TFE: The New Heartbeat of Loran

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The visionaries of the future United States Loran-C System imagined a new Timing and Frequency Equipment (TFE) with the general qualities of being a redundant computer based system that is small, easily maintained, and modernizes all the functions of a current timing baseline in a remotely controlled environment. For the past twelve months, Timing Solutions Corporation developed the new TFE system in a rapid development for the USCG Loran Support Unit. The USCG Loran Support Unit recently finished the first article unit testing of the prototype TFE.

This paper presents the new TFE system architecture, capabilities and expected performance. The many TFE functions and their implementations are discussed. TFE is described from a functional perspective with an emphasis on features that may enable Require Navigation Performance (RNP) 0.3 compliant LORAN-C operations. Command and control interfaces that make remote operation a reality are presented as well as new measurement and control methods. The link between TFE performance and GPS is detailed including flywheel performance and LORAN-only performance.

1.0 Introduction

The USCG is leading an effort to modernize the LORAN-C transmitting stations in the United States. Modifications are aimed at providing a maintainable LORAN-C network that meets the Federal Aviation Agency's (FAA) RNP 0.3 requirements, the USCG's harbor entrance requirements and timing user's Stratum I requirements. The LORAN-C network is receiving unprecedented attention that will re-shape the system architecture for the next generation of LORAN-C users. Part of this effort involves the replacement of the time and frequency equipment that is used at transmitting stations. The existing time and frequency systems consist of obsolete hardware based on outdated technology and have become difficult to maintain. The new time and frequency equipment (TFE) incorporates all of the functionality of the existing system in a single integrated solution that is based on current technology. TFE implements frequency steering of the transmitted signal and other state-of-the-art features that enable a new level of performance for LORAN-C

This paper describes the TFE design and provides implementation details for the critical components. Section 2 describes the existing timing system, Section 3 details the new TFE architecture and Section 4 presents TFE's ability to adapt to future architectures.

2.0 Existing system

The existing time and frequency system at the LORAN-C transmitting stations is a collection of hardware that has evolved over a 40-year period. Table 1 shows the major components of the existing system categorized by the decade in which they were installed. The table shows that the basic functionality of the existing timer was developed and installed in the 1960s and 1970s. Additional hardware was added in the 1980s to control the clocks and in the 1990s to monitor master stations.

Table 1: Components of Existing Timing System

1960's Vintage	1970's Vintage	1980's Vintage
➢Emergency Stop	➢Timer Units	➢Phase Micro-stepper
➢Distributions Amplifiers	➢Timer Set Control	➢Time Counter
➢Frequency Patch Panel	➢Alternating Blanking Unit	➢Multi-programmer
➢Signal Alarm Unit	➢Remote Control Interface	
➢Time Counter	➢Communication Adapter	**1990's Vintage**
➢Electronic Pulse Analysis	➢Waveform Panel	➢Time of Transmission Patch Panel *
➢Cycle Compensation Circuit	➢SSX IF	➢Timer Counter *
	➢LSM IF	➢GPS Timing Receiver *
		➢Time Reference Generator *
		➢Automatic Blink System

* Master Stations only

In its existing configuration, the current timing system has evolved into an ad hoc architecture with the following characteristics. The system utilizes cesium standards individually (rather than grouped in a timescale) and does not steer the clocks to UTC(USNO). The phase of the transmitted signal can only be controlled to the 20 ns level and phase changes are implemented in steps that are difficult for users to process. The hardware is largely obsolete and difficult to maintain. While the system has performed admirably over a long period of time, it has become a burden to maintain and must be replaced.

3.0 TFE Design

The TFE hardware architecture (seen in Figure 1) is a redundant design that includes two independent signal paths that control up to three cesium primary frequency standards to generate two identical sets of transmitter drive signals. Each signal path (operate and standby) contains a timing/measurement chassis and a Loran Integrated Timer and Signals (LITS) unit to produce transmitter drive signals that are synchronized to UTC. In addition to the redundant operational signal paths, a single (non-redundant) PFS distribution unit is used to generate copies of the PFS signals for diagnostic use.

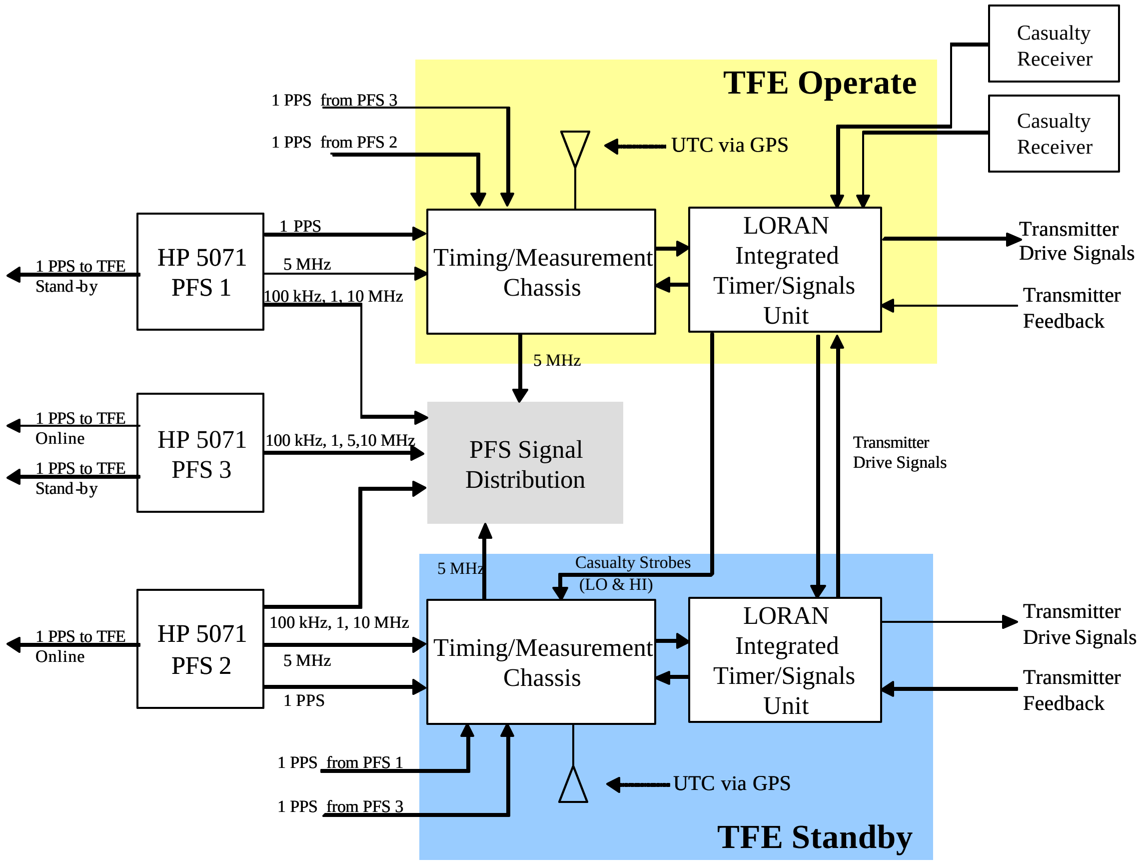

Figure 1: TFE Block Diagram

TFE has external interfaces with four other components: primary frequency standards, casualty receivers, the transmitter, and the RAIL computer that is used to control TFE. There are also two antennas that are used to receive the signals transmitted from GPS satellites. Diagnostic outputs are also available for troubleshooting situations.

3.1 Functional Description

The major functional capabilities of the TFE system include UTC recovery and timescale computation, LORAN-C signal generation, time difference measurements, closed loop transmitter control, and the automatic blink system. Each of these components is detailed in the following sections.

3.1.1 UTC Recovery and Timescale Computation

Each transmitting LORAN-C station includes three cesium standards for reference signal generation. The co-location of three atomic standards provides the opportunity to combine the clocks into a local timescale. The local timescale is formed by processing interclock measurements in an optimal filter. A 1 PPS from each clock is measured in both the operate and standby chassis. The measurements are processed into a timescale whose stability exceeds any contributing member of the group. The timescale, is steered to UTC(USNO) using measurements from a GPS receiver. Each clock is physically steered to the timescale creating a physical realization of the superior clock. The timescale is computed independently in the operate and standby paths. In the event that one or two clocks are missing, the timescale reduces as necessary and the system functions properly.

When GPS data is available, the system recovers UTC(USNO) with less than 15 ns RMS synchronization error. When GPS is not available, performance can be maintained for long periods of time by flywheeling using predictions from the optimal timescale filter. The performance of Timing Solution's KAS-2 timescale is detailed in a separate ILA 2002 paper by Samuel R. Stein.

3.1.2 LORAN-C Signal Generation

LORAN-C signal generation occurs in field programmable gate arrays (FPGA) in the LORAN Integrated Timer and Signals (LITS) unit. The LITS unit accepts a 5 MHz signal from a cesium and generates transmitter drive signals and ancillary LORAN-C signals based on that stable clock. Independent phase control circuits allow for adjustment of the TOC signal (at startup only) and the PCI signal (at each LPA). The PCI signal is used in conjunction with the 5 MHz clock to generate all other LORAN signals. Figure 3 shows the signal generation chain for each rate in a LITS chassis.

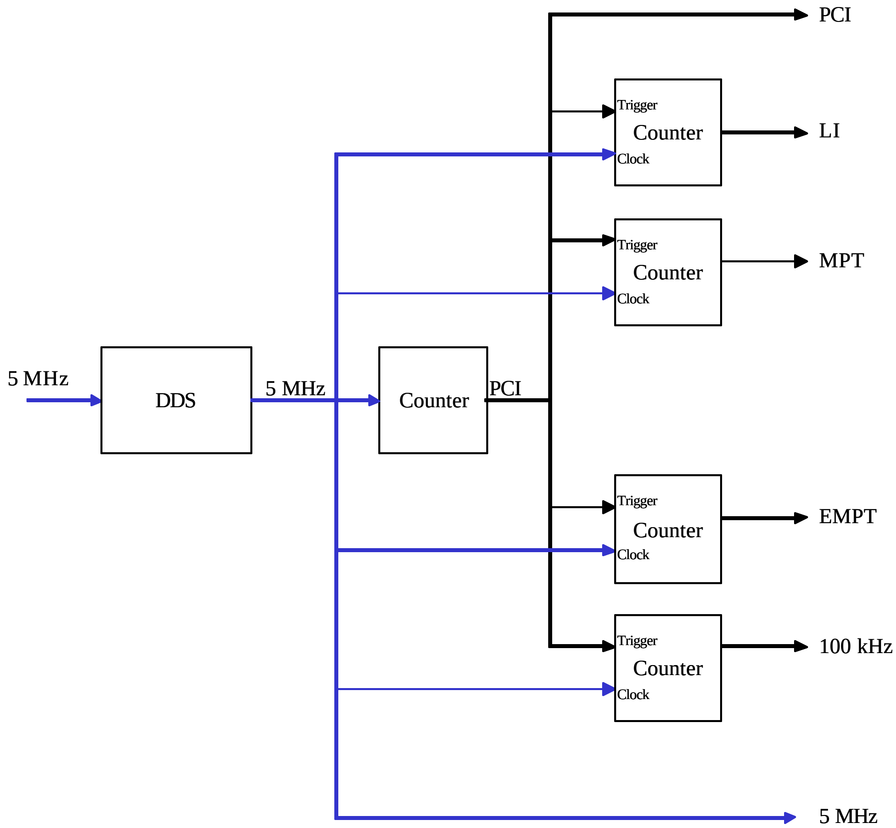

Figure 3: LORAN Signal Generation

Local Phase Adjustments (LPAs) are introduced using frequency steering of the 5 MHz clock. The 5 MHz PFS input is used to source a direct digital synthesizer (see Figure 3) that has a nominal 5 MHz output (meaning unless an adjustment is entered into the DDS, the output frequency equals the input frequency). The phase of the LORAN signal set (all signals except TOC) is adjusted by commanding frequency changes in the DDS output for finite periods of time. By slightly changing the DDS output frequency (from nominal) for a fixed period of time, a smooth phase change can be commanded. For example, a frequency change of 1×10^{-9} over 30 seconds will result in a 30 nanosecond change in phase. This method results in smooth transitions in signal phase and better frequency recovery performance by the users.

3.1.3 Time Difference Measurements

Time differences are measured in the Timing/Measurement chassis using a TSC 2054 six-channel timer. The timer measures and time tags the rising edge of six signals to sub-nanosecond resolution. Each channel is independent so there is no conflict with simultaneous measurements on other channels. Each timer (LO and HI) measures 1 PPS from the cesium, TOC, PCI, RF Gate (from the casualty receiver) and SZC detect (SZC from transmitter feedback). A six-channel unit is an efficient way of computing the LORAN time differences as event times from any two channels can be differenced to form the desired time interval (or time difference) measurement. This allows the data from a particular channel to be used multiple times to form different TDs. For example, the data from the TOC channel is differenced with the data from the PCI channel to form the UTC Recovery TD and the same TOC data is differenced with the SZC detect data to form the TOT Control TD. A single six-channel timer is used to compute four TDs for output as well as to verify the TOC against the system 1 PPS. To collect these measurements using a standard time interval counter would require five units.

TFE reports four TDs per rate during normal operation:

- Primary TOT Control TD: the time difference between the TOC signal and the detected SZC pulse
- Alternate TOT Control TD: the time difference between the RF Gate (from the Locus casualty receiver) signal and the detected SZC pulse
- UTC Recovery TD: the time difference between the rising edge of the TOC signal and the falling edge of the PCI signal
- LORAN Timebase Recovery TD: the time difference between the rising edge of the RF Gate signal and the falling edge of the PCI signal

Additional TDs can be reported by the system in the future either by combining additional differences between existing channels or adding a new signal to the empty 6th channel.

3.1.4 Closed Loop Transmitter Control

In order to keep the transmitted signal within tolerance, the phase of the pulses sent from TFE to the transmitter must be adjusted occasionally. The adjustment can be accomplished externally, via an LPA, or internally (and automatically) using the TFE proportional control loop. When the adjustment is made automatically, it is called an APA (Automatic Phase Adjustment). APAs are similar to the cycle comp loop in the existing LORAN timers. The APA enables time of emission (TOE) control in that the system can be set on-time and the APA loop will maintain the signal phase to remain on time. The APA loop can also be used in SAM control to maintain the system between LPAs. The source of the APA loop can be UTC data (derived from GPS) or casualty data (derived from other LORAN transmitters).

The TOT TD's are used to create an error signal in the APA loop. The APA loop can be configured in three ways:

- Primary TOT TD: ATA loop uses the Primary TOT TD to compute closed loop corrections. This is UTC based and depends on the existence of GPS data to maintain accuracy to UTC(USNO).
- Alternate TOT TD: ATA loop uses the Alternate TOT TD to compute closed loop corrections. This is LORAN based and uses the casualty receiver outputs (based on the reception of a LORAN-C signal from another transmitter).
- Open Loop: ATA corrections are not computed

The APA loop is seen in Figure 4. The TOT measurements are collected and averaged to reduce the noise level. The averaged value is differenced with the saved TOT TD value to form an error signal. The saved TOT TD value is basically the set point or mean of the control loop. The actual TD will vary around this value based on the dynamics of the transmitter and how the loop is configured. The saved TOT TD can be computed for time of emission (TOE) or SAM control. If the system is configured for TOE control, the transmitter delay is calibrated and a saved TOT TD is determined that results in the transmitted signal being on-time with the local UTC(USNO) estimate at the phase center of the transmitting antenna. For SAM control, the saved TOT value is adjusted each time an external local phase adjust (LPA) is entered.

The error signal resulting from the subtraction of the measured value and the saved TOT value is processed by a threshold comparator. If the error signal is greater than the minimum steer value (configured in the system) then an APA value is sent to the LITS chassis and implemented using a frequency change in the DDS. The size of the APA is determined by the gain. If the error signal is less than the minimum steer value, then there is no APA correction made.

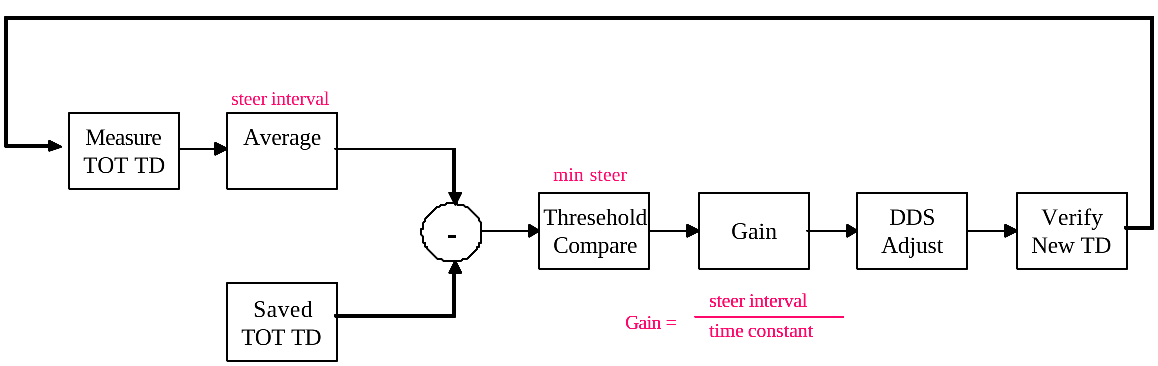

Figure 4: APA Loop

The APA loop is controlled by three variables (their use in the loop is shown in red in Figure 4). The *steer_interval* is the time in second between APAs. This sets how often the APA value can change, if necessary. The *min_steer* value is the smallest change that the system will allow. Errors below *min_steer* are not corrected. The *time_constant* is the time over which an error is removed. The magnitude of this value represents how quickly the system will respond to changes in the signal phase.

3.1.5 Automatic Blink System

TFE includes an integrated Automatic Blink System (ABS) that is designed to improve the system integrity by notifying the user of an out-of-tolerance condition at the transmitter. The ABS system monitors the following parameters and blinks in an out-of-tolerance condition:

- Time of transmission: The ABS system monitors the TOT TD (either primary or secondary) that is used to source the APA loop. If the delta between the measured TOT TD and the saved TOT TD differs by more than the set tolerance, the system initiates blink
- Signal Phase: Transmitted pulses are monitored and compared against the LORAN-C phase pattern. If pulses from successive GRIs are transmitted with the incorrect phase, the system initiates blink
- Lack of RF return from Transmitter: If TFE detects a loss of signal on the RF return from the transmitter, blink is initiated. This represents a situation where TFE is outputting pulses "in the blind" and cannot verify the integrity of the transmitted signal
- Step in the PFS: If a time step is detected in the cesium, the system initiates blink.

Blink is commanded using direct digital lines that are monitored by the microprocessor in the LITS chassis (as opposed to using the RS-232 command interface). This has multiple advantages but is mainly done to minimize the time period between the detection of an out-of-tolerance condition and the initiation of blink. TFE can transition into blink in less than one second after detection of a fault.

The blink system is implemented using software on the host computer and programmable firmware. The system is configurable with tolerances that are set by the user. The ABS system can be customized for a particular transmitter or transmitter location so that the availability of the transmitted signal is maximized while still providing integrity protection. The ABS system can also evolve to monitor new requirements in the future.

3.2 System Interfaces

The main TFE software application controls all of the hardware and provides an external interface that can be used by other software processes or by a human user. The system interface is a text-based command line interface (CLI) over standard IP sockets for all command, control and status reporting. Commands are issued over a control port where responses to commands can be monitored. There is also a diagnostic port where broadcast information can be turned on or off and collected when required. The system includes a local graphical user interface (GUI) that provides an interface for users that are co-located with the hardware. That interface is transportable to other computers running X client software. The GUI (seen in Figure 5) contains clickable buttons as well as updating status fields and slider bars for visual indication of system performance.

The use of standard IP sockets for the system interface enables remote operation of the TFE software. Access from any computer on a connected network will be possible through a telnet interface. This allows the USCG the ultimate flexibility in how the system is used. Remote operations of many systems can be conducted from a single facility allowing a consolidation of personnel and the processing of data from multiple transmitters at a single location.

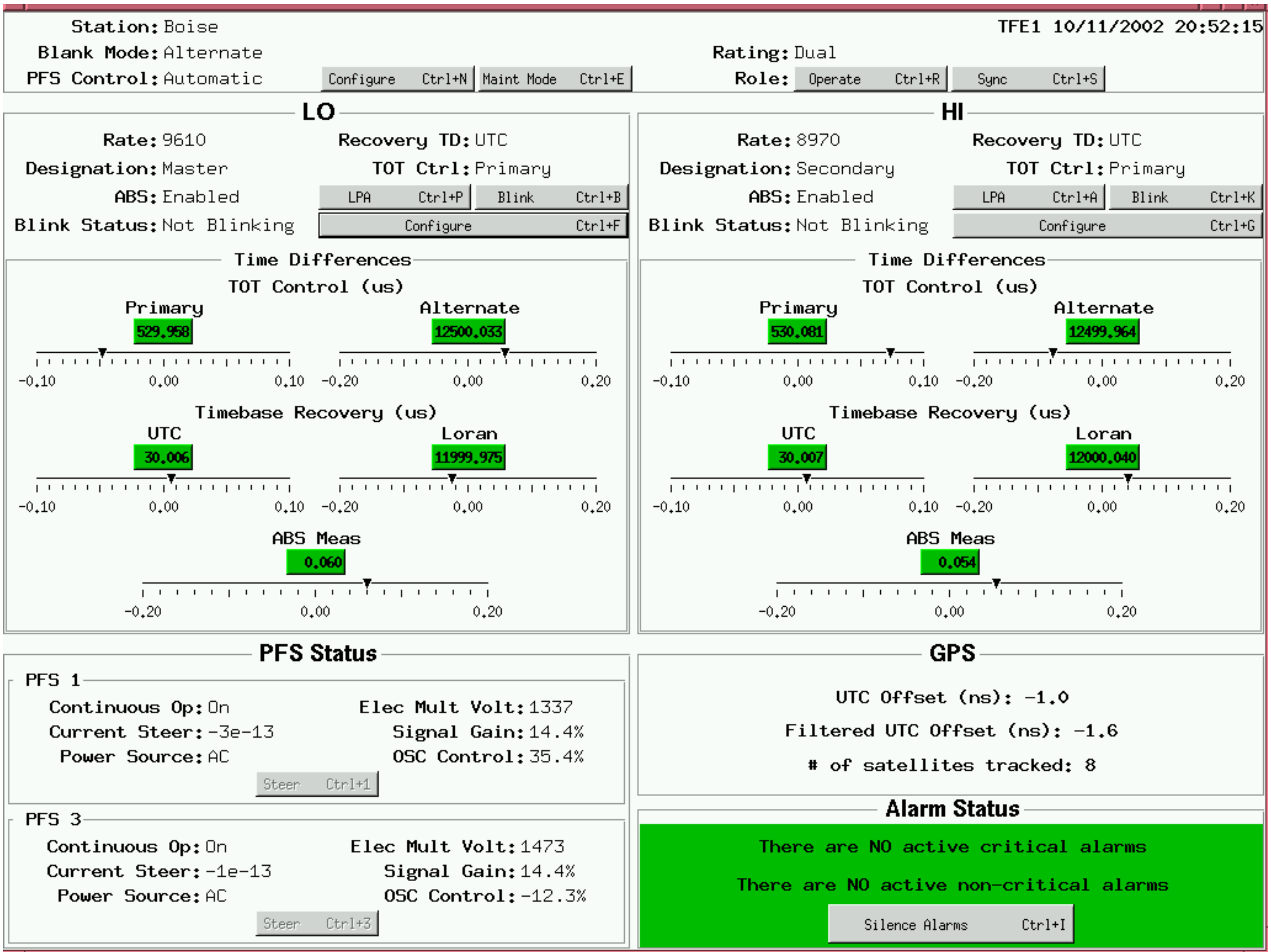

Figure 5: Local GUI interface

4.0 Modifications to Meet Future Requirements

The recapitalization of LORAN-C is ongoing and will continue over many years. Many changes to the system are being considered including the addition of a data channel, changes to the rates, elimination of master and secondary designation and other modifications to the basic signal structure. TFE has been designed with evolution in mind. The majority of the LORAN-C signal formation and processing is programmed into digital firmware that can be changed in the field. The software is written in object oriented C++ with an emphasis on modularity and compartmentalization of key functions.

The advent of data transmission on LORAN-C seems to be a foregone conclusion. While the eventual format is not certain, it is clear that some form of data modulation will be required in future systems. The LITS chassis was designed with space for a data modulation capability in the future. An edge connector on the main board was included to allow for a new data modulation board to be added at any time. Spare connectors were added (RS-232 for data input and BNC connectors for data output to the transmitter) to facilitate the addition of the data channel without hardware re-design.

The timing/measurement chassis also has room for future capabilities. There are three spare slots in the chassis that can accommodate new modules as required for future operations. The GPS receiver is modular and can be replaced by another means for time recovery (like two-way time transfer) if true GPS independence is required in the future.

5.0 Conclusions

The development of the next generation time and frequency system for transmitting LORAN-C stations is complete. TFE is a state-of-the-art time recovery system that generates LORAN-C transmitter drive signals based on a precise local knowledge of UTC(USNO). The system incorporates optimal filtering of cesium and GPS data to compute a local timescale that improves performance and robustness. The system is capable of operating without GPS by using the transmitted LORAN-C signals from other stations to drive the control loops. The Automatic Blink System is integrated into the system providing a link between real-time integrity monitoring and user notification. The software utilizes standard interfaces over IP sockets that enable remote operations.

TFE will enable a new concept of operations for the USCG. The system will evolve with future modifications and host the LORAN-C data channel via modular additions. The advent of frequency steering of the transmitted signal will enable a new level of user performance that will further solidify LORAN-C's role as a US radionavigation system.

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