aspect is necessary for the information to be available to the decision-makers in the command centers. The real-time aspect is also used today to overcome reliance on the diverse time references used in these systems and the inherent error between them in asynchronous operation.

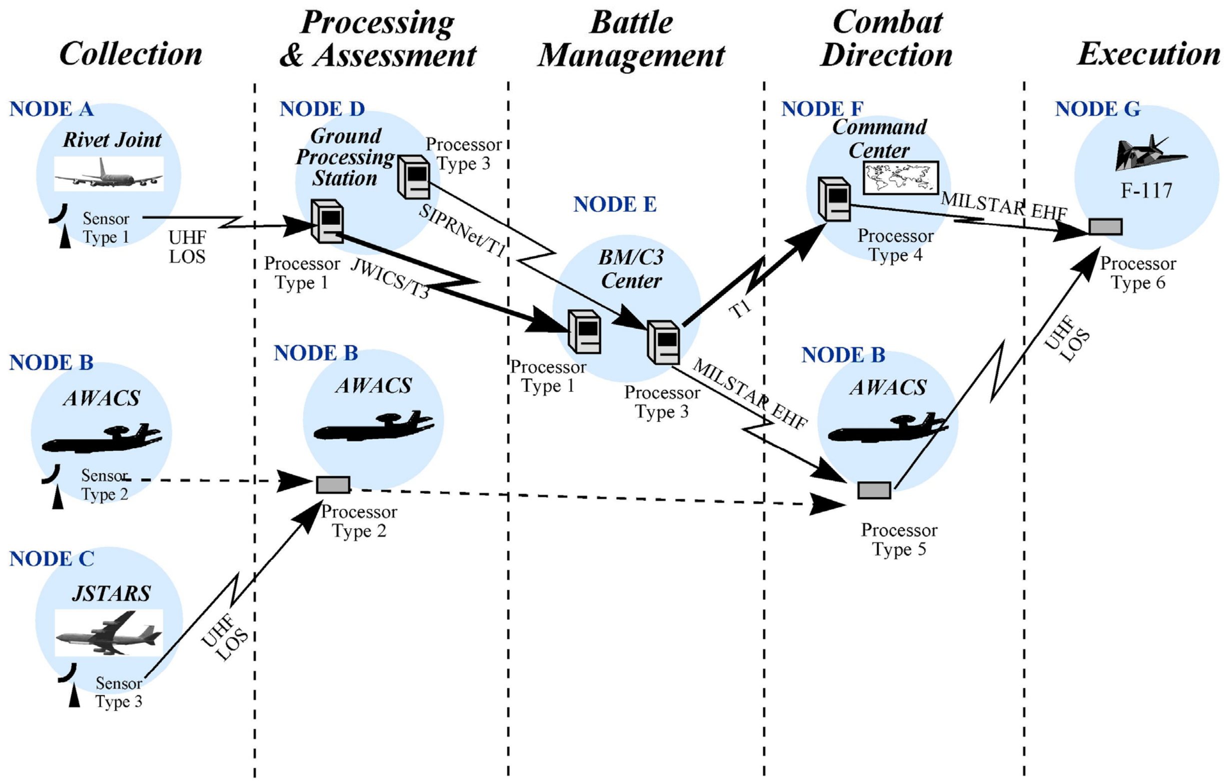

Fig. 3 — Notional System Architecture View (SV1) adapted from C41SR Architecture Framework, Version 2.0, Coordination Draft, 19 Nov 1997

"Real-time" is a technique for achieving simultaneity of events among distributed observers by immediate direct communication of information. But given the limitations of communicating information, such as signal propagation and processing, the elapsed time required for that process severely limit communication as the means of achieving "real-time" simultaneity. Precise synchronization between observers has demonstrated simultaneity of events, measurements, and time intervals precisely measured with accurately known common time globally. To use a CTR for precise synchronization for simultaneity of events, each individual system's timekeeping must be precisely compared to the common reference. Atomic clocks do not intrinsically possess the capability of determining time independently. Accurate comparison on a global scale enables timekeeping. Time is observable by being "set" on time through comparison to another more accurate reference.

The ability to precisely compare time and frequency can be used either continuously or at intervals to maintain a timekeeping system "on time." The comparison interval is dependent upon the nature of the timekeeping system and the clocks used. GPS positioning accuracy is accomplished by continuous correction of the receiver clock error. The continuous correction capability enables use as a time transfer system to provide precise time comparison virtually anywhere continuously.

A remote clock, once set on time, is then the means of "keeping time" and for comparison with other systems to further distribute reference time. To maintain accuracy in comparing additional timekeeping systems, all delays and errors in the comparison or time distribution between this local reference and the others must be precisely known through measurement or calibration. The resultant comparison time can then be corrected for these errors so that the time error is minimized.

SYSTEM TIME UTILIZATION

Most DOD systems deployed for operational use today were designed 10 to 20 years ago and are now known as legacy equipment. In the original design of these systems, maintaining clocks independently synchronous with absolute time over widely dispersed units was difficult primarily because of the unavailability of a universal means of accurate comparison with a reference time. Precise absolute time dissemination systems available had limited coverage and capabilities. Consequently, precise synchronization was designed for local relative operation. Initial synchronization was facilitated through the use of synchronization protocols and tracking beacons as guides for synchronizing the participating units clocks to one another. With precise relative time between the units operating together, they were synchronized sufficiently for tactical operations and individual coherent measurements in their tactical area. Absolute common time necessary for synchronized worldwide operation was inaccurate, but did not seriously impact these relative networks operating independently. Cooperative engagements involving multiple relative systems required external coordination or operational restrictions on the engaging units. Absolute common reference time was then considered unnecessary for successful mission operation. However, today's interactive systems are requiring an increasing closer degree of interoperability, and the volume and precision needed in data exchange have changed these operational needs significantly.

Telecommunications Systems

Timing is of primary importance in modern telecommunication systems, especially with the increasing use of digital techniques [7,8]. In telecommunications, timing is also used to refer to the frequency of the signals or bit rate being generated. In the communication of digital information, the rates at which the bits that make up the signals and messages are generated must be in step with one another or the message cannot be read. The ability to decode the message bits at the same or nearly the same rate that they are generated requires the bit generators to be syntonized. Syntonized is the term used for two oscillators or signal generators operating at identical bit rates or frequencies [9].

Operating with multiple signals over the same physical transmission lines has always been concerned with signal synchronization. Switching and multiplexing signals over telephone lines and networks without loss of information requires the signals at two communicating sites to be frequency-synchronized, or syntonized. The need for frequency-synchronizing widely distributed sites operating at increasing bandwidths and frequencies, such as those in the national and international telephone systems, led to standardization of the means of "timing" the systems. This led, ultimately, to establishing a timing hierarchy of oscillators and frequency standards to syntonize these networks.

The types of timing networks are categorized as

(1) asynchronous — each component runs with its own free running clock;
(2) synchronous — components and networks are <u>traced</u> back to a common clock and the timing is very precise;
(3) mesochronous — all components are timed by <u>one</u> single clock source, timing is exactly the same; or
(4) plesiochronous — components are timed from different clocks and component timing is almost the same [10].

Tables 1 and 2 show the relationship between baud (the number of signal events per second) and the signaling interval (one/baud). Baud refers to the signaling speed or the keying rate of a communication device such as a modem. It is related to but not necessarily equal to the number of bits per second.

Table 1 — Signaling Requirements

Signaling Rate (Baud)	**Bit Interval (s)**
300	0.003333
600	0.00166
1200	0.000833
1600	0.000625
2400	0.000416
1,544,000	6.477×10^{-7}

Table 2 — Stratum Level Requirements

Level	**Free Running Accuracy (Min)**
1	$\pm 1.0 \times 10^{-11}$ (0.00001 ppm)
2	$\pm 1.6 \times 10^{-8}$
3	$\pm 4.6 \times 10^{-6}$
4	$\pm 32 \times 10^{-6}$

Timing is addressed in these systems by the use of

a. Elastic Store – Using buffers
b. Phase-locked loops
c. Centralized network clock (best approach)

Tactical communications and data systems have been designed to operate with a local master clock in relative synchronization within local areas [11,12]. Clocks and oscillators used in these networks need precision in making synchronized time interval or frequency measurements [13,14]. Precise time was only necessary between the system units, so short periods of free running performance could be used between resynchronization with theater units. Long-term global time was unnecessary in these tactical operations. Long-term performance was required by strategic, widely dispersed worldwide systems such as secure communications systems, and was handled by other worldwide relative networks for that purpose. For tactical systems, quartz crystal oscillators, such as Temperature Compensated Crystal Oscillators (TCXO) and more stable Ovenized Crystal Oscillators (OCXO), are quite capable under these conditions [16, 17]. Figure 4 illustrates a locally syntonized tactical communications system.

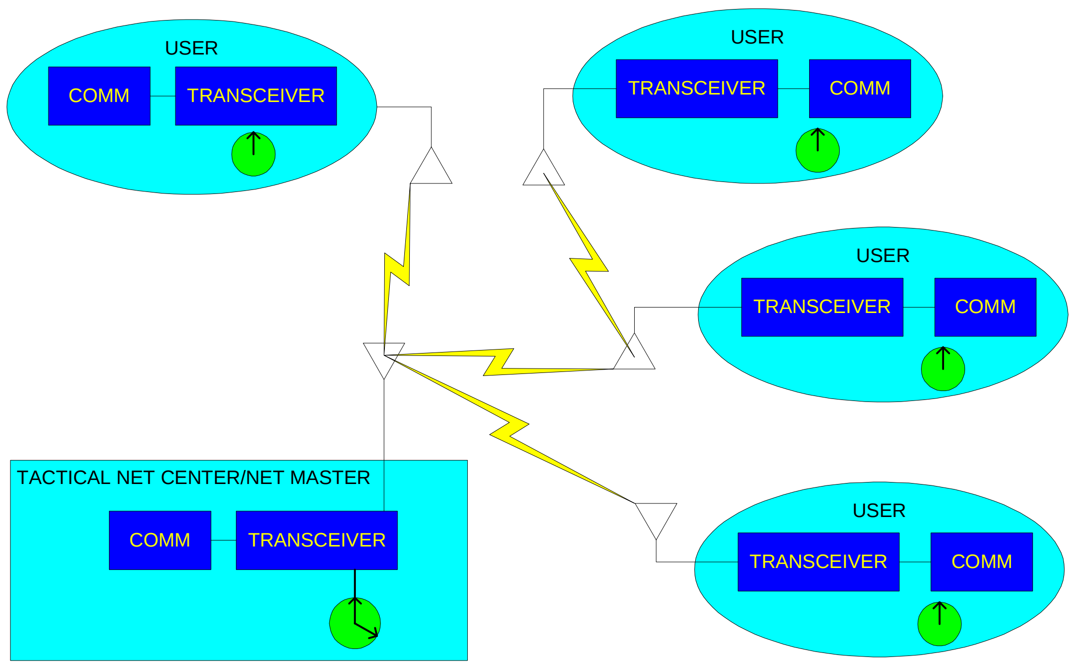

Fig. 4 — Tactical Communications Network

The Net Master controls system synchronization and, thereby, participation of the users in the network. User clocks are synchronized by special acquisition preambles for net entry, monitored in normal system operation so that they can be periodically updated through special synchronizing signals. These updates adjust the time (or signal phase) difference of the clock in the user terminal and monitor the frequency of the clocks over multiple updates to maintain system signal tracking and reception. This technique is simulated on the clock frequency as shown in Fig. 5. Changing the time offset introduces time steps. These time steps can be made small enough so they will not seriously affect system operation and the synchronization integrity. Consequently, if the Net Master Clock were compared to UTC (USNO), as in the bottom plot of Fig. 5, it could be almost any value and the network would still work perfectly. Relative time in independent operation is the means of satisfying that system's mission. However, for common joint operations forming groupings with other systems or multiple relative networks, the ability to synchronize and correlate data to an accurate common time becomes significant.

Clock Hierarchies

The nature of synchronization and clock comparison, combined with the difficulty of maintaining clock synchronization, has led to techniques that use a hierarchy of clocks. This concept has been used extensively in hardwired telephone networks. The network arranges the switching centers in a hierarchy from the most accurate to the least accurate so that the more precise and accurate clocks control or update the lesser ones to keep them in synchronization. Dissemination of absolute time with a variety of time transfer techniques to global systems requiring synchronization uses a similar hierarchical concept. Such a stratum hierarchy is illustrated in Fig. 6. A Primary Reference Standard (i.e., a Master Clock) controls subordinate clocks in a hierarchy known as Stratum Levels. Stratum 1 is the most accurate and stable of

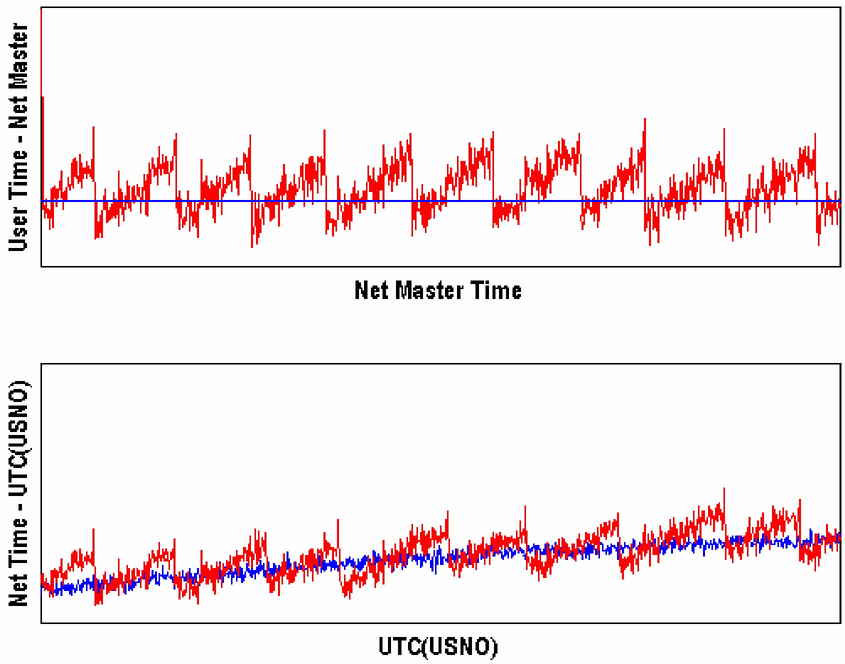

Fig. 5 — Network user time updates

clocks, typically a cesium beam standard. It would then maintain Stratum 2 level clocks, and so forth. This arrangement is economical since the better clocks are also the most expensive. The interfaces and connecting links between clocks in these hierarchies must also be sufficient to maintain the accuracy in the clocks further down in the hierarchy.

It should be noted that timing as applied by the stratum hierarchy in telecommunication systems is the frequency of the network links. Syntonization, or the process of adjusting the frequency of a clock to a reference frequency, is a process in the metrological sense rather than time adjustment (synchronization).

The hierarchical approach is the basis for Master Clock operation and application to time transfer, clock comparison, and system design for synchronization. The use of distributed time standards can potentially provide synchronization without a fixed hierarchy with a single Master Clock if the elements' clocks can be maintained synchronously to a common reference. The telecommunications industry adopted this implementation in cellular networks using precise time provided by GPS receivers.

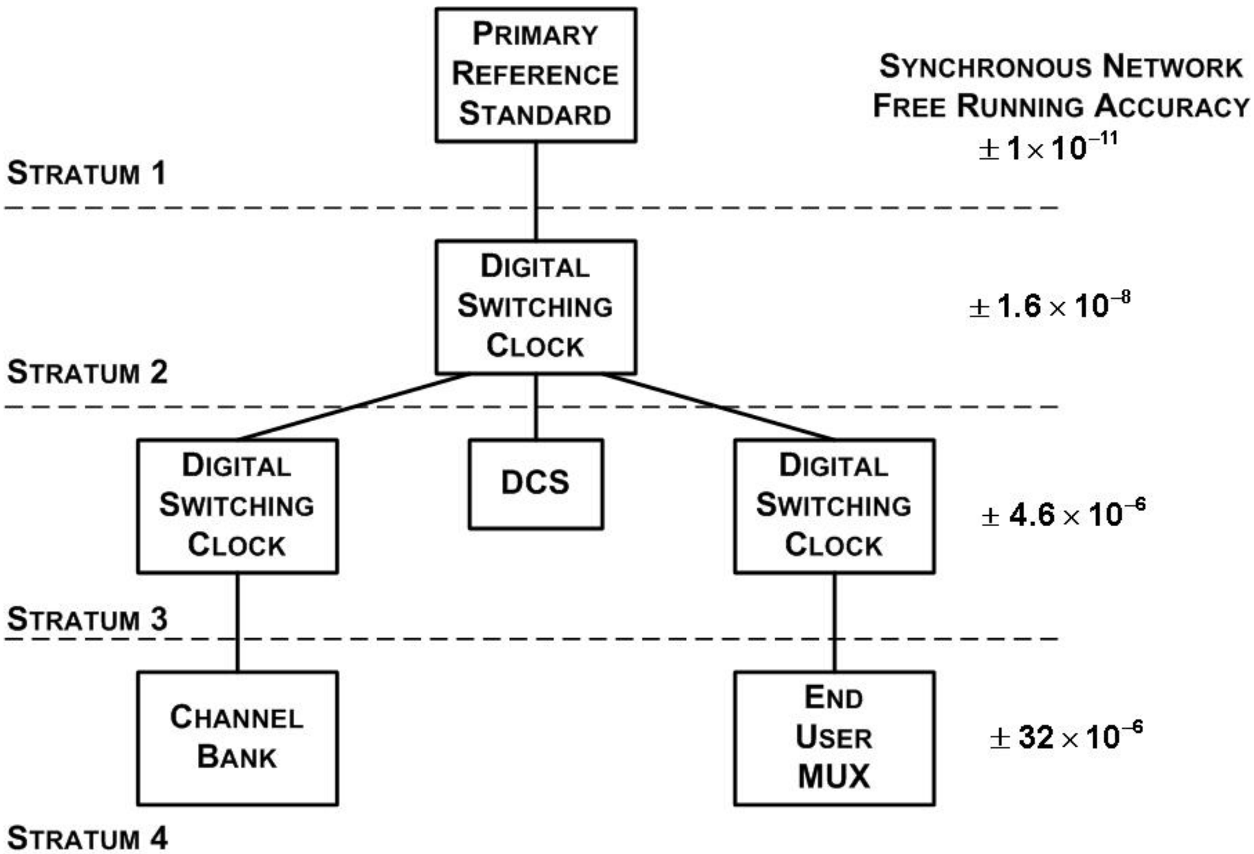

Fig. 6 — Clock stratum hierarchy

Radio Frequency (RF) Systems

Figure 7 shows the typical Naval RF communications links currently in use [18]. Networking with the variety of links available today is focused on the higher bandwidth circuits to enable higher data transfer rates. Efforts are being conducted to evaluate applications within the ADNS network environment in using RF links in a wide area network (WAN) architecture. The links involved are predominately direct line-of-sight (LOS) links.

The LOS links refers to a large family of links within the military, service, and aviation frequency bands in the VHF/UHF spectrum. The VHF communication band is from 30 to 300 MHz (10 to 1 m wavelengths). The UHF communication band is from 300 to 3000 MHz (1 to 0.12 m). Communications in the 1000 to 2000 MHz range is frequently referred to as L-band (which is traditionally the radar band designation). These systems include both LOS surface-to-surface and satellite links. Table 3 lists some of these system characteristics, and a short description of the waveform involved follows.

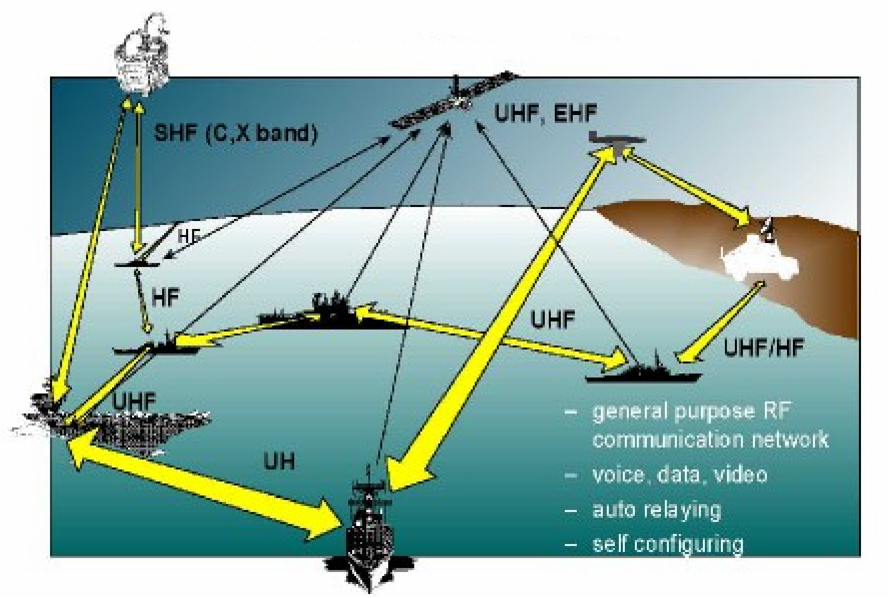

Fig. 7 — Navy RF communications

Table 3 — VHF/UHF Communications Characteristics

Waveform/Function	Bandwidth (kHz)	Baseband Data Rate (kbps)
Frequency Shift Keying/SINCGARS	25	16
Amplitude Shift Keying/UHF HAVEQUICK	25	16
4-ary Coherent Phase/Frequency Shift Keying	5	4.8/9.6
UHF DAMA SATCOM	25	9.6 to 56
16-ary Trellis Code Modulation/VHF/UHF	25	64
SSB/VHF	25	21 to 64
Phase Shift Keying/UHF DAMA SATCOM	5 & 25	2.4

UHF HAVEQUICK

The HAVEQUICK waveform is supported by a variety of radios, including the AN/WSC-3, the AN/VRC-103, the AN/ARC-164, and the AN/ARC-210 and will be supported by both the Digital Modular Radio (DMR) and the Joint Tactical Radio System (JTRS). The system operates in the 225 MHz to 400 MHz VHF/UHF frequency band. Slow, frequency–hopping amplitude shift keying (ASK) is used over 7000 frequency channels. HAVEQUICK radios use precision time, normally taken from a GPS receiver, in order to help them to get into and stay in the network. The specific time interface is described in ICD-GPS-060 [19]. This interface provides the HAVEQUICK radio with UTC (USNO) time accurate to 10 μs.

SINCGARS

The Single Channel Ground and Airborne Radio System (SINCGARS) is a VHF-FM (30 to 88 MHz) military radio using frequency-hopping to provide a combat communication radio that includes both voice communication and a digital data transmission capability. SINCGARS is widely deployed by DOD, in manpack, vehicular, and airborne configurations. The system operates on any of the 2,320 channels between 30 and 88 MHz, using an encrypted signal to provide robust, secure communications to the troops while providing commanders with real-time command and control data. There are Receiver-Transmitter Units that are specifically developed for SINCGARS applications, but the waveform is also supported by other military radios including the current AN/ARC-210 and AN/VRC-103 and the emergent DMR and JTRS.

DWTS (Digital Wideband Transmission System)

The DWTS is an L-band (1350 to 1850 MHz), line of sight, wideband (144 kbps to 2 Mbps) multiplexed communication system used by the ships of an Amphibious Ready Group (ARG) to communicate with each other and with the Marines ashore. The system uses binary frequency shift keying (FSK) modulation. The capability also provides ARGs connectivity to embarked Marines ashore as well as the Army Tactical Internet (TI).

Link-11

Link-11 or Tactical Digital Information Link A (TADIL A) operates in the HF and UHF frequency bands at either 1364 or 2250 bps data rates. It uses a netted communication technique to support a standard for data exchange between airborne, land-based, and shipboard tactical data systems. HF communications are capable of BLOS communication of up to 300 nmi and UHF LOS coverage is approximately 25 nmi ship-to-ship and 150 nmi ship-to-air. HF Link-11 modulation is AM Independent Side Band Suppressed Carrier (ISBSC) and operates from 2 to 30 MHz with a channel bandwidth of 6 kHz. UHF Link-11 modulation is FM with a frequency deviation of ± 20 kHz in a frequency band of 225 MHz to 400 MHz. The common data terminal sets include the AN/USQ-74, AN/USQ-83, AN/USQ-120, and AN/USQ-125.

Link-16

Also referred to as TADIL J, Link-16 is used by the Joint Services as well as NATO allies. It uses a TDMA (Time Division Multiple Access) architecture with the “J” series standard message format. Although using concepts similar to Link-11, there are improvements in security, robustness, throughput, jam resistance, and the addition of relative navigation. The system operates in the 969 to 1206 LX frequency band. UHF Link-16 supports data rates of 28.8, 57.6, or 115.2 kbps. The system uses frequency hopping (51 3-MHz channels) and binary Continuous Phase Shift Modulation (CPSM). The Link-16 waveform is supported by the JTIDS (Joint Tactical Information Distribution System) and MIDS (Multifunctional Information Distribution System) terminals.

Link-22

Also referred to as NILE/Link-22 (NATO Improved Link Eleven), is being developed together by several nations and will use a standard “J” series message format as well as the newly defined “F” series message. Link-22 will operate in the HF (3 to 30 MHz) and/or UHF (225 to 400 MHz) bands. It will also use the existing TDMA architecture or a new Dynamic TDMA (DTDMA), increasing its flexibility. Link-22 could be considered the "Link-16 Family" because it will also support previous message formats.

EPLRS

The Enhanced Position Location Reporting System operates in the UHF band (420 to 450 MHz). It provides relative navigation as well as providing the communications (up to 56 kbps aggregate) backbone to the Army's Tactical Internet and the Marines Tactical Data Network (TDN). It is also used by the Navy to support the amphibious ships including the LCACs as well as the Air National Guard and its SADL (Situational Awareness Data Link) project. EPLRS provides a secure, jam resistant, robust waveform with the capability to support VMF (Variable Message Format).

EPLRS Net Manager (ENM)

The EPLRS Net Manager is the next generation of EPLRS. Although the first revisions share similar characteristics with the current system (same data rate, waveform, frequency range), there are significant software changes to the radio. The system will become more of a decentralized system but will still implement a TDMA architecture. However, the intent is to migrate to the 225 to 450 MHz and 600 to 800 MHz bands as well as to increase the aggregate throughput to 520 kbps. This migration will also include six new waveforms and hardware modifications to the radio. The different services plan on transitioning to the new system at different maturity levels as it develops.

UHF MILSATCOM

Current UHF Follow On (UFO) operates in the 290 to 320 MHz uplink and 240 to 270 MHz downlink VHF/UHF frequency bands. The function of using these frequencies is to provide reliable communication to penetrate heavy weather and foliage. The system includes 38 UHF communication channels plus a Fleet Broadcast channel. Modulation and access modes for the Satellite Communication (SATCOM) systems are phase shift keying (PSK) Demand Assigned Multiple Access (DAMA) and are either 5 kHz narrowband or 25 kHz wideband channels operation in the range of 2.4 kbps to 56 kbps. The demand for UHF SATCOM has led to the proliferation of terminals such as the AN/WSC-3. The DMR and JTRS will incorporate these waveforms.

SHF SATCOM

Super high frequency (SHF; 3 to 30 GHz) SATCOM systems provide wideband communications services to the Fleet. These systems include Defense Satellite Communications System (DSCS), Wideband Gapfiller System (WGS) and the future Advanced Wideband System (AWS). DSCS signals are broadcast in X-band on six channels with a 7250 to 7750 uplink frequency band and a 7900 to 8400 MHz downlink frequency band. Newer DSCS III satellites provide channelization with a total usable bandwidth of 405 MHz. Channels 1 and 6 have a 50-MHz bandwidth, channel 2 has a 75-MHz bandwidth, channel 4 has an 85-MHz bandwidth, and channel 5 has a 60-MHz bandwidth. Guard bands are 15 MHz between channels 1 through 4 and 25 MHz between channels 4 through 6. WGS and UFO satellites carry the Global Broadcast System (GBS) capability in the K/Ka band. GBS is a worldwide receive-only capability that incorporates spot beam capability (to allow for movement of coverage as directed by operational theater commanders) and Earth coverage beams. Data rates range from T1 (1.544 Mbps) to E1 (2.048 Mbps).

EHF SATCOM

The Military Strategic and Tactical Relay (MILSTAR) system is an EHF (44 GHz) uplink and SHF (20 GHz) downlink satellite communication system. The uplink communication bandwidth is 2 GHz and the downlink bandwidth is 1 GHz. Two primary waveforms are supported: Low Data Rate (LDR) and Medium Data Rate (MDR). The LDR MILSTAR system was initially envisioned as to provide the U.S. military forces with new capabilities:

a. minimized propagation degradation due to high altitude nuclear effects

b. increased communication bandwidth (2 GHz uplink, 1 GHz downlink)

c. high-gain, narrow-beamwidth antenna with increased antijam and low probability of intercept (LPI) characteristics.

LDR MILSTAR was developed to provide extremely robust communications primarily to support the threat of a nuclear war. As such, it uses strong error correction and detection and antijam techniques including convolutional encoding, interleaving, hop repeating, frequency permutation, frequency hopping, and m-ary FSK modulation. The system employs Time Division Multiplexing (TDM) communication channel access. The techniques used to assure a robust link restrict the useable available bandwidth to 75 bps to 2.4 kbps data rates. MILSTAR II capabilities add an MDR payload and also retain LDR capability. MDR is capable of 4800 bps to 1.544 Mbps data and voice communication over 32 channels to support higher throughput requirements for DOD forces. Follow-on Advanced EHF, which will replenish the MILSTAR satellite constellation and provide even higher data rates (6 to 8 Mbps), uses the MDR waveform.

Challenge Athena

Challenge Athena is a commercial high data rate (1.544 Mbps) satellite communications link capable of providing access to high-volume traffic such as national imagery dissemination; intelligence database transfers; and video teleconferencing services and other data communication systems. The system is INTELSAT-compliant, full duplex, and operates in the C-band at 5.850 to 6.425 GHz uplink and 3.7 to 4.2 GHz downlink. The Challenge Athena system uses commercial satellite connectivity and commercial off-the-shelf equipment and non-developmental items (COTS/NDI) to augment existing extremely overburdened military satellite communications systems.

AN/VRC-99

This radio has been demonstrated for the Extended Littoral Battlespace (ELB) Advanced Concept Technical Demonstration (ACTD). The system is used in Theater High-Altitude Area Defense (THAAD) communications systems and operates as a networked communications system. The frequency range is in the L-band and can accommodate up to 16 users within a 27-slot media access protocol. Channel bandwidth is 316 MHz with data rates ranging from 625 kbps to 10 Mbps.

Time Requirements

Requirements may be categorized according to the system’s needs. From the system’s needs, the categories and the range of accuracies/precisions required can be grouped as follows:

- ***Positional Reference Time:*** This category deals with time-tagging observations of platform positions or sensor measurements relating to position determination. The position and change of position of the particular vehicles determine the associated accuracies, precision limits, and requirements. An example would be associating the time an aircraft is at a particular position.

- ***Measurement Time Interval:*** Computation of time interval for RF or optical measurements determine the 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 than positional reference time.

- ***Communication Signal Synchronization:*** Data transfer links ranging from the local systems discussed above, 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 limits are relative to the speed of light.

- ***Data Processing:*** For calculation of information and transmission through processing nodes and networks. Processing delays for the calculations that take place are the dominant element of the timing requirements. Even asynchronous data transfer requires timing and set limits.

Multiple User Systems

As systems are 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 define clearly. A ship and aircraft system is shown in Fig. 4 (Tactical Communications Network). The clock symbols show some of the clocks that are contained in these systems, since virtually all electronic systems contain clocks and oscillators. The time requirements of the system depend not only on the clocks used but also on how they are used. Clocks within the system control the time of the system elements but the manner in which they are applied also controls the timing of the system. Within the same platform, systems are still predominately organized as relative and self-contained. A radar system and weapons system may each use its own internal time for operation. Moving data processed with one internal time scale to another system determines the relations between the clocks and sets the timing paths. "Timing" is then more accurately defined as the ability of information or data to move through the systems. Limits are determined by instrument delays, uncalibrated transmission delays (latencies) between units, and processing delays, all of which play a role in timekeeping. Timing of the transmission and data flow does not necessarily represent time of the system, but the arrangement of how time and clocks are used.

Time and the Infrastructure

Even within a single platform there are many clocks and timing systems. The interfaces and distribution of data and timing signals between the existing systems can be quite complex. As shown in Fig. 8 [5], this can be readily illustrated by looking at the interfaces within an AEGIS ship.

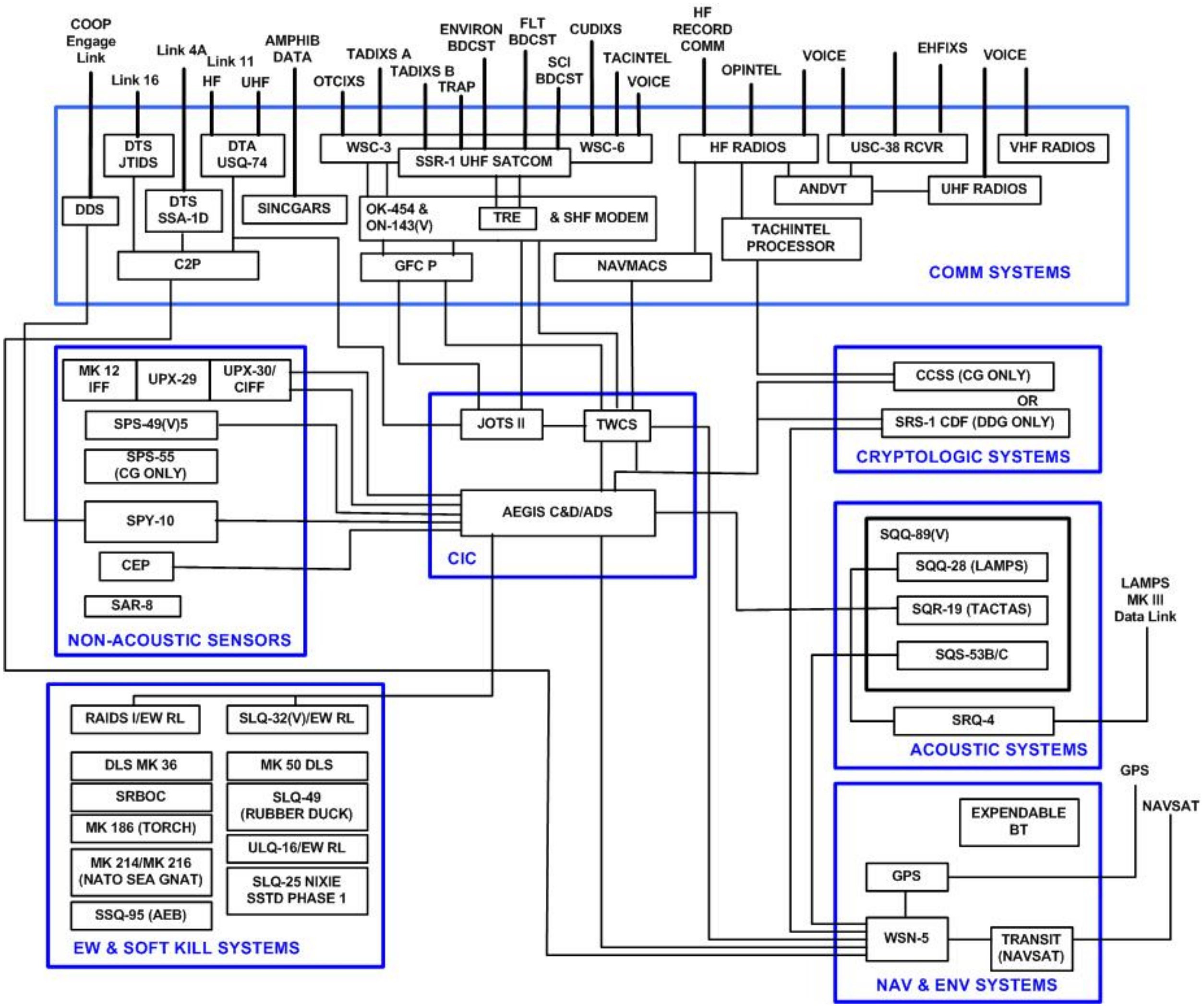

Fig. 8 — CG/DDG AEGIS CIC example interface [3]

With the clocks distributed within the infrastructure, their relationship for synchronized operation is a function of the ability to keep and provide accurate time between them. In the example of Fig. 3, the time kept by each unit and the potential time delays of data passing through the system is illustrated in Fig. 9. The figure also shows simulated times kept by individual unit clocks and their interactive roles. The time associated with the aircraft's clock is shown as a saw tooth function. This is the result of updating the unit's clock to the time maintained by the ship through a tactical data link system to keep the unit in synchronization for communication. Each unit's time is applied as a time tag to the radar observations. The time generated is the result of supporting functions not directly involved in the tracking operation and consequently must rely on the accuracy provided by these supporting functions. These data are then processed, reformatted, and transmitted to the next unit. Time measurements or correlation to absolute time used for processing and transmission further refines and alters the data. The data are received, re-formatted, processed, and then relayed again until the data arrive at the Command Center (CC) for final processing. The cumulative elapsed time resulting from processing and communications relay of data is commonly referred to as "latency." Other steps in the handling of the data, such as data processing, may retime the data and add additional complications in correlating or maintaining overall synchronization.

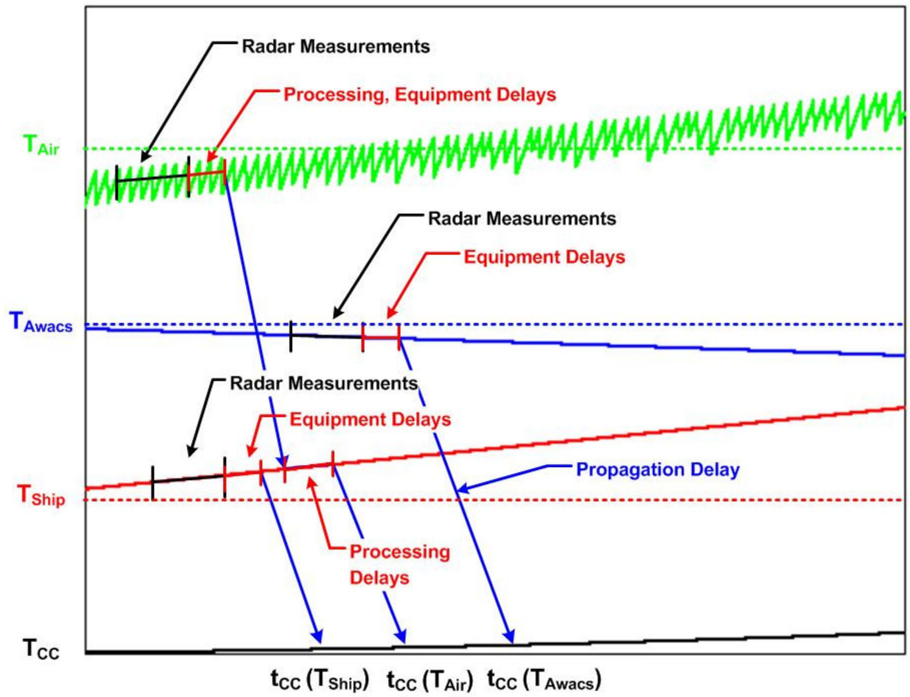

Fig. 9 — Data time tagging and references

Once the data finally arrive at the CC for correlation with other units' data, they are again correlated with the CC clock. Simple comparison of the respective unit time in the data messages, $t_{CC}(T_{Ship})$, $t_{CC}(T_{Air})$, and $t_{\mathrm{CC}}(T_{Awacs})$ results in

$$T_{Unit}\,(t) - t_{CC}\,(T_{Unit}) = \varepsilon, \tag{1}$$

where ε may be presumed to be the overall time error, or "latency," between the time at the CC and the user. Since the unit clock time, delays, and signal propagation affecting the time are not observable throughout the data links and supporting systems, such a simple comparison is misleading. Even if all of the clocks involved in the data transfer are perfectly synchronized, latency will still exist in the system. Latency is present because information cannot be sent instantaneously from one unit to another. This delay can be reduced through better equipment and knowledge but not eliminated.

Correlating the observations, unit positions, and velocities into a common, accurate, time-ordered position and velocity estimates of the unknown and known units in the area depends not only upon the accuracy of the time tags in the data, but also on the processing and data transmission handling as well. That correlation process is illustrated in Fig. 10. If the time references onboard the units and in the processing centers are presumed to be synchronized by some independent means, the effects on overall accuracy of the process can be assessed by a more detailed investigation of the supporting infrastructure. Referring to the diagram of a tracking process, a unit produces data at $T_{Unit}(t)$ (e.g., T_{Radar}). Processing, transfer, and formatting a time-sequenced data word for transmission on a data link will introduce a time delay Δt_U. The format of the time message will have a certain precision introducing a limit on time resolution ε_U. Transmission will take additional time Δt_t. Reception, decoding, and processing of the data message will introduce similar terms leading to

$$[(T_{Unit}(t) + \delta T_{Unit} + (\Delta t_U + \varepsilon_U) + \Delta t_t + (\Delta t_R + \varepsilon_R + \Delta t_p)] = T_{Unit} \text{ (Received)} \tag{2}$$

$$\begin{aligned} T_{GA}(t) - T_{radar}(t) &= \delta T_{radar} + (\Delta t_{ei} + \varepsilon_i + \Delta t_{ti}) + (\Delta t_R + \varepsilon_R + \Delta t_P) \\ &= \delta T_{radar} + (\Delta t_{ei} + \Delta t_{ti} + \Delta t_r + \Delta t_p) + (\varepsilon_i + \varepsilon_R) \\ &= \delta T_{radar} + \Delta t_{total} + \varepsilon_{total} \end{aligned}$$

where

Δt_{ei} = Equipment Delays, (3)
ε_i = Quantization
Δt_{ti} = Propagation Delays
Δt_R = Reception
Δt_p = Processing Delays

and where δT_{Unit} represents the synchronization error of the unit clock. These terms, although not large in and of themselves, can represent a large factor in timing uncertainty when taken together. Observability of system clocks, time delays, uncalibrated propagation delays, and interfacing factors can increase these errors significantly for data and time messages throughout the supporting infrastructure.

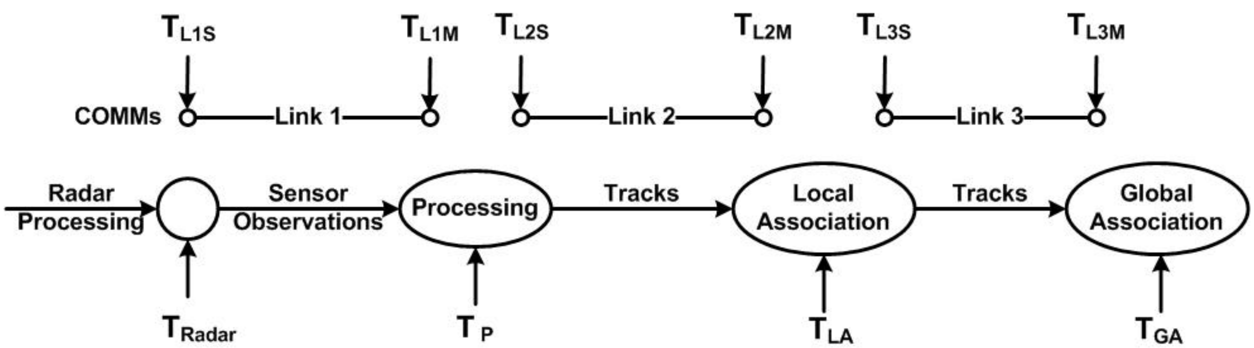

Fig. 10 — Timing in tracking process

For overall synchronization, the unit clocks are the means of establishing synchronization as designed into these systems. The implications of the variety of methods and assumptions used maintaining this process are discussed in the following sections.

Sensor Data Processing and Fusion

Time accuracy in sensor systems is affected by the following parameters:

1. Geospatial coordinates and time reference
2. Synchronization of other participating sensors
3. Dissimilar sensor measurement accuracy
4. Dissimilar sensor resolution
5. Asynchronous data availability and entry into processing.

The availability of accurate references for timekeeping and maintaining synchronization was a significant problem in legacy systems due to the basic nonavailability of accurate epoch time [22]. Consequently, synchronization techniques were built around localized relative systems whose clocks and oscillators could be compared by system unique local comparison and synchronization signals. More emphasis was placed on the short-term performance of standalone clocks that could maintain precise time intervals independently for coherence during the measurements.

Clock comparison is the basic mechanism for synchronization and monitoring time/clock error components [23]. Environmental factors (e.g., vibration, temperature, acceleration, and magnetic fields) are not commonly applied in clock comparison analysis, but should not be ignored, especially in field or operating systems [24,25]. System design usually relies upon manufacturer's environmental specifications and periodic calibration. The random term in clock performance is measured by special statistical means after the systematic components such as frequency offset are removed [26,27]. Performance, predicted or limiting, is based on the characteristics or limits of the random components. However, operating conditions and environmental factors further influence performance and can vary even further from prediction based on random components.

A DISTRIBUTED REFERENCE ARCHITECTURE

The basic approach to providing common time/frequency references is simple but robust [2]. It must satisfy the following fundamental requirements:

1. Provide a continuous reference source of common frequency with low-phase noise and good accuracy;

2. Provide a continuous common timing reference with long-term timing accuracy;

3. Provide time and frequency distribution capabilities using various signals and coding formats;

4. Provide autonomous diagnostics capability and frequency standards assessment with the ability to maintain accurate continuous output despite possible anomalies;

5. Make optimum use of the existing timing resources already present;

6. Establish a robust, enduring source of accurate time and frequency even in the prolonged absence of updates from time dissemination links.

Figure 11 shows the overall architecture. The source acronyms are defined in the following section.

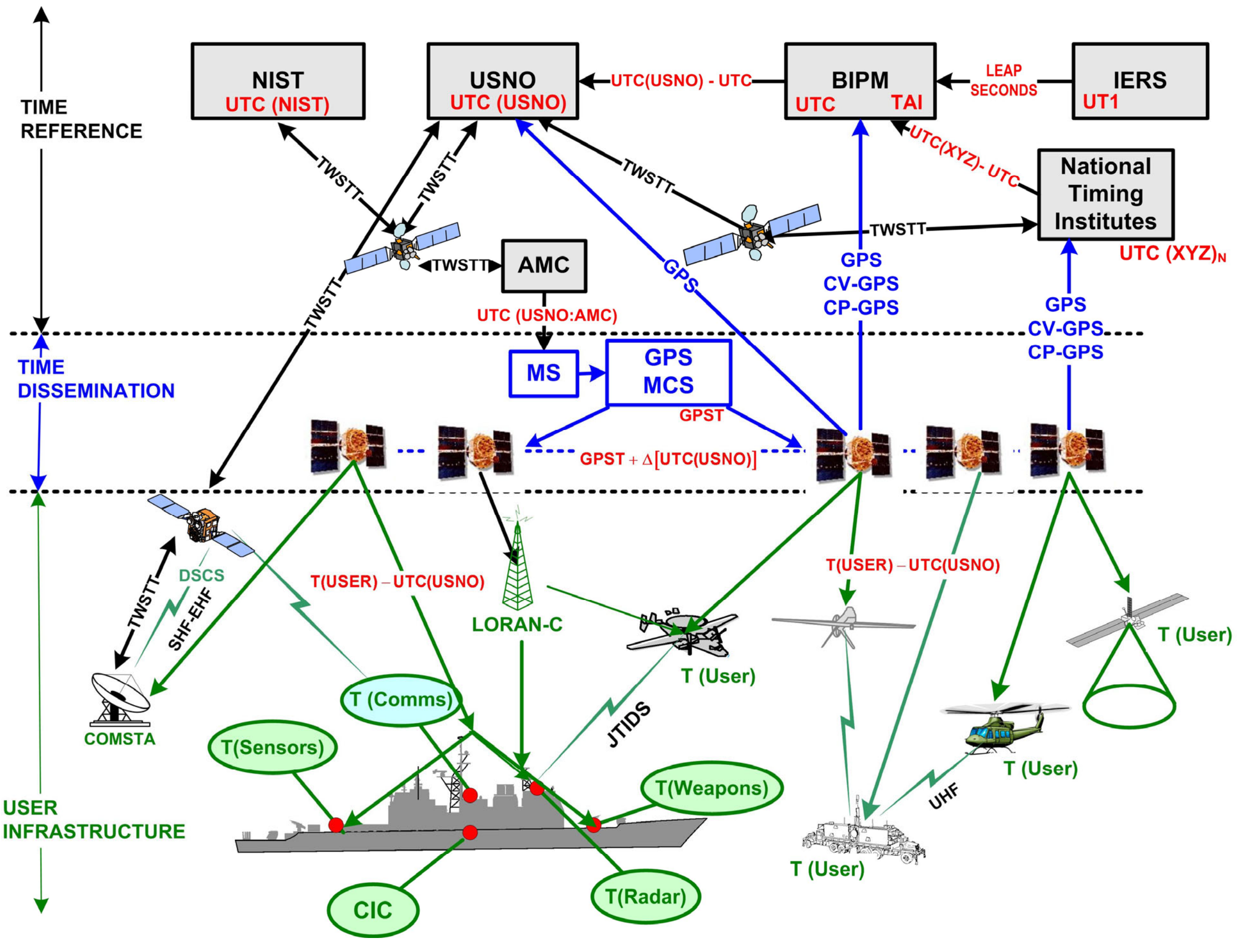

Fig. 11 — CTR architecture overview

Common Time - Coordinated Universal Time (UTC)

The time scale designated for use by DOD systems [21] is Coordinated Universal Time as maintained by the U.S. Naval Observatory, denoted UTC (USNO). The international time scale is coordinated with the Bureau des Poids et Measures (BIPM) and International Earth Rotation Service (IERS) [28] as the U.S. contributor to the international determination of UTC.

UTC is the basis of civil time and generally replaced Greenwich Mean Time [29]. The time scale is a combination of Universal Time (UT1) or solar time, based on the rotation of the Earth with its precessing axis, and International Atomic Time (TAI) [30]. TAI is based on the SI (Systeme Internationale) second [31], as defined as a specific hyperfine resonance of the cesium atom. The SI second is maintained by intercomparison of the cesium hyperfine resonance from primary standards, which are cesium-beam atomic frequency standards especially built and operated under rigid environmental conditions by national metrology centers, such as the National Institute of Standards and Technology (NIST) [32,33]. These primary standards are designed for the highest accuracy and precision possible. Combining with other standards, such as hydrogen masers operated by the various international timing centers, a comparison network of high precision links is used to determine the international time scales, as shown in Fig. 12 [34]. Commercial cesium beam frequency standards for industrial and military use are considered primary

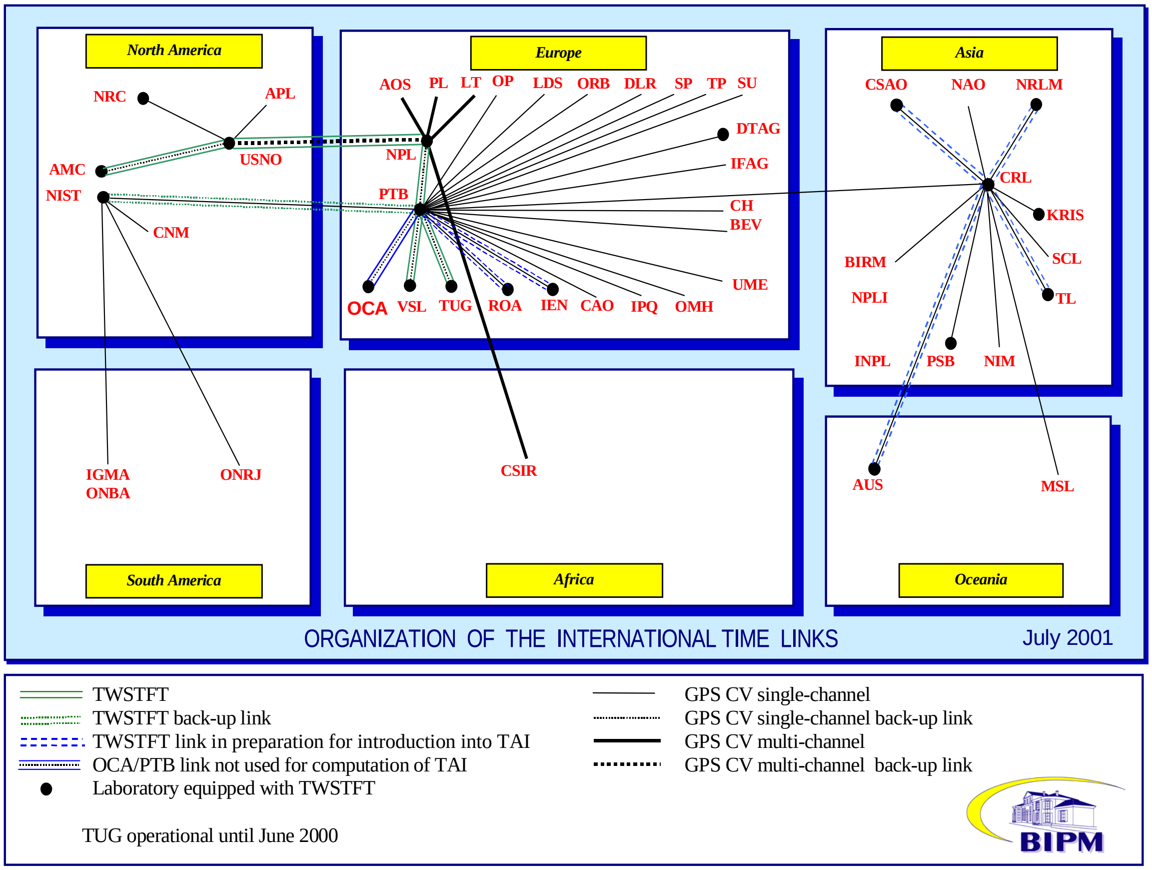

Fig. 12 — International time links used by the BIPM for UTC generation [4]

standards, but are not “primary standards” in the metrological sense. Designed for use in different, and in many cases nonoptimal field environments, their accuracy is degraded by design compromises for size, power, and ruggedness. Consequently, they must be periodically recalibrated from a superior standard to maintain accuracy.

International timing centers typically maintain an ensemble of clocks whose composite output is realized as the signal from a “master” clock or timing system, whose output signal is designated as that center’s (or Nation’s) realization of UTC [35]. To distinguish a timing institute’s realization of UTC from the international UTC time scale, which is determined through post-processing of the time comparisons between these international centers, it is designated as UTC (XYZ). XYZ is the unique identifier of the center, so users can distinguish between the sources of their timing reference. The difference between UTC (USNO) and UTC is shown in Fig. 13 [34]. Standards for telecommunications and time dissemination are established by the International Telecommunications Union (Radiocommunication Sector) (ITU-R).

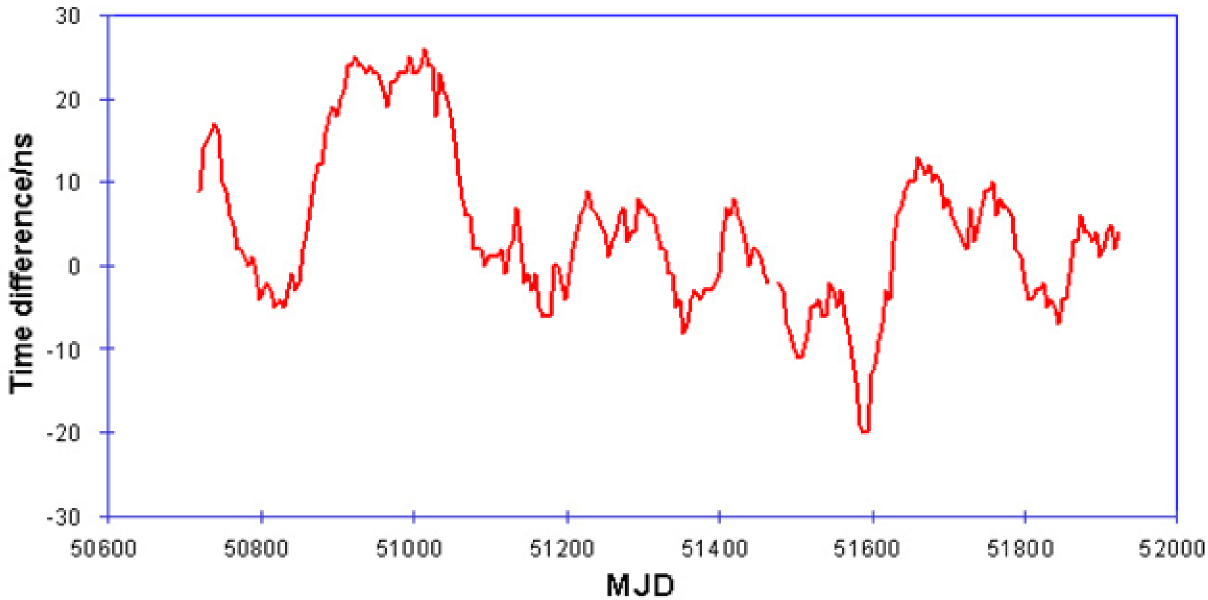

Fig. 13 — UTC (USNO) difference from International UTC; MJD is modified Julian date

Using a time scale such as UTC has presented significant problems for the military user. First of all, it is not uniform. Leap seconds can be introduced at irregular intervals to keep UTC within 0.9 s of the UT1 time scale, solar time corrected for nonuniform Earth rotation. UT1 relating the Earth's rotation and orientation in inertial space is needed for celestial navigation and inertial systems. The largest problem with this unpredictable nonuniformity has been the distribution of the information to the military user so the time step may be introduced at the proper moment. Some legacy systems are designed for this correction to be entered manually. This creates a double problem. Since the leap second introduction is actually known months in advance, the distribution of the occurrence and direction (+ or -) to operating forces around the world could reduce what has been a major issue significantly.

The choice of the common time also poses a problem in joint operations with NATO or Allied forces, since the time scale in use by those forces could be different from U.S. forces. The time reference NATO has designated is UTC [21]. This designation without an indication of the physical source signifies the international time scale that is a post-processed time scale. Military needs are for an immediate time for coordination and operations [36]. UTC maintained by different reference sources can vary in accuracy and availability from nation to nation. Limits are established as a recommendation by the ITU-R. Identifying sources of UTC time in NATO operations has been a problem in recent operations, which still needs to be resolved. Synchronization of forces within local areas by using their distributed time standard will make information flow among military systems (within the U.S. forces or on a worldwide scale) much more fluid.

Common Time Reference for Warfighting Units

Global common time is based on the capability to accurately reference clocks and oscillators to a central time scale or established reference time. The means of reference is a critical parameter in the ability to establish an accurate traceable reference over global distances. Just as there were different techniques for synchronizing communication systems, there are different techniques for establishing a common reference. They depend upon the characteristics of the systems to be referenced.

Timekeeping devices and clocks do not intrinsically possess the capability of determining UTC time independently so their time must be determined by comparison to the time scale being referenced. This comparison “sets” the clock on time. Consequently, precise comparison systems must be used for continuous comparison or at regular intervals to maintain a timekeeping system “on time.” The comparison interval depends on the nature of the timekeeping system and the clocks used. GPS is currently the primary time comparison system because of its precision and ability to maintain accuracy as well as its availability. Time transfer is the common means of comparison and correction of a remote clock to the reference timekeeping system. The remote clock is then the means of “keeping time” or comparing other systems to the reference time. To provide accurate comparison, all delays and errors in the comparison process or time distribution subsystem between the reference and remote timekeeping system must be either precisely known for correction of the resultant comparison data, or the uncertainty must be added to the clock comparison or time transfer accuracy estimate.

Global Time Dissemination

Time can be transferred via a number of techniques depending on the application and accuracy required [37-44]. The primary means of accurate time transfer today for operating forces is GPS. GPS uses a constellation of satellites each containing four atomic clocks. These space borne atomic clocks, combined with the monitor station cesium standards establish GPS Time (GPST), the common system synchronization time. Use of GPS for combat and weapons systems is required to use the military encrypted satellite signals, known as P(Y) Code transmissions. The capability provided for positioning relies upon the receiver’s ability to precisely measure multiple transmission time of the P(Y) Code signals with GPST. Time dissemination via GPS relies upon the stability of GPST and its correction to UTC (USNO).

Simultaneous passive reception of multiple GPS satellites for positioning requires the satellites to be precisely synchronized with less error than that expected from the individual satellite pseudorange measurement to the user receiver. The stability of the individual satellite clock between updates or re-synchronization with GPST determines the system synchronization error. Signal propagation of the GPS signals, receiver instrumentation, user position uncertainty and UTC (USNO) satellite correction message offset are the other determining factors in passive time transfer accuracy to the operating forces.

The ability to disseminate time accurately and precisely to remote operating forces is the essence of maintaining a CTR. Timescale operations can be focused into one site with sufficient technical personnel and scientists to produce an extremely good time scale. Taking the time and frequency generated by the time scale out to diverse users and providing the instrumentation and subsystems for accurate application, since these diverse users have differing capabilities, involves different problems. The different techniques and supporting systems are currently tailored specifically for the application.

Passive GPS Time Transfer

This passive technique is the primary mode of time transfer operation for the military user [39,45]. As a passive service, the GPS broadcasts are available over a wide area independent of the user’s position for reception. The timing information is determined along with the position and velocity in the user’s calculations during flight or other operations. Consequently, estimates of time transfer accuracy depend on the uncertainty of the user’s location in the navigation process. For fixed sites with accurate knowledge of position, such as at USNO, near optimum results of less than 10 ns, 1 σ, can be expected.

Effective use of this capability in mobile platforms depends on the user's instrumentation and ability to use the high precision timing information.

Using GPS for mission critical and combat systems relies on the stability and precision of GPS Time for positioning and time transfer received through the military encrypted satellite signals known as P(Y) Code transmissions. Simultaneous passive reception of multiple GPS satellites requires the satellites to be precisely synchronized to each other with less error than that expected from the individual satellite pseudorange measurement with the user receiver. The stability of the individual satellite clock between updates or resynchronization with the composite clock of GPST determines the system synchronization error.

Analyzing the difference between local time references compared to the GPS solutions leads to expressions for the errors and the user system time. The associated time transfer errors are derived from the solution for GPS real-time position in the passive mode. User equipment and instrumentation vary, but basically they all receive at least four satellites' signals simultaneously for pseudorange measurements. Four simultaneous measurements enable the determination of the three position and velocity elements and time offset of the receiver clock. Military systems operate with the encrypted P(Y) code signals at two frequencies that measure the propagation delay from the satellite to the receiver antenna. The pseudorange ρ is determined from $\rho = c(t_U - t_{SV})$, where c is the speed of light, t_U is the time of reception, and t_S is the time of satellite transmission. The propagation time ($\Delta t = t_S - t_U$) multiplied by the speed of light c measures the range to each satellite. The satellites are mutually and precisely synchronized to the system common time for positioning. The time used for precise system synchronization is GPST. The satellite atomic clocks are free running but steered to within 1 μs of GPST. Precise synchronization is attained by software correction of the individual satellite time to the system time (Δt_{SV}) at the receiver with parameters transmitted in each satellite's navigation message,

$$\Delta t_{SV} = a_{f0} + a_{f1}(t - t_{0C}) + a_{f2}(t - t_{0C})^2 + \Delta t_r \,. \tag{4}$$

The term t_{0C} is the update reference time of the clock parameters a. The Δt_r term represents a small additional relativistic time correction necessary to account for the elliptical satellite orbits. Although the orbits are nearly circular, the relativistic correction for this orbital altitude amounts to meters of error. The major relativistic effects are compensated for in adjusting the clock frequency by -4.45×10^{-10} Hz before launch. The residual error in correcting the satellite time to GPST, δt_{SV}, is the largest in the system. Determining the receiver clock's time offset from GPST (Δt_U) effectively synchronizes the receiver to the satellites so that the signal propagation time can be accurately measured, and, therefore, the range to the satellite is also calculated. The corrected receiver clock time now synchronized to GPST can be further corrected to UTC (USNO) by the time offset parameters also contained in the navigation message. This correction is discussed below.

To determine a receiver's position, pseudoranges $\rho^{(i)}$ are received from multiple satellites (i = 1, …, 4) simultaneously and expressed as

$$\rho^{(i)} = c\Delta t + c\left[t_U - t_S^{(i)}\right] + \varepsilon^{(i)}. \tag{5}$$

The term ε is a cumulative error term. The true range r given t_U and t_S comes from

$$c\Delta t = r\left(t_U, t_S^{(i)}\right) + I_\rho(t) + T_\rho(t), \tag{6}$$

where the *I* term is error due to transionospheric propagation, and the *T* term is error due to trans-tropospheric propagation.

The precise position of each satellite is calculated from orbital parameters transmitted in the each satellite's navigation message. Their orbital elements are in an Earth Centered Inertial (ECI) reference frame, which is transformed into the WGS-84 Earth Centered Earth Fixed (ECEF) frame for specifying satellite position and providing reference in the same frame as the receiver to prevent relativistic complications in the final calculations. The satellite positions can be calculated coincident with the signal transmission times so the precise three-dimensional position of the satellite $\vec{p}_S^{(i)}$ is accurately known. The residual satellite position error $\left(\delta \mathrm{p}_S^{(i)}\right)$ along the vector direction between the satellite and the receiver also produces an error in the measured pseudorange. After correcting the known values for satellite time, two frequency propagation corrections, an ionospheric delay correction, tropospheric model corrections, and grouping these errors, the corrected pseudorange is

$$\rho_C^{(i)} = \left|\vec{p}_S^{(i)} - \vec{p}_U\right| + c\,\Delta t_U + \tilde{\varepsilon}_\rho^{(i)}, \tag{7}$$

where

$\vec{p}_U$ is the dimensional position of the user,

$c\,\Delta t_U$ is the speed of light times the receiver clock time offset, and

$\tilde{\varepsilon}_\rho^{(i)}$ is error.

The solution of Eq. (7) results in the receiver's position. This expression can also be used as the basis for analyzing overall system performance.

Since this expression is nonlinear, it is approximated using a Taylor series as

$$\rho_C^{(i)} + \delta\rho^{(i)} = \left\{\left|\vec{p}_S^{(i)} - \vec{p}_{U0}\right| - \frac{\vec{p}_S^{(i)} - \vec{p}_{U0}}{\left|\vec{p}_S^{(i)} - \vec{p}_{U0}\right|}\delta\vec{p}_U\right\} + c\left\{\Delta t_U - \Delta t_{U0}\right\}\delta t_U + \tilde{\varepsilon}_\rho^{(i)}, \tag{8}$$

where

$\delta\rho^{(i)}$ is the pseudorange correct term

$\vec{p}_{U0}$ is the initial user position vector

$\delta\vec{p}_U$ is the residual user position error

Δt_{U0} is the initial user time offset, and

δt_U is the user time offset,

and in matrix form as

$$\left[\delta\rho^{(i)}\right] = G\begin{bmatrix}\delta\vec{p}_U \\ \delta t_U\end{bmatrix} + \left[\tilde{\varepsilon}_{\rho}^{(i)}\right]. \tag{9}$$

The measurement errors can be considered independent and uncorrelated so that $E(\tilde{\varepsilon}_{\rho}^{(i)}) = 0,$ and

$$Cov\left(\tilde{\varepsilon}_{\rho}^{(i)}\right) \equiv E\left[\tilde{\varepsilon}_{\rho}^{(i)}\tilde{\varepsilon}_{\rho}^{(i)T}\right] = \sigma^2 I, \tag{10}$$

where I is the identity matrix.

By iterative least squares, the solution is

$$\begin{bmatrix}\delta\vec{p}_U \\ \delta t_U\end{bmatrix} = [G^T G^{-1}]\, G^T\left[\delta p^{(i)}\right]. \tag{11}$$

This solution provides corrections to an initial estimate of position and time, and

$$Cov\begin{bmatrix}\delta\vec{p}_U \\ \delta t_U\end{bmatrix} = \left[G^T G\right]^{-1}\sigma_{UERE}^2. \tag{12}$$

σ_{UERE} is the satellite link measurement error, denoted UERE (User Equivalent Range Error). The UERE is an rms (root mean square) composite of the errors and is grouped into User Range Error (URE) and User Equivalent Error (UEE) denoting the space segment related errors (satellite position and SV clock) and user segment errors (propagation, signal effects such as multipath, and receiver errors) for analysis of the system.

The receiver positional accuracy is then the product of the link measurement error and a dimensionless constant, $\left[G^{-1}G\right]^{-1}$. This constant is the GDOP (Geometric Dilution of Precision) between the satellites and receiver. GDOP is made up of the direction cosines of the line-of-sight vectors to the GPS satellites at the time of the pseudorange measurements. Also known as the *Geometry* matrix, H $(=\left[G^{-1}G\right]^{-1})$, it is a significant multiplying factor in the projected position error. Expanding H into matrix form shows that along the main diagonal are the variances of the independent position and receiver clock parameters:

$$\left[G^{-1}G\right]^{-1} = \begin{bmatrix}\sigma_x^2 & \bullet & \bullet & \bullet \\ \bullet & \sigma_y^2 & \bullet & \bullet \\ \bullet & \bullet & \sigma_z^2 & \bullet \\ \bullet & \bullet & \bullet & \sigma_t^2\end{bmatrix}. \tag{13}$$

The dilution of precision (DOP) definitions are then

$$GDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + c^2\sigma_t^2} \quad (14)$$

$$PDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad (15)$$

$$HDOP = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (16)$$

$$TDOP = \sqrt{c^2\sigma_t^2} \quad (17)$$

GDOP varies with the changing geometry of the satellite constellation, consequently so do the position and time accuracies. Also, the position determined by the process above is the position of the receiver antenna, which may be located some distance from the receiver as may happen on a large ship. TDOP associated with the user receiver's clock correction varies to a lesser degree. However, the time correction reference is the signal correlation in the receiver, so additional corrections are necessary to output UTC time from the receiver.

GPS Receiver Output Time

The difference between the receiver clock and GPST, Δt_U, determined above is the receiver-determined internal difference to its local clock. For output, it must be corrected by the receiver calibration factor that accounts for internal and external processing delays, and a calibration term for the specific receiver installation accounting for the propagation delay through the antenna and cabling to the receiver. GPST determined in this process must also be corrected to UTC (USNO) by the correction terms broadcast by the satellites in their Navigation Message. The process for determining and providing these correction terms to GPST in the Navigation Message and Earth orientation terms necessary for orbit determination are contained in ICD-GPS-202 [46].

The GPST values are corrected with the parameters in the navigation message to UTC (USNO*)* as described in GPS-ICD-200C [47]. The correction is

$$t_{UTC} = t_E - \Delta t_{UTC} \text{ (modulo 86,400 s).} \quad (18)$$

The value t_E is the start of the GPS week (Saturdays at midnight) which runs in seconds for the week, giving t_{UTC} in seconds. The current GPS week number *WN* accounts for the accumulation of weeks since the beginning of GPS Time in 1980, and WN_t is the reference for the correction polynomial. The correction is

$$\Delta t_{UTC} = \Delta t_{LS} + A_0 + A_1\left[t_E - t_{0t} + 604{,}800(WN - WN_t)\right], \quad (19)$$

where t_{LS} is the correction for leap second differences, t_{0t} is the starting point of the clock correction polynomial in GPST, A_0 is the initial time offset, and A_1 is the frequency offset. The resultant value for UTC is then formatted in the time code necessary for the timing interface of the receiver. An output reference frequency synthesized from the corrected internal clock can also be used to produce a one pulse per second (1PPS) signal to accompany the time code. Standard Precise Time and Time Interval (PTTI) outputs for military GPS receivers are provided in accordance with GPS-ICD-060 [48].

The GPS output can then be used as a time and frequency source directly traceable to UTC (USNO). The accuracy and precision of the interface are determined by the GPS receiver's time solution and its internal instrumentation used to generate the physical signals and time codes. The resultant time from the GPS receiver is then

$$t_{UTC} = t_U - (\Delta t_U + \Delta t_{RC} + \Delta t_{ANT}) - \Delta t_{UTC} \,. \tag{20}$$

The output time uncertainty (1 sigma rms error) is a composite of the uncertainties in the contributing error sources. Receiver calibration and antenna delays are presumed here to be constant. The uncertainty is expressed as

$$\sigma(t_{UTC}) = \sqrt{\sigma^2(\Delta t_U) + \sigma^2(\Delta t_{UTC})}. \tag{21}$$

This time source is the physical representation of UTC (USNO) for the warfighting unit. Specific display and time code data words are defined in GPS-ICD-060 [3] as well as display specifics on the Time of Day and Day of Year in UTC for the control and display unit of the GPS receiver, and a display of the error between the Local Time and UTC (USNO).

The data shown in Fig. 14 are the result of time dissemination testing at NRL with a Precise Lightweight GPS Receiver (PLGR) in static positioning and time transfer [49]. The figure shows the accuracy with which absolute UTC (USNO) time can be disseminated to passive receivers in field or mobile locations. GPS can provide a common absolute reference time accurately across an operational theater to synchronize the variety of platforms and systems engaged.

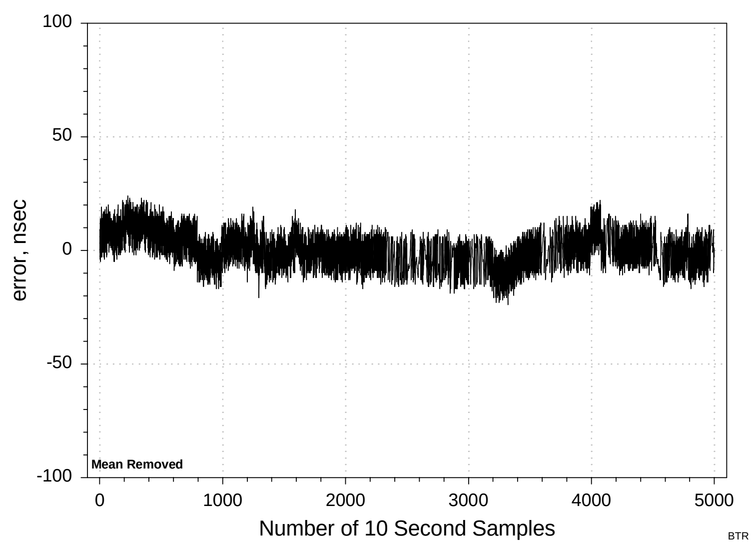

Fig. 14 — PLGR time output

Common View GPS Time Transfer

GPS time transfer between the worldwide timing centers and the scientific community use another technique known as Common View (CV) and its variant, Carrier Phase Common View [39,50]. This technique is fundamentally a point-to-point technique rather than a general broadcast as in the passive reception case discussed above. The two sites requiring time transfer exchange pseudorange measurements taken from individual GPS satellites. Differencing the raw or semiprocessed pseudorange data results in a comparison between the local clocks at the two sites. Carrier phase measurements are a mechanism for increasing the precision of the pseudorange or range measurement between the receiver and the individual satellite. This increase results from measuring the phase of the RF carrier of the signal rather than the unambiguous code modulation, 1.5 GHz signal vice 10.23 MHz. The price for this increased precision is the ambiguity of the continuous RF signal. Calibration of geodetic receiving systems by using GPS system simulators is the subject of a small effort at NRL [51]. Calibration by the use of a simulator provides complete control of all the conditions of signal reception. For passive time transfer or common view with the code signal rather than the carrier phase, the techniques can provide an absolute calibration for determination of time epoch transfer. An overall summary of GPS techniques is contained in Table 4.

Table 4 — GPS Time Dissemination Techniques

Parameter	**Passive (SPS)**	**Passive (PPS)**	**Common View (Short Base)**	**Common View (Long Base)**	**Linked Common View (LCV)**	**Carrier Phase**	**WAAS/GPS**
Accuracy (ns rms) [Range]	≤ 8 [2, 3] wrt UTC(USNO)	≤ 8 wrt UTC(USNO)	3-8 (point to point)	5-10 (point to point)	≤ 5 (Global)	≤ 5-10 (point to point, but absolute is ambiguous)	≤ 20 wrt UTC(USNO)
Major Error Sources	SA, Multi-Path, Clock, Iono, Tropo, UE, RF Enviro, Temp (RX & Ant)	Multi-Path, Clock, UE, RF Enviro, Temp (RX & Ant)	UE, Path Reciprocity, Ephemeris, Enviro (Temp)	UE, Path Reciprocity, Ephemeris, Enviro (Temp)	UE, Path Reciprocity, Ephemeris, Enviro (Temp)	UE, Multi-Path, Cycle Slips	Clock, Ephemeris
Stability	≤ 8 / 13 min ≈ 10^{-14}/day	≤ 5 @ 13 min ≈ 10^{-14} /day	≤ 4 / 1 hour ≤ 1 / 48 hours	≤ 4 / 1 hour ≤ 1 / 48 hours	≤ 4 / 1 hour ≤ 1 / 48 hours	<< 1 / 6 min	< Passive SPS
Lower limit of Calibration (ns)	3-5 Against Std Rcvr	3-5 Against Std Rcvr	3-5 Against Std Rcvr	3-5 Against Std Rcvr	3-5 Against Std Rcvr	< 1 ns (Undetermined)	3-5 ns Against Std Rcvr
Sample Rate	1 per 13 min	1 per 5 min 1 per 13 min	1 per 13 min	≥ 1 per 13 min (post-processed)	1 per 5 min 1 per 13 min or TBD	Similar To Passive & Common View	TBD
Availability	Real Time	Real Time	NRT Depends on Scheds	Can Be NRT Depends on Scheds, Orbits & Comms	Can Be NRT Depends on Scheds, Orbits & Comms	Depends on Processing	Real-Time

Notes:

1. to attain the stated accuracy

2. fixed accurately known position

3. equipment dependent

4. approaches the noise floor

GPS is so capable, and the instrumentation for civilian time applications has become so inexpensive, that small civilian receivers are being integrated into a variety of timing equipment, primarily for telecommunications, to discipline inexpensive clocks. These commercial integrated timing subsystems, available off the shelf, with their increased performance are being used to replace more expensive clocks. Newer telecommunication and data processing equipment for military systems sometimes contain these embedded GPS receivers. These embedded receivers are hidden vulnerabilities in these military systems. With accurate UTC (USNO) time now generally available with increased accuracy for systems and platforms worldwide, legacy systems designed around relative time concepts can be integrated into a more effective overall architecture.

Two-Way Satellite Time and Frequency Transfer (TWSTFT)

The most precise time transfer technique in use today is TWSTFT [37]. This technique takes advantage of the two-way capability of communication satellites (Comsats) to transmit timing signals in both directions to virtually eliminate the transmission and common instrumentation delays between the two participating sites to transfer time. This is a point-to-point technique used between timing centers suitably equipped. Originally pioneered by the Institute of Navigation (ION) in Stuttgart, Germany [52], they produced a TWSTFT modem known as the Hartl modem after Dr. Phil Hartl, the principal investigator. This finely tuned analog modem, built in limited numbers by ION, relied on an independent link for exchange of measurement data for a complete time closure. The first successes were followed by a commercial digital modem, also known as the Hartl modem. The analog modem successfully demonstrated the potential of the technique through time transfer performance in the tens of nanoseconds at a time when GPS was performing at approximately the 100-ns level. The digital modem operated unsuccessfully and the analog modem was difficult to operate, required additional communications, and became unavailable, given its noncommercial source.

At this point in development, NRL designed and built a new digital TWSTFT modem to develop the technology and transfer the manufacturing capability to industry [38]. This modem was designed to transmit data with the timing signal so that an additional data link is not required and a complete time transfer can be accomplished in one session through the Comsat. With the successful completion and test of the NRL-built modems, the concepts and design were transferred to a commercial concern [53]. This concern was to support the production of these modems for USNO and any other center wanting this equipment, especially the newly formed Subcommittee for TWSTFT of the International Consultative Committee for Time and Frequency. This subcommittee has engaged in international experiments in the technique and definition of international data exchange standards for participating timing centers. It is now the primary link for comparison of Primary Standards and for the definition of TAI [54]. Extensive deployment of these modems has been made in classified programs. They are the primary link between USNO and the Alternate Master Clock at Shriever Air Force Base. Another current application is the deployment of a network for the Air Force Eastern Range to transfer time between the Range Operations Control Center at Cape Canaveral and the other three tracking sites in downstate Florida, Antigua, and Ascension Island. A next-generation modem was designed by NRL and a new source of these modems was developed for this program, which could produce the units less expensively and with greater reliability.

The TWSTFT modem takes the 1PPS output from its local clock to generate a pseudorandom ranging code for transmission by a Comsat ground terminal. The ranging signal occupies about 2 MHz of bandwidth. The modems can operate with any Comsat terminal but generally are used with Very Small Aperture Terminals (VSATs) that are mostly used with commercial Comsats. Other types of satellite links used include mobile X-band terminals for DSCS and the C-band INTELSAT system. The receiving terminal listening to the Comsat downlink is addressed by a unique identifier, demodulates the code and compares the regenerated 1PPS with its own, encodes the comparison with other site data, and responds with a similar code generated from its local clock. An interchange of ranging signals follow, providing a number of time transfers during the communications session. The single measurement precision of a single two-way transfer is approximately 10 ps. Overall accuracy depends on reciprocal instrumentation and satellite transponder delays. Possible satellite motion during the transfer process introduces nonreciprocal delays. Time transfer accuracies of 100 ps are theoretically possible if the nonreciprocal errors can be sufficiently reduced.

The true time offsets of the two time standards can be measured very precisely (0.2 ns) and accurately (1.0 ns). By taking data over a period of time, the long-term behavior (i.e., frequency changes, rates, jumps, drifts) that will affect the accuracy and stability, and thus, the operational usefulness of a clock may be characterized. Improved confidence in reliance on accurate time is a key benefit. The day-to-day stability of two-way time transfers can nearly reach the performance of the best reference clocks. Figure 15 is a diagram of time transfer using a communications satellite.

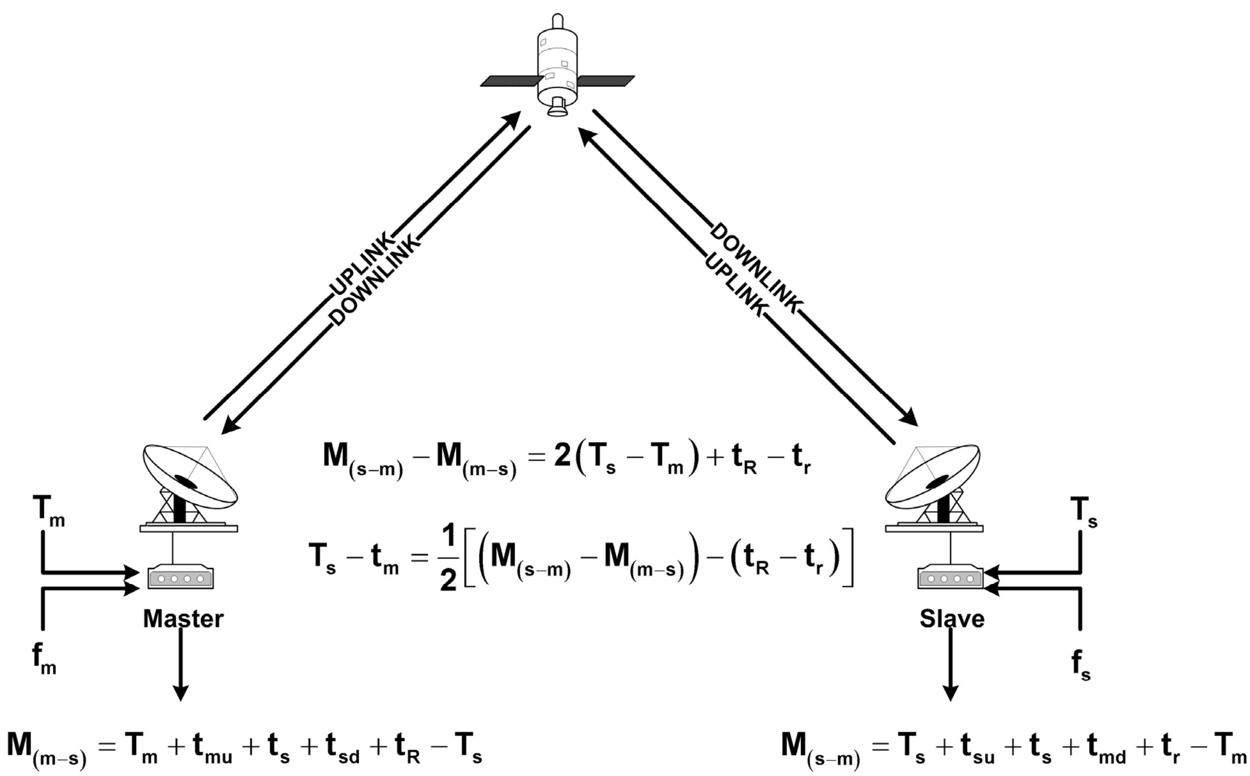

Fig. 15 — Two-way time transfer with a communications satellite

Extension of this technique to mobile platforms could provide an alternative means of providing precise time to the operating forces. By using existing communications systems combined with a smaller ruggedized modem, highly precise and accurate time could be disseminated to multiple points. Investigation of this technique could encompass the new Global Broadcast Systems and other new communications capabilities being developed.

LORAN-C

Loran-C is a long-range navigation system operated by the U.S. Coast Guard. Loran was originally developed to provide radio navigation for U.S. coastal waters. It has been expanded to cover the continental U.S. and most of Alaska. Users of the system receive messages from at least two Loran-C stations located across the U.S. and Canada. By measuring the time difference between the two messages, users can compute their location with Loran-C charts or within a receiver. Loran-C provides better than 0.25-nmi absolute accuracy within published areas [40].

Navigation, location, and timing services are furnished for civilian and military air, land, and marine users. The U.S. Government is continuing to run this program in the short term, but the system is being evaluated for cost effectiveness. The supporters of the Loran-C system contend that it should be used to complement GPS. If the government decides in the future to discontinue its support, other sponsors may be located since the system is also used for instrument flight rule and visual flight rule aircraft operations.

Loran is also used extensively to establish a precise time reference. Power companies, telephone companies, and many others use Loran-C as a source of timing information for such purposes as controlling and monitoring cesium clocks. Loran-C timing uncertainty is about 100 ns within areas of good coverage [55].

Relative System Adaptation for Time Transfer

JTIDS, also referred to as Link-16, provides data communications, navigation, and identification within a tactical area [56]. The system is jam-resistant and designated for joint/combined force interoperability. While timing and synchronization are not among the primary functions of JTIDS, relative synchronization is necessary for system operation. The capability of this system to augment other more traditional time transfer systems is being investigated [57]. JTIDS operates in a time division multiplexed network of participating terminals. The geographic limitations on the system are associated with LOS between the units in the network. This drawback can be alleviated somewhat by the use of relay stations. These relay stations pass the data and time information to all units within their LOS (any unit can be a relay station). These distant units may not be able to see the network time reference or any other unit.

To set up a network, one unit is designated the Network Time Reference (NTR). All other unit clocks are synchronized to this unit's time. The NTR clock is assumed to be correct so that the accuracy of all units within that network depends on the clock at the NTR. This aspect of the system allows for two JTIDS networks to have significantly different network time. The difference would affect, for example, an aircraft whose mission crossed more than one network and that needed precise data (both timing and navigation) to be successful. These time differences may cause delays for a unit switching from one network to another since the synchronization process described below would have to be repeated.

Once an NTR is established, it transmits an entry message. Once the entry message is received at a platform, that unit is in course sync with the NTR terminal. Once a unit is in course sync, it transmits a Round Trip Timing Interrogation (RTTI) message to a unit already in fine sync, which sends a Round Trip Reply. The unit is in fine sync when it receives the Round Trip Reply and estimates its time error relative to the network time. Only units in fine sync can transmit messages other than an RTTI.

Messages are transmitted in time slots. These time slots are distributed in different ways depending on the setup of the network and the needs of a particular unit. Each time slot consists of jitter, synchronization, time refinement, message header, data, and propagation. Time accuracy depends on the

NTR clock's accuracy. The components of the time slot are measured in µs, but the time slot boundaries are known within ns.

The disciplining of the NTR clock by GPS or other means to align JTIDS time to UTC (USNO) is the technique for managing the relative net to a common time. The capability of the system to transfer the time through this mechanism is being investigated.

Other Techniques

A summary of Two-Way Satellite Time and Frequency Transfer and techniques of time transfer by cable or fiber, which have not been discussed, is shown in Table 5.

Table 5 — Two-Way Techniques

Parameter	**TWSTFT**	**Fiber LAN-WAN**	**Fiber Long Haul**	**Two-Way In Comms (OTA)**
Accuracy (point to point) [Range] (ns rms)	≈ 1 (Ku-band) ≈ 1 (X-band) ≈ 3+ (C-band)	≤ 1 / 200 km	≤ 2 / 8000 km (TBR)	≤ 5 / 200 km
Major Error Sources	Path Reciprocity, Sys Cal, Environ (Temp)	Path Reciprocity, Environ (Temp)	Path Reciprocity, Environ (Temp)	Path Reciprocity, Sys Cal, Environ (Temp)
Stability (Value @ Avg Time)	200 ps @ 1 hour 100 ps @ 12 hour	100 ps rms	TBD	TBD
Calibratibility (Level in ns)	≈ 1	≈ 1	≈ 2	≈ 3-5
Sample Rate	1 per 5 min	Continuous	Continuous	Continuous
Timeliness	Near Real Time	Real Time	Real Time	Real Time

SYSTEMS TIMING INFRASTRUCTURE

With the time reference defined and the precise and accurate means of transferring time, the users need to be able to accurately keep time and coordinate between systems and platforms to effectively maintain a CTR. A systems architecture using the time standards already distributed through the Naval systems and platforms could use the existing assets already in place and functionally incorporate them into a combined clock group. The resulting group could be combined with comparison, interfacing, and the local time would then be compared with the common time via the time dissemination element, i.e., GPS receivers and other means, such as TWSTFT, or through a local comparison via JTIDS to Task Group participants. The dissemination systems, including alternatives, would be active participants in the composite time group, maintaining time throughout the other task group elements. For this process to be realized, the system interconnection infrastructure must be able to support these functions.

Distributed Time Standards Overview

The elements of an architecture of Distributed Time Standards would be able those to generate, compare, maintain, and distribute a local time referenced to common time within the platform's systems. Integral to this approach are the time source, the dissemination interface, and the means of distributing time. The approach to combining the timing resources within the infrastructure and incorporating them is shown in Fig. 16.

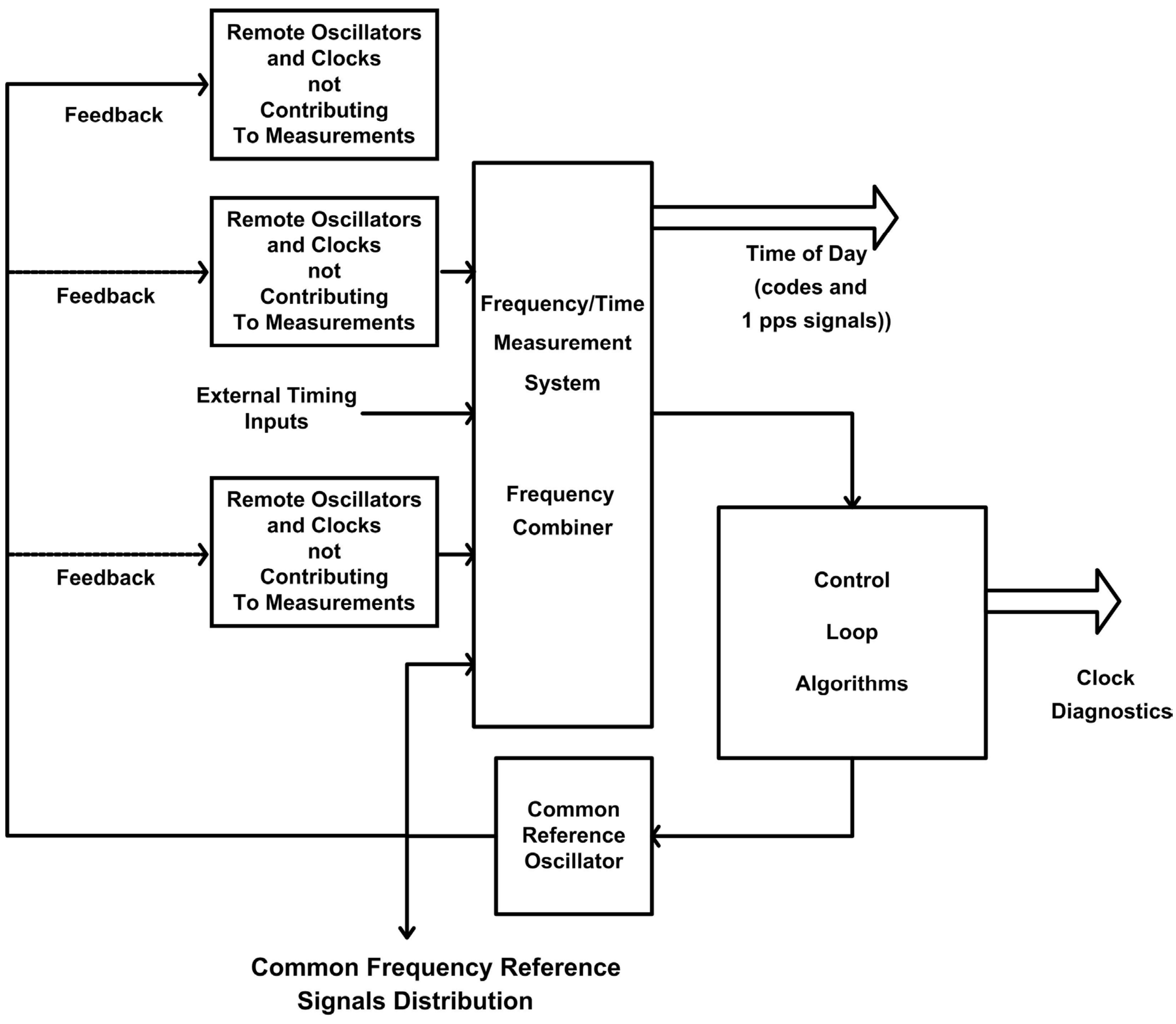

Fig. 16 — Generic distributed time standard implementation

Reference Frequency

By isolating the frequency reference from the rest of the system, a redundant common frequency reference with low phase noise and good accuracy can be achieved. If very low levels of phase noise are required, atomic frequency standards without internal synthesizers should be used. Alternatively, disciplined oscillators based on low-noise crystal oscillators can be introduced to follow the atomic frequency standards to clean up the phase noise. While the second solution may be applicable to most situations, care must be taken in applying crystal oscillators to clean up phase noise in vibration-prone environments, since the acceleration sensitivity of the crystal may make matters worse.

To improve the frequency accuracy over that of a single atomic clock, the oscillator frequency source offset can be measured against a reference source. A Cesium beam frequency standard is capable of reaching a frequency stability floor of parts in 10^{-14} or better at one day sampling time, and the flicker floor may last several days. Therefore, precise timing measurements from an external accurate source can be averaged over several days to precisely estimate the frequency offset to a few parts in 10^{-14}. In doing this, reliance is placed on the intrinsic stability of the frequency standard to improve its frequency accuracy. Once the frequency offset is precisely measured, it can be used to correct the frequency of the oscillator.

Frequency corrections can be applied directly to the oscillator to steer it towards the external reference. However, applying a frequency correction affects the frequency stability and the spectral purity of the oscillator, and in some systems this cannot be tolerated. Therefore, if the intrinsic frequency accuracy of the oscillator only limits its timekeeping capabilities, the correction can be applied via a synthesizer or a micro-stepper further down in the signal chain, just before the clock circuits, leaving the spectrally pure signal output by the oscillators free from any disturbance due to the frequency control.

Local oscillators or remote oscillators may contribute equally to the common time and frequency reference system, if they meet the required low-phase noise specification and are comparable in long-term stability. Multiple oscillators within this system are not intended to be ensembled to improve their stability, but are intended to provide redundancy and an uninterrupted, continuous signal. In this case, each will have to fulfill the requirements of the timing system, either by meeting the full specification or just a reduced requirement in a degraded condition.

A redundant common timing reference, steerable to a long-term frequency accuracy better than that provided by the common frequency reference using an external link, is achieved by preceding the local clocks (two for redundancy) with two-phase micro-steppers. These micro-steppers allow control of the long-term stability of the time scale by generating precise frequency offsets without affecting the spectral purity of the frequency standards.

Time and Frequency Adjustment

Timing errors arise because of initial setting errors (initial synchronization), phase jumps, or frequency changes. Regardless of their cause, timing errors can be corrected by applying time steps or by properly adjusting the frequency of the reference oscillator (input to the clocks) with a minute amount, so that the resulting accumulated error vs time cancels the timing offset. After the correction, the frequency is restored to the nominal value. Both techniques work in practice, even if the second technique is generally preferred. A time step can be regarded as a correction obtained by applying a very large frequency offset for a very short amount of time. Frequency corrections achieve the same result, but they avoid sudden timing transients and allow better control of the amount of the correction and the time required to recover the timing offset.

Frequency distribution provides clean signals to the users; by placing the frequency distribution amplifiers after the redundant frequency switching system, continuity is ensured. High reverse-isolation buffer amplifiers, providing galvanic isolation, isolate the common frequency reference from disturbances that may be fed back from the user equipment and reinjected into the system.

Timing Signals Distribution

Time codes and reference pulses (i.e., 1PPS signals) are generated and distributed to the users, providing a common time reference with various levels of accuracy and resolution. Codes may range from specialized codes, such as the InterRange Information Group (IRIG) family of codes [58] (both in the nonmodulated and modulated formats), to simple time-of-day information, coded as ASCII characters on normal RS-485 or RS-422 serial lines.

Measurement Subsystem

Monitoring is accomplished via start-stop time interval measurements on the 1PPS pulses generated by the primary oscillators, the two reference clocks, the timing distribution equipment, and the 1PPS signals provided by the GPS timing receiver(s) and two-way time transfer modem. The reference (start) pulse for all the measurements is the signal provided as the common time reference to the users, and derived from the online clock. Time interval measurements allow users to assess the rate of the individual clocks with respect to an external reference (UTC (USNO)), correct the phase micro-steppers to compensate for the frequency offset of the online frequency reference, and monitor the general conditions of the overall system.

Intercomparison Techniques

In the system shown in Fig. 17, the intercomparison of oscillators and clocks is carried on using 1PPS pulses. The use of 1PPS signals vs intercomparison carried on at the output frequency (10 or 5 MHz) of the oscillators has advantages and disadvantages. Obviously, 10 MHz allows higher resolution and use of a double mixer system; however, for timing purposes, it carries an intrinsic ambiguity of 100 ns (1 period of the signal) that must be accounted for. On the other end, intercomparing oscillators using 1PPS pulses requires frequency dividers on each oscillator being monitored to derive the 1PPS signal necessary for the measurement.

GPS timing receivers and two-way synchronization modems, conversely, work by outputting 1PPS signals, and using all 1PPS signals in the measurement system, this makes the system simpler to design and operate. Even if 10 MHz phase comparison allows higher resolution in the measurement, modern time interval counters are equally capable of high resolution (typically 25 ps resolution and ~300 ps accuracy, depending on the time base selected). 1PPS measurements of multiple clocks can be accomplished with a single time interval counter by a switching arrangement or via an Event Clock or a TDC (Time-to-Digital Converter), which time-tags the events occurring on multiple ports with a given resolution.

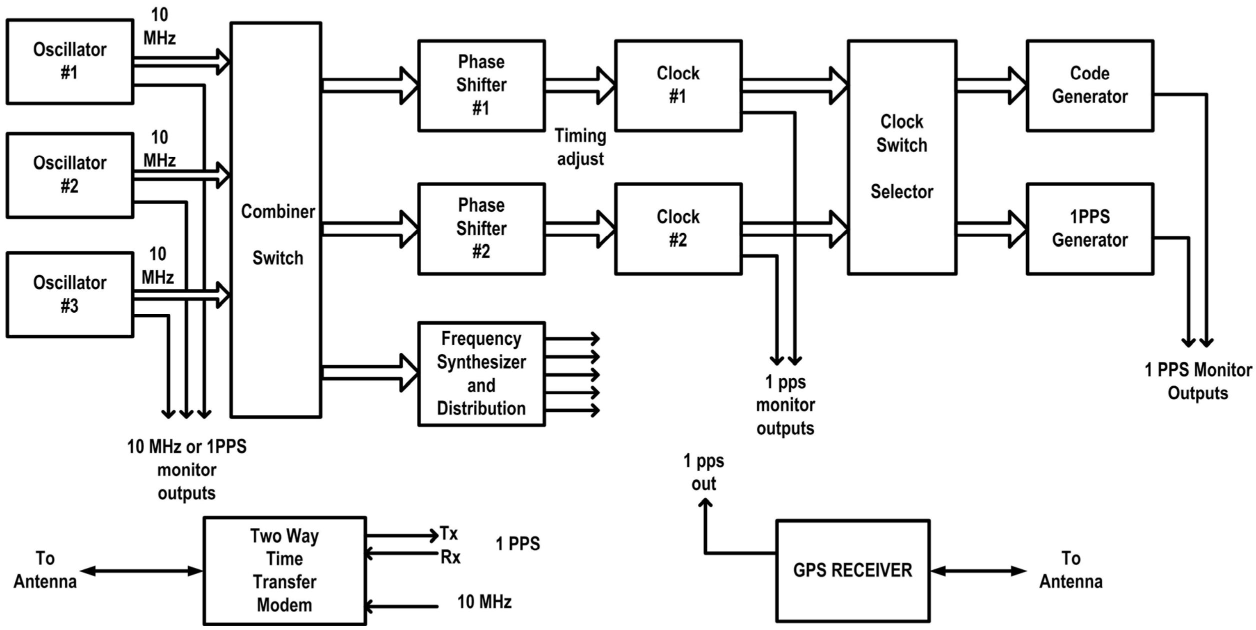

Fig. 17 — Basic common frequency and time reference system

Advanced Approach

The next step will be to combine the two measurements (time and frequency) and their control systems into a single unit. This can be readily done since frequency can be measured by timing system measuring time intervals. The intervals may be used to derive estimates of the frequency offset between two clocks from measurements of the time offset taken at different times. The measurement technique must first be established.

Phase Measurement System

To effectively use available oscillators and clocks locally associated with other equipment onboard the platform, some means of intercomparing these same oscillators and clocks must be provided. In addition, it is desirable that the same measurement system be able to intercompare the local clocks to remote references so that the platform (local) reference time may be steered to the CTR.

Phase measurements must be performed either as angular measurements or, preferably, as time intervals, since they can be measured with greater accuracy and resolution. Time interval measurements provide the additional advantage that the same measurement technique can be applied to frequency reference signals (sine waves) as well as to timing signals (generally in the form of 1PPS pulses), thereby allowing a direct intercomparison of different frequency and timing sources.

Dual Mixer Measurement System

Direct intercomparison is feasible, but not advisable, due to the poor resolution of the measurement. Resolution can be substantially increased by the use of the well-known dual-mixer technique [59], shown in Fig. 18. Define Δx as the phase difference $\Delta\varphi = \varphi_2 - \varphi_1$ between two oscillators, $\Delta x = \frac{\Delta\varphi}{2\pi\cdot\nu_0}$, normalized in units of time, where ν_0 is the nominal frequency of the oscillators. Since the downconversion process preserves the phase information, $\Delta x_{beat} = \frac{\Delta\varphi}{2\pi\cdot\Delta\nu}$, where Δν is the beat frequency, i.e., the difference between the nominal frequency of the oscillators and the frequency of the offset oscillator. The measurement of the time interval Δx_{beat} yields $\Delta x_{beat} = \frac{\nu_0}{\Delta\nu}\cdot\Delta x$, where the effective gain $K_{downconversion}$ on the phase measurement (in units of time) in the measurement process is $K_{downconversion} = \frac{\nu_0}{\Delta\nu}$. Since ν_0 = 10 MHz and Δν = 10 Hz, then $K_{downconversion} = 1\cdot10^6$. If Δx_{beat} is measured by a Time Interval Counter (TIC) with a resolution $\Re(\Delta x_{beat})$= 20 ns, the measurement of Δx implies an equivalent resolution of $\Re(\Delta x)$= 20 fs. The basic arrangement shown in Fig. 18 can be easily extended to a setup designed to measure multiple oscillators as shown in Fig. 19.

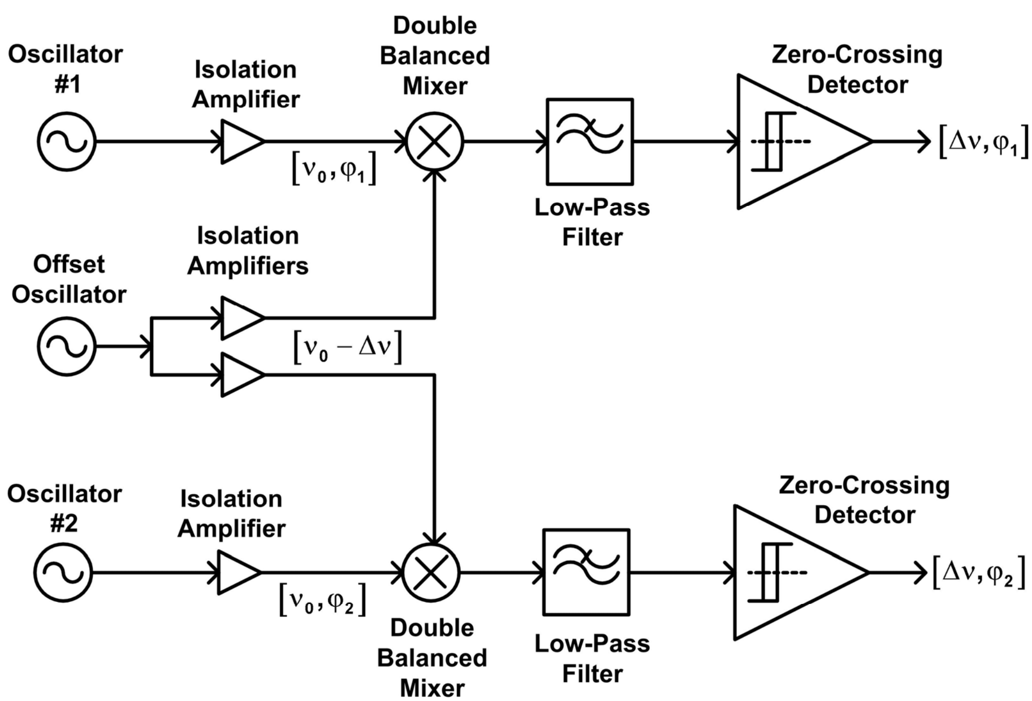

Fig. 18 — Dual mixer block diagram

This arrangement shown in Fig. 19 allows measuring the phase difference Δx_i between one (reference) oscillator (say #0) and all the remaining *N* oscillators to be precisely measured: $\Delta x_i = x_i - x_0$, or

$$\Delta x_{i,\,beat} = \frac{\nu_0}{\Delta\nu}\cdot\Delta x_i = \frac{\Delta\varphi}{2\pi\cdot\Delta\nu} = \frac{\varphi_i - \varphi_0}{2\pi\cdot\Delta\nu}, \tag{22}$$

providing effectively a multiple-phase measurement system.

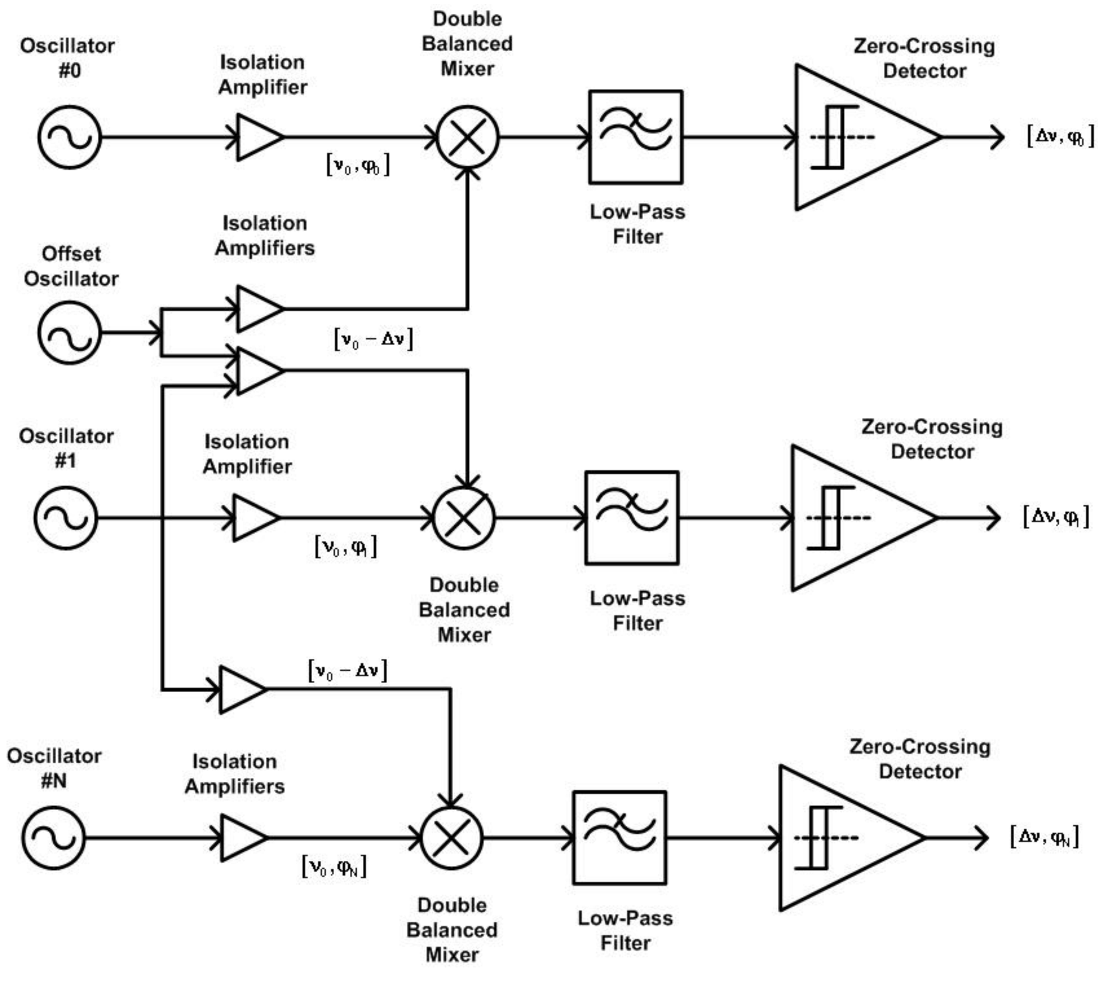

Fig. 19 — Multiple mixers high-resolution phase measurement system

Event Timer

A TIC can still be used with the multiple-phase measurement system to measure Δx_i [i = 1, *N*] through a switch, but multiple measurements can be performed simultaneously by using an Event Timer or Time Interval Analyzer (TIA); in instrumentation for nuclear physics it is also referred to as a TDC [60].

An Event Timer is a device with multiple inputs. Each input accepts a signal; a selectable feature of the signal represents an event, and an event can be, as an example, any zero crossing of a signal waveform, the positive zero crossing only, the signal reaching a predefined value, etc. The occurrence of the event triggers the instrument to store the time corresponding to the event with a given resolution and an associated ambiguity. The resolution relates to the minimum time interval occurring between two consecutive events on different inputs such that the relative timing can be discriminated. The ambiguity is the overflow of the time scale in which the events are dated. Or, in electronic terms, the ambiguity is directly related to the number of bits of the internal counter (clock) with respect to which the events are dated.

A general block diagram is shown in Fig. 20 for an Event Timer with 16 input channels. The input signals are conditioned for event detection. The channel on which the event occurs can be encoded (4-bit) but if simultaneous events are detected on different channels, this type of encoding limits the capability of the instrument to detect simultaneous events. To fulfill the latter requirements, 16 bits are required for channel identification. The occurrence of an event on any of the input channels stores the Time-of-Day (TOD) into a local memory, conveniently arranged as a first in, first out circuit (FIFO) to allow data readout from an external computer.

The clock (a 40-bit counter) used to generate the TOD is reset at the end of the day so that the actual reading represents the number of periods of the reference frequency elapsed from midnight of the current day. In this way, the measurements are also related to absolute time, if desired.

The combination of the dual (multiple) mixers phase measurements system and event timer effectively acts as a high-resolution multiple phase-difference measurement system.

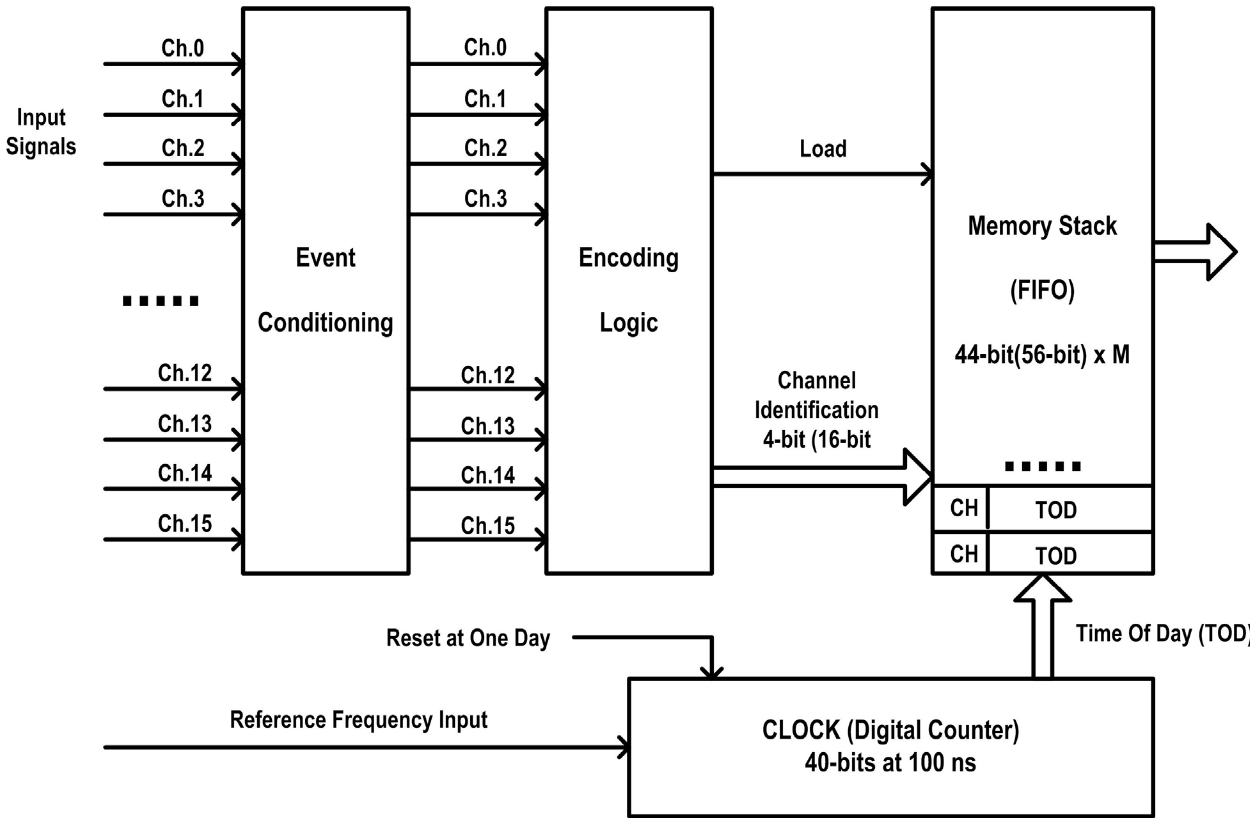

Fig. 20 — General block diagram for a 16-input Event Timer

Phase Differences

Phase-differences obtained in by these techniques can be used for various purposes:

1. providing a measure of the systematic parameters (phase and frequency offset, and frequency drift) of each oscillator with respect to a particular oscillator chosen as the reference;

2. providing a measure of the stability of the oscillators with respect to the reference;

3. using the phase difference measurements to control the phase and frequency of a VCO in a phase-locked loop configuration.

The systematic oscillator parameters and stability can be used to provide the capability to detect anomalies in the input oscillators. As the means of controlling external oscillators through control loops, this is particularly appealing if the system is implemented with an Event Timer, since in this case the input signals may originate from a mix of frequency references, providing 10 MHz sine wave signals fed to the multiple mixer arrangement for downconversion, and timing references providing 1PPS signals directly to the Event Timer inputs.

Multiple-Input Time/Frequency-Disciplined Oscillator

If the multiple-input phase measurement system can be regarded as a kind of generalized phase detector, then it can be used as the phase detector to implement a multiple-reference phase-locked loop (PLL). A local oscillator may be steered to the CTR using a mix of local oscillators and clocks to provide added stability and redundancy to the local reference time and external timing references (GPS, two-way measurements, etc.). The resulting time is then steered to UTC (USNO) in the long term, thereby providing long-term accuracy to the Local Reference Time and synchronization widely separated platforms and systems. Figure 21 depicts an implementation of this system.

The use of a multiple-input phase measurement system as a phase detector is particularly versatile. The input signals can come from a mix of frequency references providing 10 MHz signals to the multiple mixers arrangement for downconversion and 1PPS signals directly to the inputs of the Event Timer.

The output of the Event Timer provides phase (time) differences in the form given by

$$\Delta x_{i,\,beat} = \frac{\nu_0}{\Delta\nu}\cdot\Delta x_i = \frac{\Delta\varphi}{2\pi\cdot\Delta\nu} = \frac{\varphi_i - \varphi_0}{2\pi\cdot\Delta\nu} \qquad (23)$$

These can be averaged (with the proper weight) to contribute an error signal to the integrator(s) that outputs the control signal to the voltage-controlled oscillator (VCO).

Obviously, after the Event Timer outputs the phase differences, the data processing can be carried on in numerical form, where the data average and integration can take the usual structure of a recursive filter. Even the VCO can be digitally implemented (for instance, using a direct digital synthesis (DDS)), if the phase noise is acceptable in terms of the given requirements.

Distributed Clock Implementation

By using a multiple-mixer system in combination with an Event Timer, the goal of combining the frequency and time measurement systems, as shown in Fig. 22, has been achieved. The next step will be to implement the real-time clock, i.e., the integrator of the common frequency output by the VCO in the system. This can be accomplished very simply since a single connection will suffice, the clock being already available in the system, embedded in the Event Timer. It is only required to feed the Event Timer with the signal originating by the VCO.

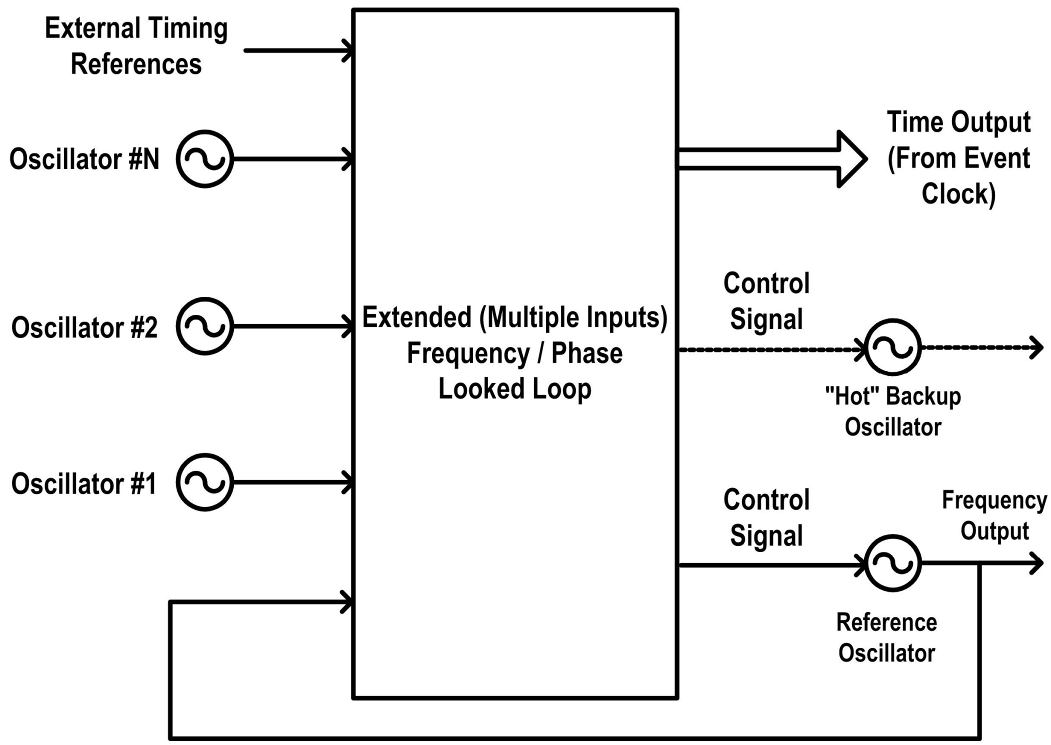

Fig. 21 — Multiple-references phase-locked loop implementation

Except for the initial synchronization procedure of the system, stepping the clock to correct for time offset should be avoided, since, if not properly taken into account, it will affect also the continuity of the series of measurements taken by the Event Timer. Instead, preference shall be given to rate corrections to steer the system (in time and frequency) to a common reference.

Obviously, greater freedom in the steering algorithm to incorporate time steps can be gained by including a separate clock, but the solution proposed is effective in the sense that it makes maximum use of the system resources. The common clock and the frequency and time measurement units have been combined into a single assembly that can minimize the interconnections between different units, increase the overall reliability, and allow the system to be configured in a compact form.

Digital Phase Measurement System

The implementation of software radios has led to the development, in recent years, of a family of components intended for high-speed data conversion (using (analog-to-digital converters (ADCs)) and processing. Digital phase modulation in various forms (BPSK, QPSK, m-PSK, FQPSK, etc.) requires carrier phase recovery for data demodulation. Carrier phase is usually recovered by digitizing the input signal into in-phase and quadrature components that feed a digital Costas-loop to recover the suppressed carrier and demodulate the data. Figure 23 illustrates the digital electronics of such an input stage.

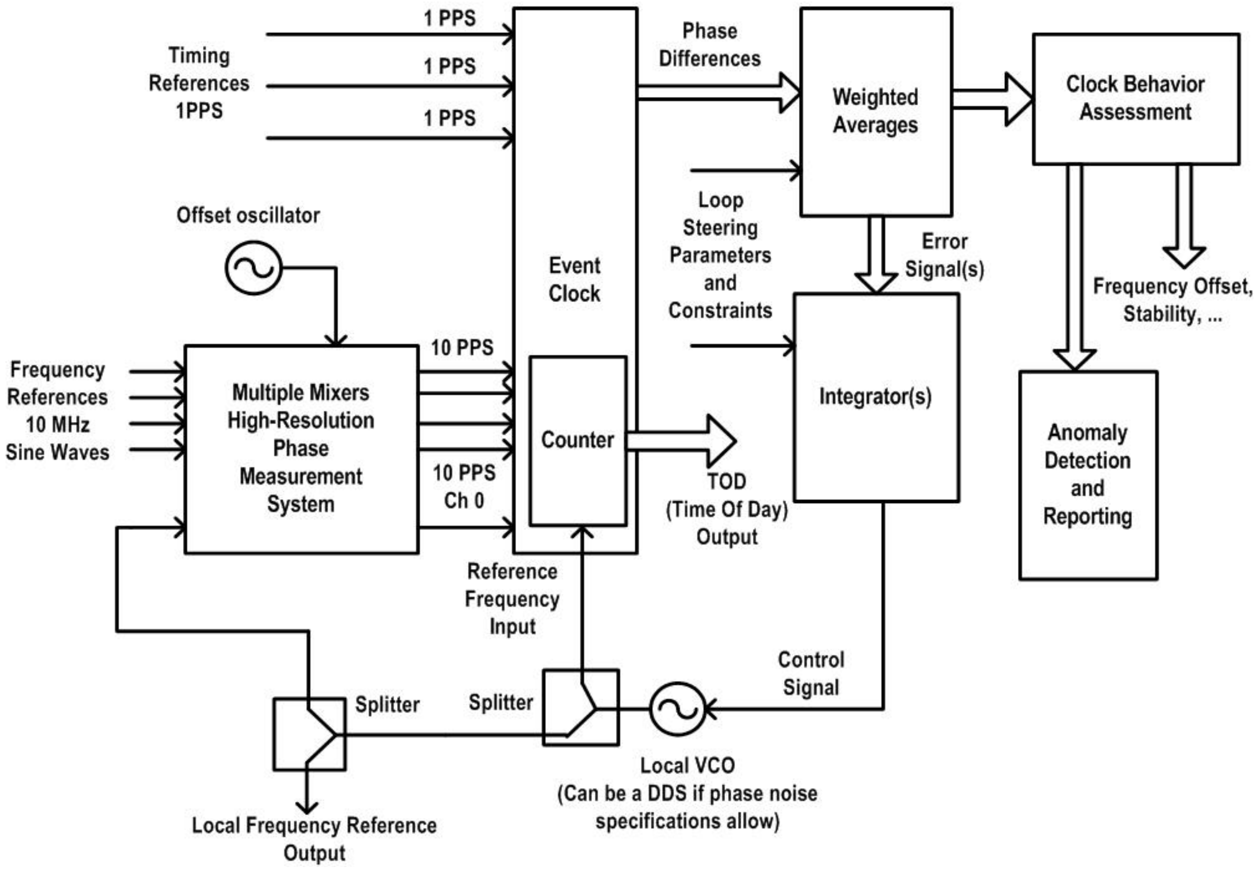

Fig. 22 — Possible implementation of a centralized time and frequency reference system

Recovering the carrier implies phase-locking the local oscillator to the input signal, and the Costas-loop, in its various implementations, behaves as a generalized phase detector. The advantage of this approach is that undersampling can be used to simultaneously provide downconversion and analog-to-digital conversion. Post-decimating the data will reduce the data rate to what is required by Nyquist criterion after the downconversion associated to the sampling process. Since all of the process is numerical, the phase detector can be made to work with different input frequencies, reducing the data by numerical processing instead of by analog synthesis of the proper frequencies as required by an analog phase measurement system.

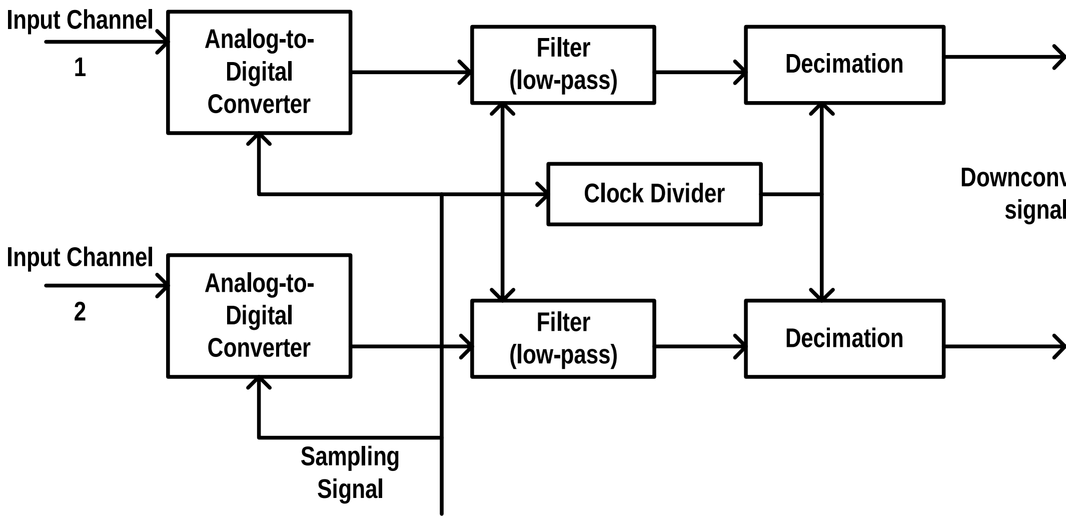

Fig. 23— Digital input stage

In practice, an in-phase and quadrature arrangement of the ADCs is required to fully resolve any phase ambiguity from the measurement. This is achieved by paralleling two ADCs on each channel, fed by the common input signal, whereas the sampling clocks have a 90-deg skew. The resulting sampled sine and cosine components allow precise resolution of the phase measurement in the interval $(0, 2\pi)$. The development of a digital comparison system has been the focus of a space project supporting the GPS program [62] and the modification of this system for ground and mobile platform use is now being investigated at NRL.

LOCAL COMMON TIME

The formation of a local common time from existing and planned system clocks is possible if continuous precision signal comparisons can be made. The resulting time performance depends on the specific clocks involved but can be used to synchronize all the participants in the composite. There are various ways in which this can be accomplished; the method chosen depends on the number, type, and connecting media that can be interfaced. Forming a composite time such as suggested here is a form of "ensembling" [63]. Clock ensembles are used to generate time scales in major timing centers, such as USNO, to establish the most accurate time scale possible [64].

The different techniques for combining the clock signals result in comparisons of the output of a number of clocks with known characteristics and applying an algorithm to form a stable, predictable time. Clock ensembling at timing centers is used to derive a time output that is more stable than the individual clocks. A number of identical types of clocks are used to derive a more stable time. The number and similarities of the clock performance characteristics can be a determining factor in the amount of stability improvement. For CTR composite time, the number and similarity of units cannot be assured within the system clocks available for use. Consequently, ensembling for increased performance is not a specific objective, but such techniques can be used to produce a common time related to the performance of the clocks available. A common time locally generated would facilitate cross-system synchronization and management of the composite to external reference sources such as GPS. As systems and their timing approaches change due to upgrades and obsolescence, they may benefit from an ensembling technique to produce better performance and insensitivity to individual clock failure. A significant benefit is to increase the overall reliability of the timing system. Forming a mean time among the local group of systems will be necessary for synchronization anyway, and a configuration adaptable to composite techniques will provide the potential for performance growth.

The initial step in forming a composite clock algorithm deals with the general model of clock behavior and their use in systems [65,66]. The model proposed includes both systematic effects (clock parameters and environmental effects) as well as stochastic processes affecting the clock performance and the characterization of the systematic effects through measurements.

Modeling clock performance involves principally the ability to model nonstationary noise processes and to predict the mean of the contributing signals for different periods into the future. To deal with this complex subject in detail is beyond the purpose of this report; consequently, for further information, the reader is referred to the references. A brief introduction leads a discussion of ensembling techniques.

Clock Error Model

A clock is a numerical integrator of the periodic signal produced by a stable oscillator; therefore, the timekeeping function is implemented by counting cycles, i.e., by numerically integrating the output frequency of the oscillator. Frequency accuracy is of paramount importance for an accurate clock, while stability ensures that accuracy is maintained over time, thereby ensuring the uniformity and reproducibility of the time scale.

Stable atomic clocks are affected by systematic and stochastic errors that must be accurately modeled and characterized to ensure optimum performance in the use of the device. Generally, the basic model for a stable clock includes three parameters:

1) an initial time offset, Δt_0, which represents the inaccuracy in the setting of the initial time at t_0;

2) an initial frequency offset, Δf_0, which represents the inaccuracy in setting the frequency of the clock at the time t_0; this parameter is customarily represented as normalized with respect to the nominal frequency of the oscillator f_0, and in this case it is referred to as the initial fractional frequency offset of the oscillator, $\frac{\Delta f_0}{f_0}$;

3) a frequency drift (a parameter referred to as aging in crystal oscillators), which represents the change in time of the initial frequency offset, i.e., it is the first derivative of the frequency $\dot{f}(t_0)$. This parameter is generally assumed constant (or slowly varying with time) for all practical purposes.

Considering the clock as a numerical integrator, the above three terms can be regarded as the integration constants for the cascaded integrations that made up the oscillators and the clock; these are schematically shown in Fig. 24. Here, oscillator model and the clock model are separated through temperature dependence, acceleration, and magnetic field sensitivity, or voltage and load frequency pulling effects. But also the clock integration may be affected, for instance, by delay changes in the electronics induced by temperature effects.

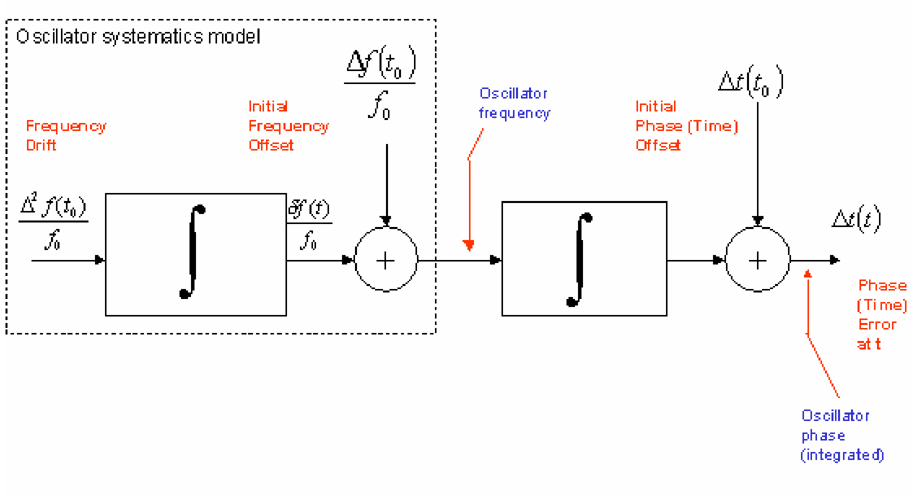

Fig. 24 — Clock systematics model

Adding these additional environmental effects, the resulting model is graphically shown in the Fig. 25 block diagram.

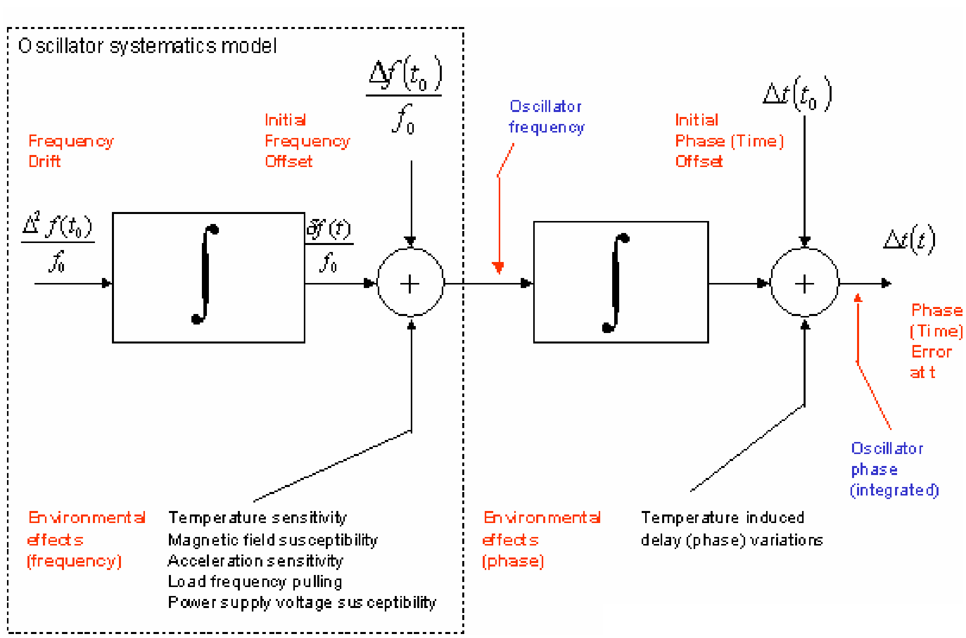

Fig. 25 — Clock systematics model, including environmental effects

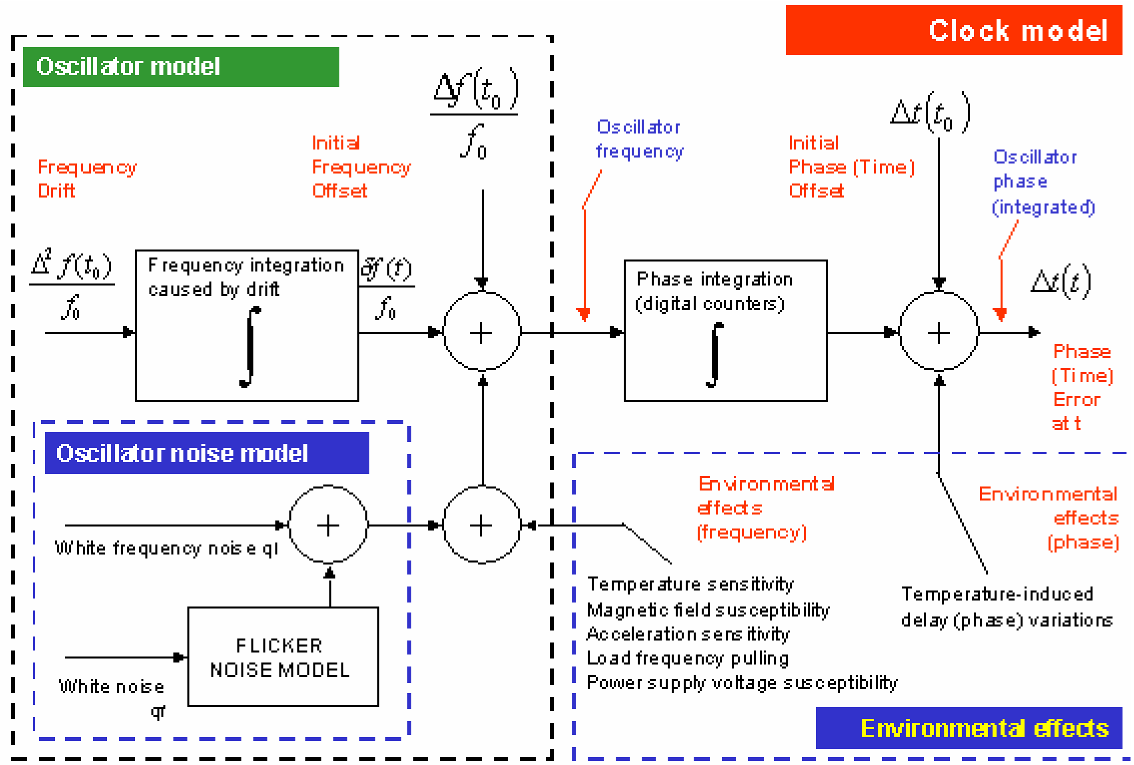

Fig. 26 — Complete clock model (includes environmental effects and noise processes)

The noise processes affecting the output frequency of the oscillator dominate the stochastic behavior of the clock (see Fig. 26). These processes have been intensively studied during the past 40 years, and are characterized by a measurement of frequency instability expressed as the spectral density of the phase noise (in the frequency domain) and Allan variance (in the time domain). Since for a clock we are usually interested in the time domain aspects of frequency instabilities, the equation is completed to account for stochastic effects as follows (environmental effects are included):

$$\Delta t(t) = \Delta t(t_0) + \frac{\Delta f(t_0)}{f_0}(t - t_0) + \frac{1}{2}(t - t_0)^2$$

$$+\sigma_y[(t - t_0)]\ (t - t_0) + \sum_k \frac{\Delta f_k(p_k)}{f}(t - t_0) + \Delta t_{temp} \quad (24)$$

The first three terms in Eq. (24) account for the systematics, the fourth term accounts for the non-stationary noise processes of the oscillator, the fifth term for the environmental effects affecting the frequency (k includes such parameters as temperature sensitivity, magnetic sensitivity, and load pulling effects), and the last term the delay (phase) fluctuations induced by temperature in the clock electronics.

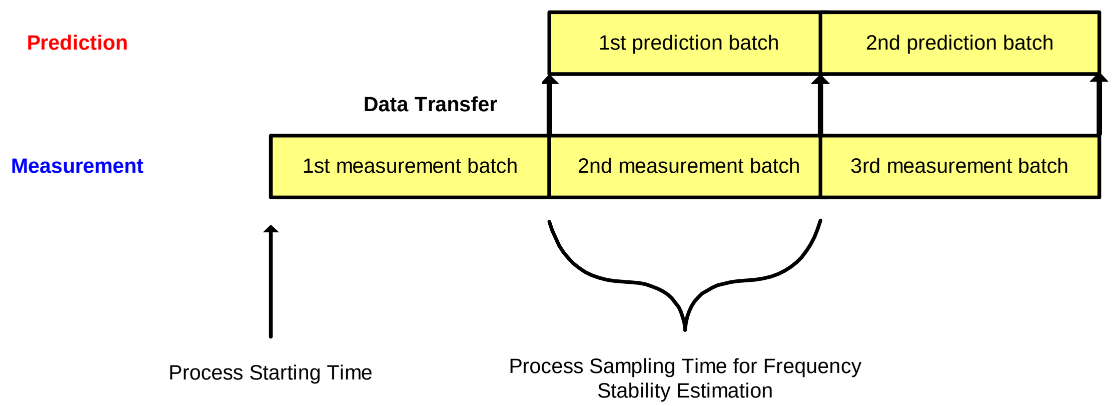

Fig. 27 — Clock behavior prediction diagram

The clock can now be modeled with the aim of providing insight into the final operations and an improved ability to predict its performance, at least in a mean sense. Figure 27 portrays the prediction process. In practice, two steps are required to maintain a timing system when the data are acquired in batches and the clock state vector is estimated at regular intervals:

1. Characterization of the clock behavior, i.e., estimation of the relevant parameters from measurements entering Eq. (24), namely:

   — Time offset Δt at some (initial) time t_0 — for all purposes, t_0 can be selected as completely arbitrary;

   — Fractional frequency offset $\frac{\Delta f(t)}{f_0}$ at t_0;

   — Frequency drift $\frac{\Delta^2 f}{f_0}$, assuming that this term is constant to avoid a further integration in the model;

   — Frequency stability, expressed as the Allan variance, $\sigma_y^2(\tau)$, over the time interval of interest; in this case, the time required to make the measurements for characterization and the prediction interval; and

   — Sensitivity parameters, p_k, of the clock to the various environmental factors.

2. Prediction of the clock behavior; that is, forecasting of the clock error $\Delta t(t)$ in time over some future time interval, based, again, on the clock model expressed in Eq. (24).

The two steps will overlap when the composite is in operation, since the clock error is propagated while making a batch of measurements for characterizing the clock for estimating the time error over the next prediction interval. At the epoch in which a new estimate is generated, the measured error at the same epoch can be compared with the estimated error from the prior epoch and the inaccuracy of the characterization/prediction process can be assessed. The process is the recursive filter and estimator process [67]. This process can then be used to validate measurements and the state model and produce diagnostic indicators of the process in operation.

The frequency stability of the oscillator plays a key role not only in the prediction of the clock behavior, but also in the estimation of the systematic parameters at the end of each measurement interval. As a matter of fact, the frequency stability limits the estimation of the systematic parameters, resulting in $\Delta t \neq 0$ at the beginning of the prediction interval. Since the aim is to minimize Δt over the prediction interval, when a new batch of data has been acquired and a new clock state estimate is available, two constraints should be met to minimize Δt :

— The length of the measurement/prediction periods should be made as short as possible taking into account all operational constraints, since during the prediction the error increases with time; and

— The length of the measurement/prediction periods should be made long enough to allow the estimation of the clock parameters with sufficient accuracy.

Clearly, a tradeoff of the above conditions will highlight the necessity to reach the flicker frequency floor of the oscillator as soon as possible, to allow a precise characterization of the clock systematic parameters in the shortest possible time, again, assuming that operational constraints will not pose further limitations. Further, the clock model can be simplified by dropping terms that have negligible effects over the measurement/prediction interval. Simplification needs to consider possible operational situations that would affect the prediction interval, such as that due to extended independent free-running performance.

Noise Processes Characterization

A power law model generally defines noise processes for clocks and oscillators [68,69]. The power spectral density in the frequency domain is given as

$$S_y(f) = \sum_{\alpha} h_\alpha f^{\alpha}. \tag{25}$$

For most oscillators, α assumes integer values between –2 and +2. The corresponding power spectral density in the time domain for phase fluctuations, x, is

$$S_x(f) = \frac{S_y(f)}{(2\pi \cdot f)^2} = \frac{\sum_{\alpha} h_\alpha \cdot f^{\alpha}}{(2\pi \cdot f)^2} = \frac{\sum_{\alpha} h_\alpha \cdot f^{\alpha-2}}{(2\pi)^2}, \tag{26}$$

where the spectral noise density for a single value of α can be shown in Table 6 [2], with summation assumed and without loss of generality.

Table 6 — Noise Processes Affecting Oscillators

Noise Type	α	$S_y(f)$	$S_x(f)$
Random walk	–2	$S_y = \frac{h_{-2}}{f^2}$	$S_x = \frac{h_{-2}}{(2\pi)^2 \cdot f^4}$
Flicker *y*	–1	$S_y = \frac{h_{-1}}{f}$	$S_x = \frac{h_{-1}}{(2\pi)^2 \cdot f^3}$
White *y* Random walk *x*	0	$S_y = h_0$	$S_x = \frac{h_0}{(2\pi)^2 \cdot f^2}$
Flicker *x*	+1	$S_y = h_1 \cdot f$	$S_x = \frac{h_1}{(2\pi)^2 \cdot f}$
White *x*	+2	$S_y = h_2 \cdot f^2$	$S_x = \frac{h_2}{(2\pi)^2}$

The translation between the spectral density of the frequency (phase) fluctuations in the frequency domain and the Allan deviation in the time domain generally involves the integration of $S\varphi(f)$. However, in the case of the noise affecting oscillators, the integration has been computed analytically and the results [68] are summarized in Table 7.

Table 7 — Translation Between Frequency and Time Domain Stability Measures

Noise Type	α	$\sigma_y^2(\tau) = f(h_\alpha)$
Random walk	–2	$\sigma_y^2(\tau) = h_{-2} \cdot \frac{(2\pi)^2 \cdot \lvert\tau\rvert}{6}$
Flicker *y*	–1	$\sigma_y^2(\tau) = h_{-1} \cdot 2 \cdot \ln 2$
White *y* Random walk *x*	0	$\sigma_y^2(\tau) = \frac{h_0}{2 \cdot \lvert\tau\rvert}$
Flicker *x*	1	$\sigma_y^2(\tau) = h_1 \cdot \frac{1}{\tau^2 \cdot (2\pi)^2} \cdot \{3 \cdot [\gamma + \ln(2\pi \cdot f_h \cdot \tau)] - \ln 2\}$ where γ = 0.5772156649 is the Euler constant
White *x*	2	$\sigma_y^2(\tau) = h_2 \cdot \frac{3 \cdot f_h}{(2\pi)^2 \cdot \tau^2}$

The relationships shown in Table 7 apply to measurements with zero dead time between them (i.e., measurement rate T equal to the sampling time τ) $r = \frac{T}{\tau} = 1$ and $N = 2$ (as in the Allan two-sample variance). For flicker and white x noise processes: $0 \le f \le f_h$, where $2\pi \cdot f_h \cdot \tau >> 1$, to satisfy (as a minimum) the Nyquist principle.

Time Scale Algorithms

The purpose of including a discussion of time scale algorithms is to review the principles of these algorithms so that they may be applied to producing a common time among a group of different performing clocks on-board platforms and grouped together in facilities. The principle of combining their signals is similar to generating a time scale, but the primary purpose with a group of clocks in a platform is to determine a common time and discipline the resulting common time to an external platform time reference.

Definitions for the following discussion are as follows:

t = date of time scale update

H_i = identification of each clock contributing to the time scale, where $i = 1, \ldots, N$ (N = number of clocks)

$h_i(t)$ = clock measurement at update

p_i = weight assigned to clock H_i

$x_{ij} = h_j(t) - h_i(t) = x_i(t) - x_j(t)$ = measurement between clock Hj and clock H_i at t

τ = time interval between measurements.

The N contributing clocks each produce measurements of the form

$$x_i(t) = CC - h_i(t), \text{ with } i = 1, \ldots, N. \tag{27}$$

The Weighted Average of the clock measurements can produce a free-running time scale denoted as *CC(t)*. It may be expressed as

$$CC(t) = \sum_{i=1}^{N} p_i(t)\, h_i(t). \tag{28}$$

In this expression, $p_i(t)$, $i = 1, \ldots, N$, are the weights assigned to the individual clock H_i. The weights are introduced in order to discriminate between the clocks according to their intrinsic qualities. They are related by

$$\sum_{i=1}^{N} p_i(t) = 1. \tag{29}$$

The time produced by a clock is in general in error from the time scale because of both systemic and random deviations. The weighting function is typically chosen to optimize stability and is not dependent upon the systematic deviation of frequency offset and frequency drift, but only on the random deviations. So if a clock is changed, added, or subtracted, the resulting time scale determined by the specific combination of clocks being used will change. This occurs because the weights also apply to the systematic deviations of the clock measurements. In practice, clock changes are unavoidable, so the expression above is not acceptable for a practical time scale.

The time scale equation is adjusted by

$$CC_i(t) = \sum_{i=1}^{N} p_i(t)\left[h_i(t) + h_i'(t)\right], \tag{30}$$

where $h_i'(t)$ is a time correction applied at t, the measurement of clock $H_i(t)$, to ensure continuity where changes are made, such as adding a clock. The correction is expressed as

$$h_i'(t) = x_i(t_0) + y_{ip}(t - t_0)\,, \tag{31}$$

where $y_{ip}(t)$ is the frequency of clock H_i relative to CC, which has been predicted for the interval $[t_0,t]$. The frequency of clock $H_i(t)$ can be estimated from

$$y_i(t) = \frac{\left[CC(t) - h_i(t)\right] - \left[CC(t_0) - h_i(t_0)\right]}{t - t_0}. \tag{32}$$

Until the time scale is computed for the date in question, the frequencies are unknown. From the equations above, the following system of equations results:

$$\begin{aligned} &\sum_{i-1}^{N} p_i x_i(t) = \sum_{i=1}^{N} p_i(t)\, x_i(t_0) + \sum_{i=1}^{N} p_i\, y_{ip}(t)(t - t_0) \\ &x_{ij}(t) = x_i(t) - x_j(t). \end{aligned} \tag{33}$$

The time measurements are selected such that the equations are deterministic with N equations and N unknowns, so they may be solved at each step or date of data availability. The difference between the clock H_i and $CC_i(t)$ may then be calculated as

$$x_j(t) = \sum_{i=1}^{N} p_i(t)\left[h_i'(t) - x_{ij}(t)\right]. \tag{34}$$

This equation is the basis of all the time scales in use today.

A weighted average is a basic form of time scale that could be easily implemented for the common platform time. However, the determination of the weights and clock comparisons can lead to undesirable characteristics.

Weighting Procedures

Since time scales are designed to optimize frequency stability, each clock is weighted according to its frequency stability. The weights are based on the frequency variance σ_i^2 determined for the particular clock:

$$p_i = \frac{1/\sigma_i^2}{1/\sum_{i=1}^{N} \sigma_i^2}, \ I = i, \ldots, N. \tag{35}$$

The rationale for this weighting is that if the clocks are really independent of one another and the weights are not limited by some other means, the resulting variance of the time scale will result in

$$\frac{1}{\sigma_{CC}^2} = \sum_{i=1}^{n} \frac{1}{\sigma_i^2}, \tag{36}$$

and the time scale produced will be more stable than the clocks making it up. Since there are other test variances that may be used, the choice is dependent upon the application for which the time scale is being generated.

There are two limitations to this weighting scheme. First, the time interval between the measurements for the time scale, τ, will be at regular intervals. The test variance used, such as the Allan variance, is defined in terms of equal intervals. Consequently, the variance of the contributing clocks at τ will set the performance of the resulting time scale. For optimum time scale performance, the time interval between updates would be selected based on the clocks' variance at that interval. Secondly, the contributing clock frequencies are measured against a reference for comparison in order to make up the time scale. The best reference available is most likely the time scale itself. Consequently, the individual variances measured are biased. This is known as "clock-ensemble correlation." It has been shown that the correlation can be estimated by the expression

$$\sigma_{i,bias}^2 = \sigma_{i,true}^2 (1 - p_i), \tag{37}$$

where $\sigma_{i,bias}^2$ and $\sigma_{i,true}^2$ are the "biased" and "true" variances of clock H_i, respectively.

Approach to Common Time

A traditional time scale as discussed above has been extended in recent years to Kalman filtering theory, which can be applied to the clock comparisons before averaging or combining to adapt the resulting time to a particular application [71]. One example is producing a time scale using clocks with good short-term performance and those with good long-term performance to produce an optimum time-scale in both regimes. Kalman filters have been written that prefilter the measurement data for continuous, uninterrupted stable signal, the Kalman Aiding Software, KAS-1 [71], to improve stability, KAS-2 [72], and to evaluate uncertainty of the estimates and detect abnormal behavior, the Atomic Time Algorithm at NIST TA2(NIST) [73]. Perhaps the widest-known Kalman approach is the Composite Clock algorithm used in the GPS system to generate GPST [74]. In that case, a virtual clock is used as the reference for estimation, resulting in a "paper clock" (not represented by a physical signal). These approaches are tailored for their purposes with advantages and disadvantages.

The primary desirable characteristic of this filtering approach is the ability to use irregularly spaced data. These filtering approaches have been adapted to using clocks with different frequency variances and can be used to detect anomalies that could result in failure or errors. The primary purpose of using this type of implementation within a system is to provide systems with an uninterrupted, continuous signal under all operating conditions. A Kalman approach to combining the platform's existing and supplemented resources can have this result.

Common Time Algorithm

Most system internal clocks may be set to arbitrary values from power cycling or free-running operation of the system, resulting in potentially large phase jumps in the clock estimates over the operating intervals. Moreover, the overall phase bias between the GPS receiver and contributor clocks is largely unknown (i.e., receiver systems are uncalibrated for phase delays). Because of these considerations and because frequency is the fundamental quantity in atomic clocks, the algorithm for filtering the clock estimates into a time scale was formulated as an integrated frequency scale. That is, phase estimates for each clock are used to form fractional frequency measurements (over 5-minute intervals) of each clock. Outliers (i.e., phase jumps) are removed, and discrete jumps in frequency are detected. A simple linear model (quadratic in phase) is fit to the frequency measurements used to detrend each clock against the frequency scale, which is formed on-the-fly in the filter using a standard weighting scheme. After iterating with respect to the weights, the time scale is formed by taking the final weighted average of the detrended fractional frequency estimates of each clock and integrating back into a time series. This time scale is then steered to GPST with a slow time constant. That is, the new time scale is loosely steered to GPST, resulting in a reference, which is more stable than GPST in the short term but maintains a link to GPST in the longer term. Each clock is then re-referenced to the new steered time scale.

Clock Model

The frequency and frequency aging of each clock can be estimated using a two-state vector polynomial $\dot{p}(t)$ driven by white noise processes. This is denoted in the usual state-space discrete-time formulation as

$$\dot{p}(t_{i+1}) = \varphi(\tau)\dot{p}(t_i) + \dot{e}(t_i), \tag{38}$$

$$\varphi(\tau) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \tag{39}$$

where $t_{i+1} = t_i + \tau$, the first and second components of $\dot{p}$ are rate and drift, respectively, and where the two components of $\dot{e}$ are independent white noise processes.

Given frequency measurements $Y(t)$ for a clock, the measurement model can be specified as

$$Y(t) = \mathbf{h}\dot{p}(t) + n(t), \ \mathbf{h} = [1\ 0],$$

where n is a scalar white noise sequence which is assumed independent of the process noise. For approximate modeling of Random Walk FM and Random Run FM, i.e., small τ, the covariance $\mathbf{q}$ for $\dot{e}$ can be specified as

$$\mathbf{q} = E\left[\vec{e}\,\vec{e}^{T}\right] = \begin{bmatrix} a_{-1}\tau + a_{-2}\dfrac{\tau^3}{3} & a_{-2}\dfrac{\tau^2}{2} \\ a_{-2}\dfrac{\tau^2}{2} & a_{-2}\tau \end{bmatrix}, \tag{40}$$

and for approximate modeling of White FM the covariance, r, for n can be given as

$$r = E\left[n^2\right] = \frac{a_0}{\tau}, \tag{41}$$

where a_0, a_{-1}, and a_{-2} are the noise spectral densities of White FM, Random Walk FM, and Random Run FM, respectively. The value of these densities would be experimentally determined from analyzing Allan variances or Hadamard variances, because they are insensitive to drift, of the specific clocks involved. The time derived through this process would then be compared and adjusted to the Common Time Reference. Through this process, the clocks would be compared to determine synchronization coefficients between them and maintained to the common reference. This would result in all participating clocks being synchronized to a common time.

SUMMARY

The impact of providing time and maintaining synchronization between them is just beginning to be recognized and may have an even more significant extension of military capability and operations. GPS has major impact on the capability to determine position and navigate military platforms and systems as well as changing the way time is used. 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 interoperability at the most basic level, that of 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.

GLOSSARY

ACTD	Advanced Concept Technical Demonstration
ADC	Analog-to-Digital Converter
ARG	Amphibious Ready Group
ASK	Amplitude Shift Keying
AWS	Advanced Wideband System
BIPM	Bureau International des Poids et Mesures
BLOS	Beyond Line of Sight
CC	Command Center
COMSTA	Communications Station

COP	Common Operational Picture
COTS/NDI	Commercial Off-The-Shelf/Nondevelopmental Items
CPSM	Continuous Phase Shift Modulation
CTR	Common Time Reference
DAMA	Demand Assigned Multiple Access
DDS	Direct Digital Synthesis
DMR	Digital Modular Radio
DOD	Department of Defense
DSCS	Defense Satellite Communications System
DTDMA	Dynamic Time Division Multiple Access
DWTS	Digital Wideband Transmission System
ECEF	Earth Centered, Earth Fixed
ECI	Earth Centered Inertial
ELB	Extended Littoral Battlespace
ENM	EPLRS Net Manager
EPLRS	Enhance Position Location Reporting System
FIFO	First In, First Out
FSK	Frequency Shift Keying
GBS	Global Broadcast System
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
GPST	GPS Time
IERS	International Earth Rotation Service
ION	Institute of Navigation, Stuttgart, Germany
IRIG	Inter-Range Information Group
ISBSC	Independent Sideband Suppressed Carrier
ITU-R	International Telecommunications Union (Radiocommunication Sector)
JTIDS	Joint Tactical Information Distribution System
JTRS	Joint Tactical Radio System
LDR	Low Data Rate
LOS	Line of sight
LPI	Low Probability of Intercept
MDR	Medium Data Rate
Milstar	Military Strategic and Tactical Relay
MJD	Modified Julian Date
NATO	North Atlantic Treaty Organization
NILE	NATO Improved Link Eleven
NIST	National Institute of Standards and Technology
NRAC	Naval Research Advisory Committee
NTR	Network Time Reference

OCXO	Ovenized Crystal Oscillators
PLGR	Precise Lightweight GPS Receiver
PLL	Phase-Locked Loop
PSK	Phase Shift Keying
PT&F	Precise Time and Frequency
PTTI	Precise Time and Time Interval
RTTI	Round Trip Timing Interrogation
SADL	Situational Awareness Data Link
SATCOM	Satellite Communications
SHF	Super High Frequency
SI	Système Internationale
SINCGARS	Single Channel Ground and Airborne Radio System
TADIL A	Tactical Digital Information Link A (Link 11)
TADIL J	Tactical Digital Information Link J (Link 16)
TAI	International Atomic Time
TCXO	Temperature-compensated Crystal Oscillators
TDC	Time-to-Digital Converter
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TDN	Tactical Data Network
THAAD	Theater High-Altitude Area Defense
TI	Tactical Internet
TIA	Time Interval Analyzer
TIC	Time Interval Counter
TOD	Time of Day
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UEE	User Equivalent Error
UER	User Equivalent Range
UERE	User Equivalent Range Error
UFO	UHF Follow On
UT	Universal Time
UTC (USNO)	Coordinated Universal Time (US Naval Observatory)
VCO	Voltage-Controlled Oscillator
VMF	Variable Message Format
VSAT	Very Small Aperture Terminal
WAN	Wide Area Network
WGS	Wideband Gapfiller System

REFERENCES

1. Held, D., et al., *GPS Vulnerability Study* (U) (briefing), Naval Research Advisory Committee, 2 February 1999.

2. "Common Time Reference Architecture," Draft Version 2.1, Common Time Reference System Engineering Team, 22 March 2001.

3. A. Cebrowski and J. Garska, "Network Centric Warfare: Its Origin and Future," *Proc. of the U.S. Naval Institute*, January 1998, pp. 28-35.

4. Joint Chiefs of Staff Instruction CJCSI 3151.01, Global Command and Control System Common Operational Picture Reporting Requirements, 10 June 1997.

5. C4ISR Architecture Framework, Version 2.0, Coordination Draft, 19 Nov. 1997.

6. U.D. Black, *Data Communications, Networks and Distributed Processing* (Reston Publishing Co., A Prentice-Hall Company, Reston, VA, 1983).

7. P. Kartaschoff, "Synchronization in Digital Communications Networks," *Proc. IEEE* **79**(7), 1019-1028, 1991.

8. J.C. Bellamy, "Digital Network Synchronization," *IEEE Communications Magazine*, April 1995.

9. "Handbook Selection and Use of Precise Frequency and Time Systems," International Telecommunication Union, Radiocommunication Bureau, 1997.

10. CCITT Blue Book, Vol. III – Fascicle III.5, "Digital Networks, Digital Sections and Digital Line Systems, Recommendations G.801-G.961, IXth, Plenary Assembly, Melbourne, 14-26 November 1988, ITU publication Geneva, Switzerland.

11. W. Altrichter, "Introduction to JTIDS" (briefing), November 17, 1999.

12. W.R. Fried, "JTIDS Relative Navigation — Architecture, Error Characteristics, and Operational Benefits," *IEEE NAECON Proceedings*, May 1979.

13. W. Altrichter, "JTIDS Synchronization and Navigation" (briefing), April 24, 1998.

14. U.S. Department of Defense, Military Standard, MIL-STD-188-115, Interoperability and Performance Standards for Communications Timing and Synchronization Subsystems, 17 December 1998.

15. J.R Vig, "Military Applications of High Accuracy Frequency Standards and Clocks," *IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control* **40**(5), 522, 1993.

16. CECOM Technical Report SLCET-TR-88-1 (Rev. 8.0), "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications – A Tutorial," J.R Vig, U.S. Army Communications-Electronics Command (CECOM), Fort Monmouth, NJ 07703.

17. U.S. Department of Defense, Military Specification, Oscillators, Crystal, General Specification for, MIL-O-55310.

18. SPAWAR Systems Center, San Diego, “Network Centric Precise Time Distribution” (proposal to ONR), undated.

19. NAVSTAR Global Positioning System (GPS) Interface Control Document, GPS-ICD-060, Precise Time and Time Interval Interfaces, Rev. B, 1986.

20. 2002 CJCS Master Positioning, Navigation and Timing Plan, CJCSI 6130.01C of 31 March 2003.

21. NATO Military Operational Requirement for the Provision of Precise Time MMC-SFM-081-93, 28 July 1993.

22. S. Blackman and R. Popoli, *Design and Analysis of Modern Tracking Systems* (Artech House, Boston, 1999).

23. B.E. Blair, ed., “Time and Frequency: Theory and Fundamentals,” NBS Monograph 140 (May 1974).

24. H. Hellwig, “Environmental Sensitivities of Precision Frequency Sources,” *IEEE Trans. Instrumentation and Measurement* **39**(2), 301-306, 1990.

25. “IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators,” IEEE Std 1193-1994, February 27, 1995.

26. “IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology — Random Instabilities,” IEEE Std 1139-1999 approved 26 March 1999.

27. J.A. Barnes, A.R. Chi, L.S. Cutler, D.J. Healey, D.B. Leeson, T.E. McGunigal, J.A. Mullen, Jr., W.L. Smith, R.L. Sydnor, R.F.C. Vessot, and G.M.R. Winkler, “Characterization of Frequency Stability,” *IEEE Trans. Instrumentation and Measurement* **IM-20**(2), 105-120, 1971.

28. T.J. Quinn, “The BIPM and the Accurate Measurement of Time,” *Proc. IEEE* **79**, 894 – 905 (1991).

29. Recommendation TF.460-5, “Standard Frequency and Time-Signal Emissions” in *ITU-R Recommendations: Time Signals and Frequency Standards Emissions* (International Telecommunication Union, Radiocommunication Bureau, Geneva, 1998).

30. B. Guinot, “Atomic Time,” in *Reference Frames for Astronomy and Geophysics*, J. Kovalevsky, I.I. Mueller, and B. Kolaczek, eds. (Kluwer, Boston, 1989).

31. *The International System of Units (SI)*, 7th edition (Bureau International des Poids et Mesures, Sèvres, France, 1998), p. 118.

32. D. Allan, J.E. Gray, and H.E. Machlan, “The National Bureau of Standards Atomic Time Scale: Generation, Stability, Accuracy and Accessibility,” in *Time and Frequency: Theory and Fundamentals*, NBS Monograph 140, 1974, pp. 205-231.

33. J. Levine, "Introduction to Time and Frequency Metrology," *Review of Scientific Instruments* **70**(6), June 1999.

34. 38th Civil GPS Interface Committee (CGSIC) Meeting, Timing Subcommittee, "Introduction," W. Lewandowski, BIPM.

35. Recommendation 458-2, "International Comparisons of Atomic Time Scales," in *ITU-R Recommendations: Time Signals and Frequency Standards Emissions* (International Telecommunication Union, Radiocommunication Bureau, Geneva, 1998), p. 13.

36. STANAG 4430, Precise Time and Frequency Interface for Military Electronic Systems.

37. D.W. Hanson, "Fundamentals of Two-Way Time Transfer by Satellite," *Proc. 43rd Annual Symposium on Frequency Control*, 1989.

38. G.P. Landis, J.D. White, A. Gifford, R.L. Beard, and J.A. Murray, "A New Two-Way Time Transfer Modem," *Proc. 21st Annual Precise Time and Time Interval Systems and Applications Meeting*, 28-30 November 1996, pp.131-136.

39. W. Lewandowski and C. Thomas, "GPS Time Transfer," *Proc. IEEE* **79**(7), 991-1000, 1999.

40. LORAN-C Users Handbook 1992 Edition. COMDTPUB P16562.6 Originated By: U.S. Coast Guard, Radionavigation Division, U.S. Coast Guard Navigation Center, 02 May 2001.

41. J.E. Abate, W.E. Butterline, R.A. Carley, P. Greendyk, A.M. Montenegro, C. Near, S.H. Richman, and G.P. Zampetti, "AT&T's New Approach to the Synchronization of Telecommunication Networks," *IEEE Communications Magazine*, April 1989.

42. D.L. Mills, "Precise Time Synchronization," Network Time Protocol version 4 (briefing), 14 Sept. 1998.

43. G.P. Landis, S.B. Stebbins, R.L. Beard, and H.F Fliegel, "Alternative Timing Networks With GPS," *Proceedings of the 21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, 29 – 30 November 1989.

44. S.G. Stebbins, A.G. Gifford, and R.L. Beard, "A Comparison of Time Transfer Techniques," *Proc. 21st Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting*, 29-30 November 1989.

45. NATO Team, "Navstar GPS User Equipment Introduction (FOUO)," GPS Joint Program Office, February 1991.

46. NAVSTAR Global Positioning System (GPS) Interface Control Document, ICD-GPS-202, Navstar GPS Control Segment U.S. Naval Observatory Time Transfer Interface, 21 November 1984.

47. NAVSTAR Global Positioning System (GPS) Interface Control Document, PIRN-200C-007A, ICD-GPS-200C, Space Segment / Navigation Users Interface, March 2002.

48. NAVSTAR Global Positioning System (GPS) Interface Control Document, Precise Time and Time Interval Interfaces, ICD-GPS-060, Rev. B, 1986.

49. E.C. Jones, E.D. Powers, A.H. Frank, and J.A. Murray, "Static Timing Tests of the R-2332/AR, R2331/URN, MANPACK (RPU-1), and the Texas Instrument MANPACK AN/PSN-9 NAVSTAR. Global Positioning System User Equipment at the Naval Research Laboratory," NRL Memorandum Report NRL/MR/8150--95-7754, July 10, 1995.

50. W.G. Reid, "Multiple-Path Linked Common-View Time Transfer (LCVTT)," *Proc. 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting.*

51. E.D. Powers, M. Miranian, J.D. White, and J. Brad, "Absolute Time Error Calibration of GPS Receivers Using Advanced GPS Simulators," *Proc. 29th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Long Beach, California, 2 – 4 December 1997.

52. P. Hartl, N. Gieschen, K-M. Mussener, and W. Schafer, "Global Time Transfer via Geosynchronous Telecommunication Satellites with Mitrex," *Zietung Flugwiss. Weltraumforsch,*7, Heft 5 (1983).

53. G.P. Landis, I.J. Galysh, A. Gifford, and A. Osborne, "A New Two-way Time Transfer Modem," *Proc. 23rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Pasadena, California, 3-5 December 1991.

54. TW primary link for UTC.

55. J.R. Davis, "The Department of Transportation Loran-C Study," *Position Location and Navigation Symposium*, IEEE, 1998.

56. W.R Fried, "Principles and Simulation of JTIDS Relative Navigation," *IEEE Trans***. AES-14**, Jan 1978, pp. 76-84.

57. C.E. Ellingson and R.J. Kulpinski, "Dissemination of System Time," *IEEE Trans. Comm*. **COM-21**(5), May 1973, pp. 605-624.

58. W.W. Altrichter, *Link 16 Network Synchronization and a Common Time Reference Using UTC(USNO) Time via GPS*, BAE Systems Report, October 30, 2002.

59. IRIG Standard 200-98, IRIG Serial Time Code Formats, May 1998, Timing Committee, Telecommunications and Timing Group, Range Commanders Council, U.S. Army White Sands Missile Range, New Mexico 88002-5110.

60. S.R. Stein, D. Glaze, J. Levine, J. Gray, J. Hilliard, D. Howe, and L. Erb, "Performance of an Automated High Accuracy Phase Measurement System," *Proceedings of the 35th Annual Symposium on Frequency Control*, 2-4 June, 1982, Philadelphia, PA, pp. 314-320.

61. G. Kamas and M.A. Lombardi, "Time and Frequency Users Manual," NIST Special Publication 559 (Revised 1990), National Institute of Standards and Technology, Boulder, CO, September 1990, pp. 46-53.

62. G.P. Landis, I. Galysh, and T. Petsopoulos, "A New Digital Phase Measurement System," *Proc. 33rd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Long Beach California, 27 – 29 November 2001.

63. P. Tavella and C. Thomas, "Time Scale Algorithm: Definition of Ensemble Time and Possible Uses of the Kalman Filter," *Proc. 22nd Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, Tyson's Corner, Virginia, 4-6 December 1990.

64. "Comparative Study of Time Scale Algorithms," *Metrologia* 1991, 28, pp. 57-63.

65. R. Jones and P. Tryon, "Estimating Time From Atomic Clocks," *Journal of Research of the National Bureau of Standards* **88**(1), January-February 1983, pp. 17-24.

66. L. Breakiron, "Kalman Filter Time Scales for Cesium Clocks and Hydrogen Masers," *Proc. 34th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting*, 3-5 December 2002, Reston, Virginia.

67. P. Maybeck, *Stochastic Models, Estimation, and Control*, Vols. 1-3, Navtech Book and Software Store, Arlington, Virginia, 1994.

68. J.A. Barnes and S. Jarvis, "Efficient Numerical and Analog Modeling of Flicker Noise Processes," NBS Technical Note 604 (June 1971).

69. N.J. Kasdin and T. Walter, "Discrete Simulation of Power Law Noise," *Proc. 1992 IEEE Frequency Control Symposium*, pp. 274-283.

70. J. Barnes and D. Allan, "Time Scale Stabilities Based on Time and Frequency Kalman Filters," *Proc. 39th Annual Frequency Control Symposium*, May 29-31, 1985, Philadelphia, PA, IEEE 85CH2186-5, pp. 107-112.

71. S.R. Stein, G.A. Gifford, and L.A. Breakiron, "Report on the Timescale Algorithm Test Bed at USNO," *Proc. 21st Annual Precise Time and Time Interval Planning Meeting*, 28-30 Nov 1989.

72. Timing Solutions Corp. Report No. TS95.0046 Rev 1., "KAS-2: Algorithm for Time-Scale Computation and Control of Real-Time Clocks," August 2, 1995.

73. M. Weiss and T. Weissert, "AT2, A New Time Scale Algorithm: AT1 Plus Frequency Variance," *Metrologia* 1991, 28, pp. 65-74.

74. K.R. Brown, "The Theory of the GPS Composite Clock," *Proc. of the ION GPS-91*, 11-13 September 1991.