RECENT DEVELOPMENTS IN TIME & FREQUENCY DISSEMINATION SYSTEMS

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Abstract

The paper addresses the activities performed on a novel Time & Frequency Dissemination (T&F D) System based on ESA Patent 407, including its most recent developments.

The method allows to transfer the precision and the stability features of a state-of-the-art ground clock to a less performant clock module on board a satellite. By implementing the patent methodology, the on board clock module becomes the "master Time & Frequency dissemination source" for all the ground terminals located in the footprint of the satellite hosting the on board clock module.

The paper, after having addressed the basic principles of the method, provides a summary description of the Time & Frequency Dissemination System, giving an overview of the applications that can benefit of it and comparing its performances against the ones of the main competing systems.

The actions for the definition of the system and for assessing the related performances are described as well.

The final part of the paper is dedicated to the description of the most recent activity, consisting in the realisation of the experimental setup and in the performance of a Field Trial campaign for the assessment of the actual system performances. The paper is concluded by highlighting future planned activities following the Field Trial Campaign.

1. Innovative Principles for Time & Frequency Distribution

To better exploit bandwidth spectrum and to ease interconnection between different operators, telecom operators have always looked for an "independent" infrastructure able to distribute in real time an accurate and stable clock reference. In addition to telecom operators a wide range of disciplines would benefit from the availability of such an infrastructure. This is not the case as of today; available solutions are mostly spin-off of positioning systems as GPS[1], they are usable only close to ground and offer limited guarantees in terms of accuracy, stability and reliability for many applications. Even if the planned Galileo Navigation System, as a civil navigation system, is expected to improve the situation the Galileo Time distribution function , also in this case, will not be the primary system function

The ESA Patent 407 proposes a novel approach and offers a solution to this need.

The T&F D system concepts are based on the innovative principle to distribute a very accurate ground-based time reference by means of a satellite network. This is done by synchronizing a low performance on-board oscillator (slave clock) with a very accurate Ground Time Reference (master clock) and then distributing the space clock time to ground users. Fig. 1.1 shows the overall Time & Frequency Distribution system architecture.

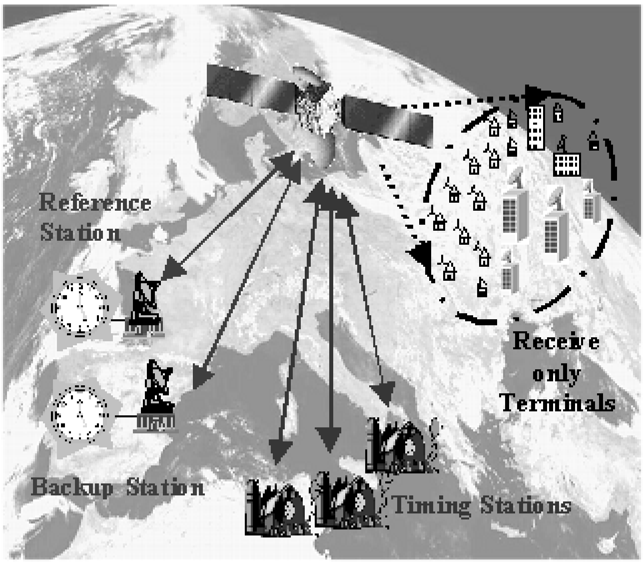

Fig. 1.1 Time & Frequency Distribution System Architecture

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[1] Despite the diffusion of GPS-based receivers, it is worth reminding that GPS is a military system and not under European control.

The system concept can be broadly summarized in the following points:

1. A state-of-the-art atomic clock located on ground in the Master Clock Station (MCS) is used as time reference.
2. A Backup Station is provided for availability reasons in order to take the role of MCS in case of its failure.
3. A less accurate clock is embarked on a satellite. The on board clock is synchronised to the ground-based time reference, using a special PLL. By implementing the Patent concepts the on board clock inherits the accuracy and stability features of the ground one and can be used as reference for the following time and frequency dissemination process.
4. The radio link connecting the ground stations and the space-based time reference is operated using existing communication techniques; in particular a TDMA access scheme is used for the uplink while TDM is used for the downlink.
5. After Satellite Clock synchronization the time/frequency reference is provided to the following categories of users:
   - "Clock Stations" and "Timing Stations"; these are transmitting/receiving stations, similar to the Master Control Station and using the same synchronisation principle. Such stations are required by users with more demanding performance requirements.
   - One-way user stations; these are receiving only stations using the timing and data information from the satellite signal to lock their clocks. Such stations are required by users with less performance requirements.

The above mentioned mechanism implies that Doppler compensation techniques are properly applied at each transmit and/or receive station in order to compensate the effects of Satellite / User Stations relative movement.

As it can be seen from the above system description, it is not necessary to set-up a complete new-from-scratch system for the implementation of the Patent concept, but this system can be seen as a “plug-in” of existing infrastructures, as the system will require a small on-board payload and traditional TDMA ground equipment (with some customisations and ad-hoc interfaces required by the application).

Being the system part of an existing telecommunications network there is no need to apply for specific frequency to Frequency Regulatory Boards.

The required mass for overall on-board clock module payload is estimated to be approximately 5kg. The on-board clock module would be a piggy-back in a standard telecommunications satellite, and it will share IF to IF interfaces of “host” satellite. The on-board clock module will consist of the following main components: (a) a clock recovery module; (b) a phase detector; (c) a loop filter (d); a DAC for controlling the local clock; (e) a local clock.

The local on board clock would be based on a “Precision quartz oscillator ” or a Rubidium clock, so there is no more need to embark high-accuracy (and then heavy and difficult to control) clocks.

It could be envisaged to have one ground clock placed under the footprints of two satellites. This will allow synchronizing clocks in one geographical area with clocks in another geographical area. This leads that with 3 GEO satellites (opportunely located) it will become possible to realise a real-time universal time.

2. Time & Frequency Distribution System Main Characteristics

The system configuration to implement this T&F distribution method consists of a ground segment and of a space segment.

Ground segment

One (or more) ground MCS(s), equipped with state of the art atomic clock, are in charge of :

- Estimating the time/frequency error at frame, symbol and sub-symbol level (delay/shift due to all propagation effects from ground to satellite) by using received loop-back timing & data from Satellite On Board Clock Module
- Transmitting a TDMA signal corrected at frame/symbol level and providing sub-symbol compensation info into TDMA burst data for further correction by Satellite On Board Clock Module

A backup of the MCS is foreseen: this one operates normally as a clock/timing station, in order to shorten the switchover phase. When the satellite looses the contact with the MCS it commands the backup station to behave as a reference. It then stops adjusting its local clock and the satellite in turn takes the backup station clock samples to synchronize its own clock.

The Two-way Clock /Timing User stations exploit the same two way method to discipline their local clocks with the Satellite clock, which is already synchronized with the MCS reference clock.

The One-way User Stations use the system in one-way mode, taking advantage of the precise reference coming from the satellite, but with lower performance with respect to two-way users. In this case the downlink delay is estimated and corrected using standard techniques.

Space segment

A GEO/MEO/LEO Satellite with one On Board Clock Module is in charge of:

- Recovering the clock from the received TDMA burst signal (data clock) and performing a further sub-symbol fine adjustment by exploiting correction data computed and transmitted by MCS
- Measuring the Time of Arrival shift wrt nominal position and transmitting it to the Ground Clock station via TDM(A) for exploitation in time/frequency error estimation.

The synchronization technique

As above mentioned, the synchronization technique relies on the measurement of the 2-way delay for estimating the uplink delay and compensating for all the asymmetries by means of either estimations or measurements in order to synchronize the Satellite Clock with the Ground Clock.

The MCS establishes a communication link with the satellite using the TDMA access. The satellite TDMA payload is regenerative, i.e. the TDMA frame is built on the satellite and retransmitted to ground in TDM mode.

The ground station is able to adjust the transmission time to the correct position by looking at the return signal.

Considering Fig. 2.2, measurements on board of the pseudodelay (PDS) and measurements on ground of the pseudodelay (PDG) are taken each time frame.

$$\text{PDS-PDG} = \text{AS}+2\text{dT} \qquad (1)$$

$$\text{PDG+PDS} = \text{2-way delay} = 2\Delta+\text{AS} \qquad (2)$$

where AS is the link asymmetry and dT is the clock offset between the satellite time Ts and the ground station time Tg.

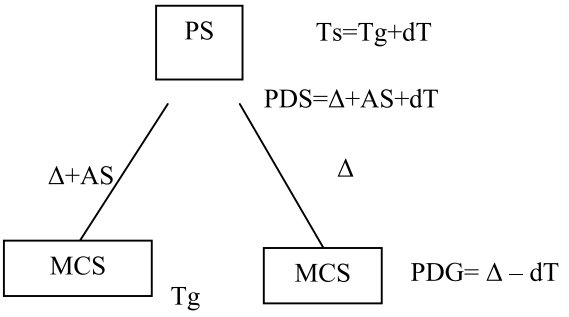

Fig. 2.2: The Synchronization Technique

The link asymmetry (AS) has contributions from the Geometry, Ionosphere and Electronic Delays.

The geometrical AS is estimated from the time evolution of the 2-way delay measurements performed at the frame rate. Other AS are estimated with link asymmetry models.

The clock offset dT is derived from Eq.(1).

The MCS sends time and data to the payload synchronized with its local clock, used as a reference for the system.

The uplink delay is compensated at different levels.

A gross delay adjustment is performed on ground by:

- Changing the frame number in the sent data packets (at frame period rate)
- Adjusting the phase of the sent packets (at symbol level)

A fine delay adjustment (under symbol level) is performed on board by adjusting the phase of the payload clock by using an information inserted in a burst field by MCS.

The clock offset is used for locking the S-Clock to the G-Clock via an on board PLL.

This circuit is fed with windowed ground clock samples recovered by the TDMA demodulator: in this way the phase and frequency differences between the satellite clock and the ground clock are compensated.

At this point the satellite clock has been synchronized with the reference clock and the synchronization of user terminals can start.

3. Applications Overview

Basically, all the applications requiring a Time & Frequency dissemination service providing high reliability and availability features can benefit of the proposed system.

Among others, the following main applications are in particular identified:

- Synchronisation of a Satellite Clock to a Master Ground Clock.
- Synchronisation of communication satellites using the technique of the on board switching.
- Independent measurements of the Galileo Satellite Clocks synchronisation, particularly during the Test Bed and IOV phases.
- Synchronisation of Clocks on board of Deep Space Probes for scientific missions.
- Timing for a Martian Navigation system.
- Time Distribution System from Space: High Accuracy (2-way); Lower Accuracy .
- Simultaneous Accurate Time comparison between an ensemble of ground stations for metrology applications.
- Digital television
- Medical applications
- Satellite and inter-satellite ranging applications

Furthermore, the T&FD system can be used as a backup for existing GPS-based applications in order to increase reliability and provide the service whenever the GPS is unavailable due to political/military reasons.

4. Comparison of T&F D System Performances vs. the ones of the main competing systems

In Table 4.1 the performances achievable by the main existing time and frequency dissemination systems, like TWSTFT and the Navigation Satellite System, like GPS, are compared with the expected performances of the T&F Dissemination system subject of the paper.

T&FD system should associate both performance and cost interests with respect to competitive solutions like GPS for mass market applications and TWSTFT for high precision clock comparisons.

	TFD	**TWSTFT**	**Navigation Sat. Sys.**
Availability	Continuous	On demand, subject to the link availability	Continuous
Performance	Real time	Presently it requires post-processing	Real time / Post processing
Users	Several stations	Two stations	Several stations
Coverage	Satellite footprint	Intercontinental	Global
Accuracy	0.1 ns (Goal)	1 ns	30 ns/ 1ns
Stability over 1 day	10^{-15}	10^{-14}	10^{-13}/ 10^{-14}

Table 4.1:T&FD system and main competitors characteristics

At the current time TWSTFT is the preferred method for time and frequency comparisons between remote sites for metrological applications, however, TWSTFT is not widely used because of the leasing cost and the limited availability of satellite communication channels. In addition, the time comparison can be performed only between two stations.

The proposed method offers, with respect to techniques already available, comparable or even better performance along with the capability of supporting several ground-stations simultaneously. This capability constitutes a significant improvement with respect to the traditional two-way systems, which support the synchronization of two stations only.

As anticipated in the introductory sections, this new feature is obtained by the adoption of already existing communication techniques and with a little payload embarked on a LEO\GEO telecommunication satellite. Furthermore, the TFD network could be uninterruptedly available in real time without the necessity of post-processing.

Moreover, with the launch of three T&FD payloads on suitably positioned geostationary satellites, the system may broadcast a global real time reference.

5. ESA Actions on T&F Dissemination Systems based on ESA Patent 407 and Main Objectives of the Field Trial Campaign

After having been granted with the patent related to this new method, ESA has funded some studies to exploit its performances and feasibility.

Via different Agency programmes, ESA has already funded the following studies:

- *Prototype development o fan On-board module (1999)*
- *Two Parallel System Studies (2000)*
- *Field Trial Campaign (2003)*

The last one of these studies, (which is object of this paper), is related to a field trial campaign: the space segment in this case is replaced by a double-hop satellite access.

It means using on ground a representative prototype of an on-board clock module.

This will allow to proof the concept with an easy deployment and also to learn lesson before embarking the “real space segment” on satellite. (The study is funded under the “ARTES-5 [2]” programme of the Agency).

At the end of this campaign it is expected not only to validate the method and the algorithms needed for its implementation, but also to use the field trial campaign configuration as a preliminary distribution system.

Once (or in parallel with) the preliminary distribution has started, it might be possible to look for a “host satellite” embarking the On-board Clock module.

The Field Trial Project team is leaded by Carlo Gavazzi Space and is composed by TEMEX Time, KYTIME and ALCATEL Space.

Carlo Gavazzi Space (CGS), as Prime Contractor, is responsible for project management and technical co-ordination, system definition, definition of design, development and AIT plan, system integration and testing, management of the links with the satellite operator and field trial campaign results evaluation. Moreover, CGS is developing the TDMA Terminal and the Station Controller which are the core of the MCS, Satellite Payload Simulator and Auxiliary/Timing stations design.

TEMEX Time is responsible of the specification and setup of the instruments to be exploited for the test campaign, including Atomic Clocks (RAFS, LPFRS), Measurement Subsystem (Picotime) and Micro Phase Stepper.

KYTIME supports CGS in the implementation of the concepts defined in the ESA Patent 407, in the theoretical analyses, in the definition of the measurement methods and in the interpretation of the test results.

ALCATEL Space supports CGS on system definition aspects.

6. Main differences between Field Trial Configuration and Final Target System configuration

The Field Trial envisaged topology is based on satellite double hopping access, allowing to use one On Board Clock (OBCK) module placed on ground resembling as much as possible the future flight OBCK module.

The following figure 6.3 shows how the different up and down links are exploited in the field trial configuration in order to synchronise at first the on board clock module with the ground reference and then to disseminate time / frequency signals to the secondary stations.

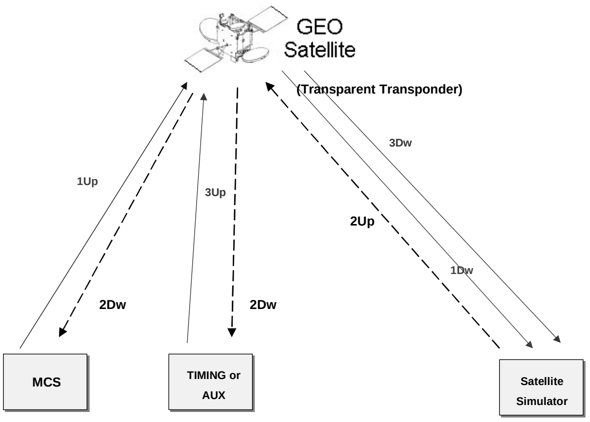

Fig. 6.3 Field Trial configuration links exploitation

It can be seen that respect to the target system the payload is now hosted on ground. The MCS-Satellite uplink has been replaced with the sum of MCS-Satellite and Satellite-Satellite Simulator (SS) links (1Up+ 1Dw), while the Satellite- MCS downlink is replaced with the sum SS-Satellite and Satellite-MCS links (2Up+2Dw).

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[2] To find more on ESA telecom programmes, please visit the website: telecom.esa.int

For the Timing/Aux station the up and downlinks have been replaced with (3Up+3Dw) and (2Up+2Dw) links respectively.
The Field Trial System is intended to provide the user community with the confidence that the Target System will offer the performances that have been analytically envisaged in the system studies.
It can be also exploited to detect practical problems that have not been identified during theoretical studies and to propose solutions to such problems before committing to the final configuration.
However, it is clear that the layout of the Field Trial System is different with respect to that of the Target System.
The following table reports the main differences between the two configurations.

Parameter	Target System (TS)	Field Trial (FT)	Notes
Doppler	Asymmetry induced by the different frequencies	Symmetry induced by the double hop.	The FT should have better performances than the TS.
Ionosph. Delay	Asymmetry	Compensated by the double hop	The FT should have better performances than the TS.
Location	The stations are in different locations	All the stations can be located in the same site	FT could allow an easier evaluation of the achieved synchronization level
Relativistic Effect	Being the Clock on board, the relativistic effect shall be compensated.	Clocks on ground (and possibly in the same location) => no need of relativistic effect compensation	The FT should have better performances than the TS.
Noise	Lower, because the single hop	Higher because the double hop	The TS should have better performances than the FT.
Down-Link	Continuous clock on the downlink	Because of the TDMA access, the clock is windowed also in the "down-link"	The TS should have better performances than the FT.

Table 6.2- Comparison between Target System and Field Trial

7. Theoretical Field Trial System Performances Evaluation

In order to assess the system performances it has to be computed the time error of the 10 MHz Payload Simulator locked oscillator with respect to the reference oscillator in the MCS.
This error is due to the overall noise introduced by elements of the system.
The following main items contribute to the overall performances:

- Delay and Doppler compensation system
- Demodulator phase recovery accuracy with noisy signal. The demodulator takes into account the effect of the link noise.
- Phase noise of the slaved clock

Moreover, the up-link transmission rate determines the achievable overall system time stability (see Table 7.3).
The Field Trial Performance Evaluation Model is shown in Fig 7.4 where:
MOD= Modulator part, DEM= Demodulator part
PROC: Processing part, SPL: Splitter
DOWN CONV: Downconverter, UP CONV=Upconverter
PLL= Phase Lock Loop
CNTR=Counter

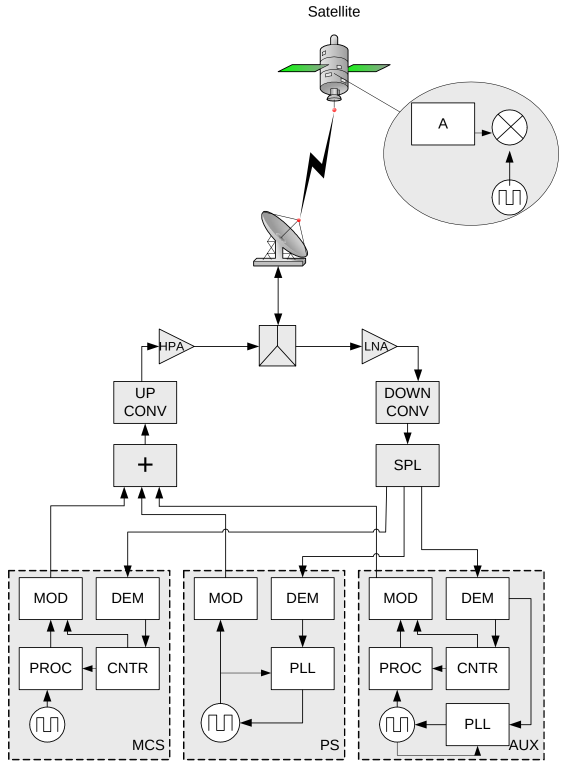

Fig. 7.4 TFD Field trial system performances evaluation model

The main entities involved in the loop are:

- Master Control Station (MCS)
- Satellite (in the Field Trial – FT - a transparent transponder)
- Payload Simulator (in the FT it is located on ground)
- Secondary Station (SS or AUX)
  This station shall perform two functions in relation to the actual test phase:
  - backup station for the MCS, in order to verify the hand-over procedure
  - clock/timing station, in order to verify the user stations achievable performances.

Table 7.3 gives an indication of the performances (Reference Clock vs. On board Clock Relative Frequency Error ε over 1 day averaging time) that can be achieved by the Target System (TS) and by the Field Trial configuration (FT) by the application of this approach in relation to the up-link access rate and the timing recovery error.
The method is frequency independent, i.e. it is limited only by the state of the art technology for phase tracking of both on board module and ground station module. This means that the results shown in Table 7.3 may evolve when a most performant technology allows a smaller peak-to-peak phase jitter for on board tracking (e.g. faster comparators, more accurate equalization of delay paths within the clock module, higher clock frequency).

Timing error	Symbol rate MHz	Relative Frequency Error over 1 day	
		TS	FT
0.1°	2	1.56E-15	2.86E-15
1°	2	1.56E-14	2.78E-14
0.1°	4	7.85E-16	1.54E-15
1°	4	7.85E-15	1.39E-14
0.1°	8	3.96E-16	9.72E-16
1°	8	3.96E-15	6.99E-15

Table 7.3 Preliminary performances estimation as function of symbol rate and of phase error in timing recovery

8. T&FD Field Trial System Description

The Time & Frequency Dissemination Field Trial System configuration is physically composed of the following main parts:

1. A Master Control Station (MCS)
2. A Payload Simulator (P/L)
3. A Secondary Station, that can act as an Auxiliary Station as well (AUX).
4. A Ground Station (RF part, including antenna) for accessing the Satellite exploited during the Field Trial campaign
5. A Satellite (ASTRA 1-A) providing a transparent transponder.

All the stations (MCS, PL, Aux) are located on ground in the same premises, in order to allow an accurate phase measurement between:

a. The MCS reference clock and the P/L clock

b. The MCS reference clock and the AUX clock

All the measurements are performed by means of two dedicated Measurement Systems, based on the Picotime Unit. The overall system is depicted in figure 8.1.

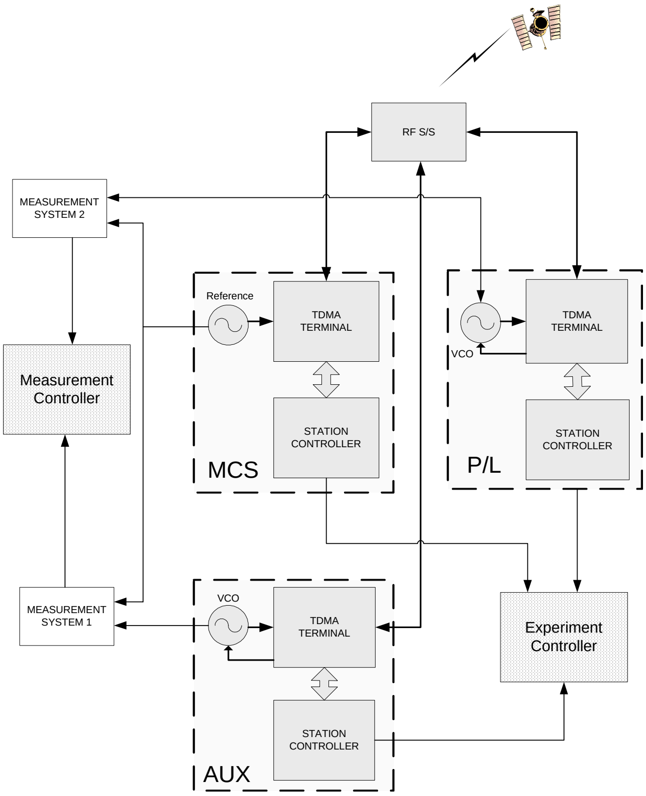

Figure 8.1 Field Trial System Block Diagram

The Experiment Controller (EC) provides the man machine interface: it shows to the experiment conductor the overall system behaviour including the contents of the three stations internal registers and the results of the Doppler compensation algorithm. The data can be displayed as numbers or plotted as XY graphs. All the acquired data are stored in log files, which can be retrieved also by remote data communication links. The EC permits also the sending of commands to the stations for debugging purposes, e.g. it can force each station in an arbitrary state.
The EC is implemented using a personal computer in a Windows environment, running a program written in ANSI C and exploiting off-the-shelf tools for the graphical part.
All the three stations are composed of a Station Controller and of a TDMA terminal.
The Station Controller (SC) is in charge of implementing the TDMA burst assembly, the TDMA slot acquisition strategy and the Doppler compensation algorithm. This module manages also the communication with the experiment controller. The SC is physically implemented in an Analog Devices TS101S Tiger Shark DSP based board running a software developed in ANSI C. The board is linked to the TDMA terminal by means of two DSP high speed serial link ports.
The TDMA Terminal is implemented on two boards, one including the digital parts and the other hosting the filters and the analog circuits.
The Digital Board hosts a Xilinx Virtex II 4MGates FPGA that contains the demodulator circuit and the modulator

control interface. The Modulator is completed by a commercial DDS IC from Analog Devices.

The P/L Simulator and the AUX stations are equipped with a DAC, necessary to generate the control signal for the local VCO.

The MCS is timed using an high-performance Rubidium Atomic Frequency Source (RAFS). The P/L and the Aux stations receive their reference from Low Performance Rubidium Frequency Source. Those devices are controlled using a built in analog input.

The measurement system is composed of two Picotime devices that permit to measure the Allan variance of a clock under test with respect to a reference. Both the Picotime Units use the RAFS as a reference: they measure the performances of the P/L and the AUX clock respectively.

The system is completed by a Power Supply unit and a power Distribution unit.

All the equipments are hosted in a standard 19" rack in order to ease the transportation and installation.

9. Field Trial Program Schedule and Status

The Field Trial Program was started on the 2nd quarter 2003 and is planned to be concluded within June 2004.

During the first program phase a preliminary theoretical analysis was performed for assessing the expected system performances prior to committing to a final system configuration. Then, the System and Subsystems Specifications were established, being the starting point for the setup of the Time & Frequency Dissemination system to be validated during the test campaign.

Based on the established specifications, the detailed design and MAIT of the items to be specifically designed for the Field Trial Campaign were performed (TDMA Terminals, Station Controller, Experiment Controller, Micro Phase Stepper).

In parallel, the off-the-shelf items complementing the custom design items were procured (Measurement SS, Precision Clock Sources).

Currently, all the custom design units have been successfully setup and the system integration is in progress at Carlo Gavazzi Space premises. At the beginning of April 2004 a first station has been successfully validated at SES ASTRA premises, in Betzdorf, while the Field Trial Test Campaign exploiting ASTRA 1-A Satellite is planned to start in the middle of May 2004.

The Final Report of the program will be available within June 2004.

10. Future Plans

After the conclusion of the Field Trial Campaign the short – medium term plans foresee the upgrading of the Field Trial Configuration for providing of a pre-operational service.

This upgraded configuration will take benefit of the lessons learnt by performing the Field Trial test campaign.

Apart from the re-engineering of the Field Trail configuration, this upgraded system would not require a long time period to be setup as it will not be required to fly the clock module on board a satellite but a transparent transponder will be exploited as for the Field Trial campaign.

At medium – long term it can be foreseen the implementation of a pre-operational mission by embarking the Time & Frequency Dissemination Payload hosting the on board clock module onto a Satellite.

Acknowledgements

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