Optical Frequency and Timing Distribution System for ESA Deep Space Tracking Stations

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***Summary*— Deep space tracking via ground-based antennas requires ultra-precise frequency and timing (F&T) distribution to ensure accurate spacecraft positioning and safe navigation. In the past decade, optical F&T distribution systems have matured significantly. Many systems are now operational 24/7 in several science facilities providing femtosecond-level residual timing jitter and drift. By considering the stringent requirements of deep space missions, we have developed, manufactured and successfully tested an optical F&T distribution system for ESA Deep Space Stations. The first system has already been installed and commissioned at GSRF, ESOC. This paper describes the general system characteristics and presents the performance results achieved during system verification.**

Keywords*— *frequency transfer, timing transfer, deep space, optical pulses, optical fiber link, low phase noise.

I. Introduction

Low-noise F&T distribution over large distances provides high temporal resolution in the order of femtoseconds for many ambitious scientific explorations [1]. Today, large-scale scientific instruments are pushing the limits of timing and synchronization to ever smaller durations. For instance, X-ray free electron lasers (i.e., largest lasers in the world) synchronize tens of optical- and microwave-sources spread over kilometer distances with relative few femtosecond timing precision [2]. Furthermore, interplanetary spacecrafts and deep space survey missions require a worldwide network of space antennas with sub-microsecond global timing accuracy between stations and femtosecond-level distribution within each station [3].

The main tasks of a deep space antenna are to ensure telemetry, tracking and commanding (TT&C) with space crafts, receive critical data science returns and support mission operations. A formidable challenge for F&T systems arises from the fact that it takes a certain time for the signal to travel between the station and the spacecraft (i.e., the roundtrip delay time). Therefore, each station must be equipped with a stable frequency reference (e.g., maser) and a precise F&T distribution system [4],[5] to ensure accurate spacecraft positioning measurements and provide safe navigation. In particular, the site layout of a ground station necessitates signal transfer between buildings which could be hundreds of meters away. Transferring F&T signals with femtosecond precision is not trivial; several techniques [1],[6],[7] have been developed during the last decades for preserving their stability and spectral purity upon transmission.

By considering recent technological developments and increasing demand in precision, the next generation F&T distribution systems of the ESA Tracking Network (ESTRACK) will be equipped with state-of-the-art optical F&T modules [8] (e.g., mode-locked lasers, and pulsed optical fiber distribution) while providing conventional electronic F&T interfaces (e.g., 5-10-100 MHz, 1PPS, IRIG-B).

The first optical F&T distribution system for ESTRACK has been manufactured, installed, and tested successfully at the Ground Segment Reference Facility (GSRF) of ESA. Performance characterization results show that the system distributes 100-MHz signals to remote locations with exceptionally low phase noise (-163 dBc/Hz at 10 kHz) and frequency instability (5.78×10^{-16} at 10,000 s, limited by maser performance) measured differentially when the redundant distribution chains are driven by two independent masers. The frequency instability hints a limit of 1.45×10^{-16} at 10,000 s when the distribution chains are driven by a single maser. This promises a solid margin for future clock performance upgrades.

II. System Architecture

The legacy F&T systems, currently operational at ESTRACK stations, were developed in the early 2000s and their designs had evolved from one deep space station to the other to address different mission requirements [4],[5]. This led to customized design for each station, and due to the aging, a

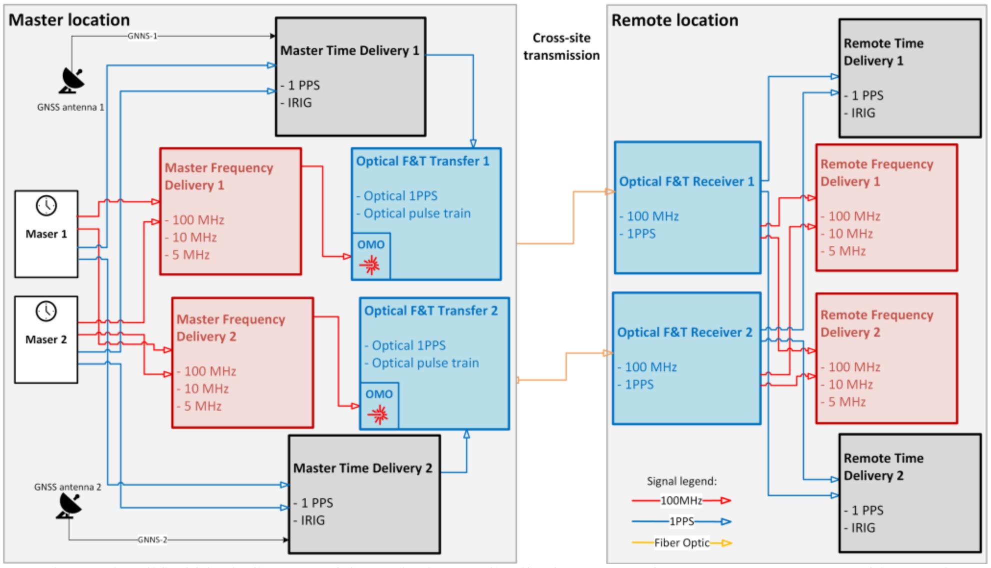


Fig. 1. Simplified block diagram of the optical F&T distribution system for ESA Deep Space Tracking Stations.

severe obsolescence problem started to manifest which makes the maintenance of the system difficult and costly. Therefore, the new generation optical F&T system is designed to harmonize the F&T architecture by using modular subsystem elements which are common for all deep space stations and allow future upgrades such as multiple antennas per site. Fig. 1 shows the simplified block diagram of the new optical F&T distribution system. The system is designed as two redundant F&T signal chains, starting from two redundant masers at the master location, providing 100 MHz and 1 PPS signals. Station-time generation and referencing to UTC are performed by the master time delivery subsystems equipped with two redundant GNSS receivers (i.e., Real Time Clock from Lange-Electronic GmbH). All 1PPS, IRIG and NTP signals are referenced and synchronized to the generated station time. The system includes two redundant multichannel phase meters (i.e., FXEs [9]) at the master location for continuous performance monitoring.

The signal providing the highest precision to the user is the 100-MHz signal from the selected maser. Two redundant frequency delivery subsystems in the master location select the prime 100-MHz signal, generate 5-MHz and 10-MHz signals, and deliver them to the users at the master location.

The selected 100-MHz signal is then transferred to two redundant optical master oscillators (OMO). The OMOs are ultralow noise mode-locked lasers [10] (i.e., MENHIR-1550 from Menhir Photonics AG) providing a pulsed optical signal for cross-site transmission. The repetition rates of the OMOs are locked to the reference maser frequency using balanced optical-microwave phase detectors (BOMPDs) [11]. The cross-site F&T transmission is realized with fiber links whose transmission delays are actively stabilized by means of balanced optical cross-correlation (BOC) [12] upon roundtrip pulse travel (i.e., PULSE Timing Distribution System from Cycle GmbH) [13].

At the remote location, pulsed optical signals are converted to electrical 1PPS and 100-MHz signals which are locked to the station time and the master maser signal. Then, the number of time and frequency signal outputs are multiplied by low noise distribution amplifiers (provided by SpectraDynamics, Inc) and made available to the users at the remote location.

Another important feature of the new system is its scalability in terms of multiple remote locations (i.e., antennas) and a third clock input. As shown in Fig. 2, the system can serve up to 4 remote locations from a common master location where the clocks are located. Since the system hardware is built in a modular way considering the additional distribution elements, future extensions will not require additional rack space in the station. Even though the current baseline for F&T generation involves two Hydrogen masers, future upgrades may consider a third clock. Therefore, the system provides extended functionalities to switch, monitor and control 3 clocks in parallel. This would allow another level of redundancy and the possibility of 3-cornered-hat calculations to estimate the instability of each clock in a set of three clocks.

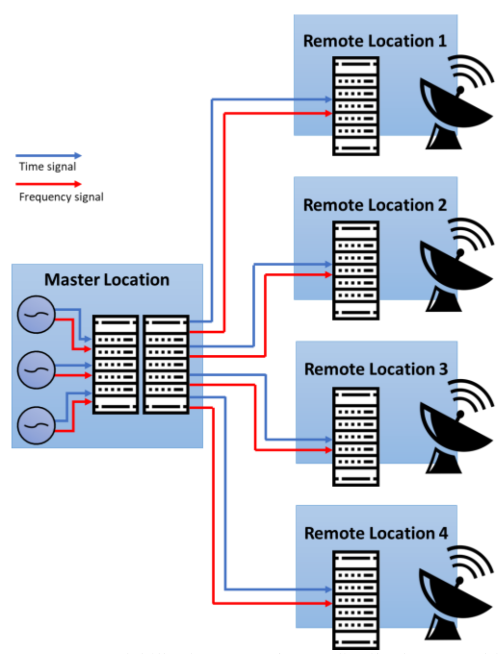
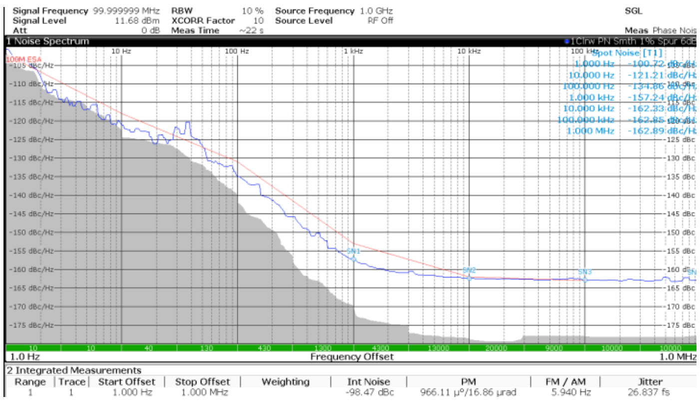


Fig. 2. System scalability in terms of F&T distribution to multiple remote locations. Figure modified from [14].

III. System Performance

After manufacturing, the system performance is first verified in the factory in Hamburg, then shipped to ESA/ESOC-GSRF in Darmstadt. After installation on site, the 2^{nd} round of validation is successfully performed where the system is driven by two Active Hydrogen Masers.

Fig. 3 shows the absolute phase noise at a remote frequency distribution output (i.e., the furthest point from the clock inputs) measured with a commercial phase noise analyzer (i.e., FSWP by Rohde & Schwarz). With an appropriate input source, the system provides 100-MHz frequency outputs at the remote rack with a phase noise -101 dBc/Hz at 1 Hz (limited by the input source) and -162 dBc/Hz above 10 kHz (limited by the distribution amplifier) (see phase noise data in Fig. 3).

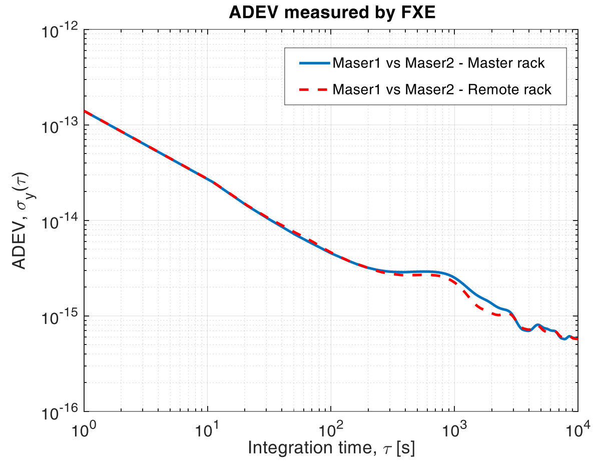


Offset Frequency	Phase noise	Project Specifications
1 Hz	-101 dBc/Hz[1]	-102 dBc/Hz
10 Hz	-121 dBc/Hz	-118 dBc/Hz
100 Hz	-135 dBc/Hz	-131 dBc/Hz
1 kHz	-157 dBc/Hz	-153 dBc/Hz
10 kHz	-162 dBc/Hz	-162 dBc/Hz
100 kHz	-163 dBc/Hz	-163 dBc/Hz

Fig. 3. Absolute phase noise measured at a remote frequency output. Top: phase noise plot, bottom: phase noise data. [1]limited by the clock input.

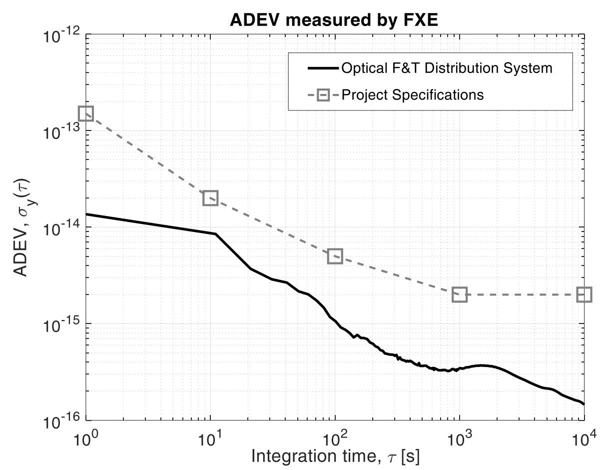
Fig. 4 shows the differential ADEV measurements performed at 100 MHz by the multichannel phase meters. The blue and red curves represent the results where one maser is measured against the other differentially at the master rack and at the slave rack, respectively. Here, one frequency chain distributes the signal from one maser, and the second chain distributes the frequency of the second maser (i.e., the results to be divided by √2 to get the instability of a single chain). As can be seen from ADEV data in Fig. 4, there is no noticeable difference between the frequency instabilities at the master and remote locations. This indicates that the noise introduced by the optical frequency distribution is negligible.

This is verified by another measurement where the output of one chain is compared with its own input indicating the added drift by the optical distribution line. As can be seen from the black curve in Fig. 5, the distribution line has much lower instability than the differential maser measurements and the project specifications. This proves that the system has a solid margin to handle future clock stability improvements.



Integration Time	Maser 1 vs. Maser 2 at Master Rack	Maser 1 vs. Maser 2 at Remote Rack
1 s	1.40×10^{-13}	1.40×10^{-13}
10 s	2.75×10^{-14}	2.76×10^{-14}
100 s	4.54×10^{-15}	4.62×10^{-15}
1 000 s	2.51×10^{-15}	2.24×10^{-15}
10 000 s	5.77×10^{-16}	5.78×10^{-16}

Fig. 4. Differential ADEV measurements using two masers. Top: ADEV plot, bottom: ADEV data.



Integration Time	Optical F&T System Limit	Project Specifications
1 s	1.36×10^{-14}	1.5×10^{-13}
10 s	8.51×10^{-15}	2.0×10^{-14}
100 s	1.06×10^{-15}	5.0×10^{-15}
1 000 s	3.46×10^{-16}	2.0×10^{-15}
10 000 s	1.45×10^{-16}	2.0×10^{-15}

Fig. 5. Additive ADEV measurement using a single maser. Top: ADEV plot, bottom: ADEV data.

Fig. 6 shows the measurements performed for the characterization of the time distribution outputs (i.e., 1PPS and IRIG-B 1 kHz). The top oscilloscope trace shows the 1PPS alignment between two remote distribution outputs. The system allows relative 1PPS synchronization of ~0.25 ns limited by the minimum step size of the 1PPS adjustment provided by the master time delivery subsystems. As can be inferred from the top figure, the rise time of the 1PPS signals is ~1 ns.

The bottom oscilloscope trace in Fig. 6 shows the relative alignment between the 1PPS (yellow curve) and the IRIG-B 1kHz (green curve) distribution outputs. The slope of the 1PPS signal and the starting point of the IRIG-B signal (i.e., the transition between the smaller and the larger amplitude) can be synchronized with ~2.5 µs which is sufficient for the IRIG signal whose period is 1 ms.

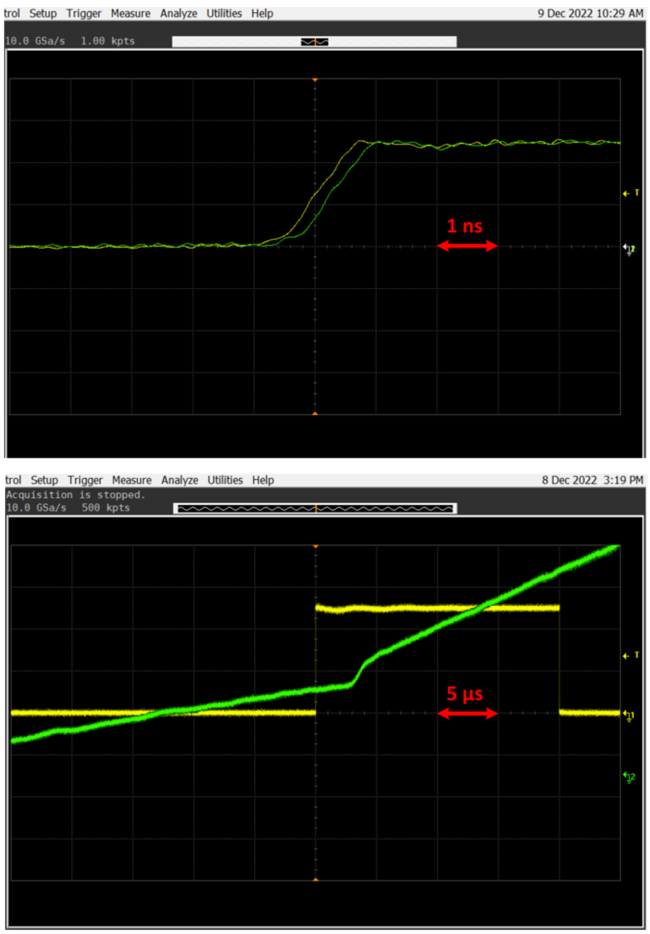


Fig. 6. 1PPS and IRIG-B 1kHz measurements. Top: 1PPS alignment between two remote distribution chains, bottom: relative alignment between 1PPS and IRIG outputs.

IV. Outlook

In summary, the first pulsed-optical F&T system for ESTRACK deep space antennas has been developed, installed and commissioned at GSRF, ESA/ESOC. The system creates a unique intersection between state-of-the art optical F&T modules and conventional microwave F&T equipment. The noise introduced by the optical distribution links are negligible as confirmed with the measurements.

The system constitutes a major milestone as it brings the optical F&T systems from laser labs into 19" inch server rack systems more compatible to an operational environment.

Our next step is to manufacture 3 further systems to be installed at ESA's deep space stations (Cebreros, New Norcia and Malargüe). Then, our aim is to design and develop optical F&T systems tailored for the ESA's near-earth stations (Kourou, Kiruna and Redu) to enhance ESA ESTRACK capabilities using the forefront F&T technology in the domain.

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