Design of the Frequency and Timing Subsystem for ESA's Deep Space Antenna 3

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***Abstract*— In December 2012, ESA inaugurated their third Deep Space Antenna tracking station near Malargüe, Argentina. Due to the nature of the deep space operations, exigent requirements for stability of reference signals and low phase noise characteristics were necessary on the ground station equipment. In order to fulfill the requirements, new concepts and hardware development were carried out, resulting in an improvement of the performance of the frequency and timing reference system.**

Keywords: maser; cryogenic saphire oscillator; deep space

I. INTRODUCTION

ESA's Deep Space Antenna 3, with its 35m dish antenna, was succesfully installed in a remote area near Malargüe in Argentina. This antenna follows the two previous Deep Space Antennas installed in New Norcia, Australia, in 2002 and Cebreros, Spain, in 2005. These three antennas are situated at about 120° with respect to each other making possible global coverage. This station profits, in addition, of minimum impact from the atmosphere as a consequence of its strategic location, which results in an enhancement of its performance [1].

New concepts and techniques to improve the overall performance of the Frequency and Timing (F&T) subsystems were developed and applied to ESA's third Deep Space Antenna. In contrast to previous stations, the clocks were not installed in the antenna, but in a distant building 100m away. Preservation of the performance along the long distribution path while maintaining the simplicity of the system as much as possible was not an easy task and was the main motivation during the design of the system. The performance achieved after adaptation and optimization of the key elements of the F&T subsystem and the reduction of the thermal sensitivity, allowed distribution to the antenna site, without degradation of the performance.

Figure 1. DSA3 antenna in Argentina – 35m dish

Independent and well environmentally-controlled clocks room, together with an improved short term stability and phase noise lead the way into the introduction of a 100 MHz frequency distribution system, in spite of the distance. Lower frequencies, such as 5 MHz and 10 MHz, were locally generated in each building out of the 100 MHz distributed signals. Timing signals, on the other hand, were regenerated and synchronized to the remote end.

Furthermore, the introduction of a cryogenic cooled sapphire oscillator (CSO) as a third source, in addition to the two redundant active hydrogen masers, accomplished to combine the CSO's good short term stability together with the better long term stability of the masers by locking the CSO to one of the available masers.

The system design, architecture, key aspects and the results of the tests carried out are presented on this paper.

II. Deep Space Antenna 3 applications

ESA's deep space antenna station incorporates a 35m dish equipped with a Cassegrain Beam Wave Guide feed RF system operated with dichroic mirrors and low noise amplifiers. Ka-band reception and X-band transmission and reception are already supported. Ka-band transmission, and K-band reception are planned to be supported in the near future [1].

The station is prepared to provide telemetry and telecommand functions, as well as serve for other purposes such as satellite tracking and ranging, Radio Science research, and support future scientific missions like LISA Pathfinder [9], Gaia [10] or BepiColombo [11]. ESA's deep space antennas already provide support to Venus express [12], Mars Express [13], Herschel [14] and Planck [15] missions.

While spacecraft tracking for orbit determination requires stable reference frequencies in the medium term and accurate time to obtain positions of satellites with sufficient precision (0.1mm/s). Some Radio Science missions impose, at the same time, high stability in the short term so that once per second events can be measured properly [2][6][7]. All these demanding requirements, added to the difficulty of having the clocks far away from the antenna made the design of the frequency and timing generation and distribution system a continuous challenge.

III. System design and Architecture

The F&T system for the Deep Space Antenna 3 station is distributed among three main locations; Clocks Room, Main Equipment Room (MER) and Antenna Equipment Room (AER). The clock room, is, in turn, subdivided into three smaller rooms, one room for the two Active Hydrogen Masers (Maser room), one room for the cryogenic sapphire oscillator (CSO room) and an Optical Clock room prepared for housing an optical clock in the future. Having the clocks so distant from the antenna results in a critical distribution, however, it has an advantage from the station level point of view. Ka-band transmission and K-band reception equipment, as well as future front-ends can be easier added, keeping the references in the main building and implementing a star topology to distribute the necessary signals to the different antennas. At the moment, reference frequency and timing signals from the clocks are distributed to the MER, and from the MER distributed to the AER, located 100m away from the Operations Building. A simplified block diagram with the different locations of the F&T system is presented in Fig. 2.

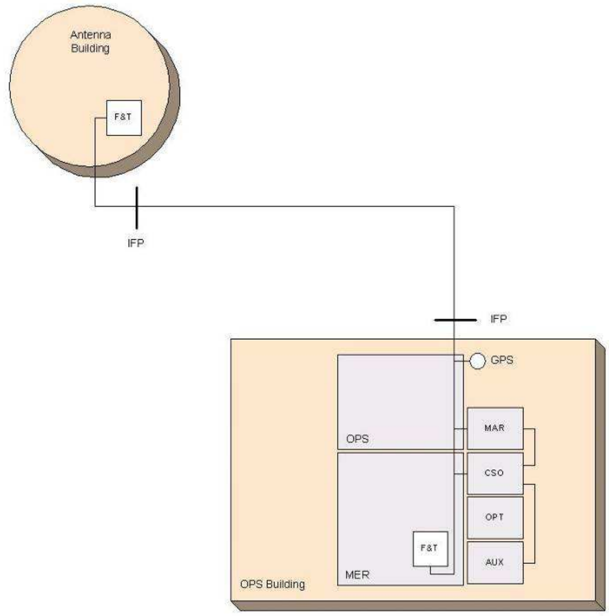

Figure 2. Simplified diagram of DSA3 locations with F&T equipment.

The system is prepared to store all data and measurements available from the system in order to provide long-term analysis of the frequency and timing signals' performance. Additionally, the system uses 3-corner hat ADEV post-processing software to determine the performance of each individual clock. Temperature and magnetic field in the maser room are continuously controlled. Undesired events are also logged for problem detection and troubleshooting activities.

A. *Reference Clocks*

Three high performing clocks are available at the station. The different rooms comprising the Clocks Room, are all environmentally controlled to avoid temperature variations of more than ± 0.5°C, assuring a stable thermal environment in which the clocks can perform at their best.

Figure 3. The two masers inside the Maser Room (MAR)

The two redundant Active Hydrogen Masers (AHM), see Fig. 3, manufactured by T4Science in Neuchâtel, Switzerland, exhibit an improved thermal design and high performance. For DSA3, the masers were modified to improve the phase noise of the 100 MHz maser frequency signal at frequency offsets below 100 Hz from the carrier, eliminating the need of external clean-up oscillators and/or Phase Locked Loops (PLL) outside of the maser. To do so, an Oven Controlled Crystal Oscillator (OCXO) manufactured by Pascall, United Kingdom, with a performance at 100 MHz of –138 dBc/Hz at 100 Hz offset was used instead of the original Voltage Controlled Crystal Oscillator (VCXO). The Pascall oscillator is locked to a 5 MHz BVA-type Ultra Stable Oscillator (USO) model 8607 from Oscilloquartz, Neuchâtel, Switzerland, which provides the good phase noise at lower frequency offsets. The OCXO is located outside of the ovenised maser electronics compartment due to heat dissipation concerns and supplied with regulated stable power supply. In addition to these modifications, the number of available 100 MHz signal outputs in the PLL board of the maser was duplicated from two to four, and distributed from the Maser interface directly to the units in MER.

Fig.4 shows the phase noise performance of the modified maser at 100 MHz. The figure represents one maser against the other. Assuming that both perform similarly, 3 dB can be subtracted from the values shown in the plot. For frequency offsets very close to the carrier (until about 30 Hz) one can appreciate the performance of the BVA, whilst, for instance, at 100 Hz, the signal already benefits from the phase noise of the Pascall OCXO, as a result of the selected PLL bandwidth .

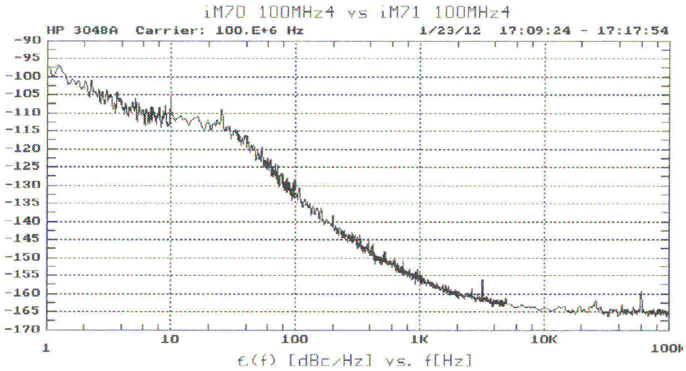

Figure 4. Maser 1 vs. Maser 2 – 100 MHz phase noise

Table 1 shows the improvement gained with respect to previous systems in terms of phase noise performance. Significant improvement can be seen at high frequency offsets.

TABLE I. MASER IMPROVEMENT WITH RESPECT TO PREVIOUS STATIONS

Phase Noise in dBc/Hz of the 100 MHz signal at the Maser interface		
Frequency Offset	***Previous Stations***	***DSA3***
1 Hz	-102	-102
10 Hz	-115	-115
100 Hz	-125	-136
1 kHz	-148	-160
10 kHz	-156	-164
100 kHz	-160	-165

In addition to the two AHM, ESA backed the design and implementation of a third clock to be used in DSA3. This clock is a Cryogenic Sapphire Oscillator prototype manufactured by Femto-ST in Besançon, France (See Fig. 5).

Figure 5. CSO in DSA3

The CSO consists of a high-Q sapphire whispering gallery mode resonator [5]. The resonator is thermally regulated by means of a cryocooler which sets the temperature close to 6K, so that any first order variation due to temperature cancels out. Electronics are comprised by amplifiers and filters belonging to the oscillator loop, and work at room temperature [5]. Finally, a synthesizer is needed in order to [6]:

- Perform the down-conversion from the CSO reference output frequency 9.989 GHz to 100MHz, 10 MHz and 5 MHz.
- Lock the CSO to the selected maser. The CSO counts with its own dedicated phase comparator which measures the phase difference between the masers and the CSO. By means of this phase comparator it is possible to lock the CSO to a maser with a long time constant (around 1000s). The result of this practice is an output frequency which profits from the good short term stability of the CSO and benefits from the good long term stability of the maser to which is locked to.

Fig. 6 shows the phase noise of the synthesizer measured during Factory Acceptance Tests. Two equal synthesizers were manufactured and measured against each other. As a result, and assuming that both units contribute the same amount to the measured phase noise, one can subtract 3 dB to obtain the real performance of one single synthesizer.

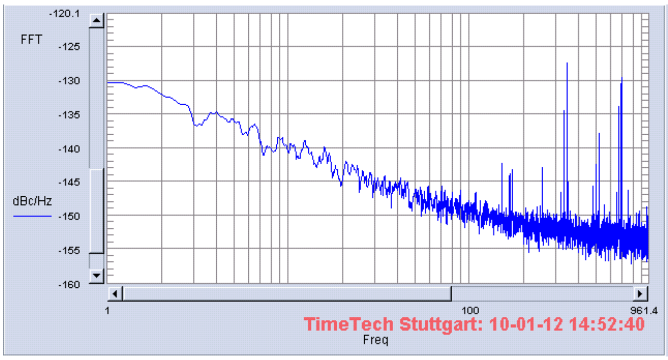

Figure 6. CSO synthesizer phase noise up to 1kHz at 100 MHz.

Moreover, having three clocks has further advantages. It is possible to measure the performance of each individual clock. Fig.7 shows the performance of the three clocks in DSA3 measured by means of the three-corner-hat method up to 1000s. One can see the better short-term performance of the CSO compared to that of the masers.

B. Frequency Distribution System

DSA3 F&T subsystem is based on a 100 MHz distribution system. Active distribution units to compensate for internal losses were equipped with low temperature coefficient (150 fs/K), standard high performance buffer amplifiers and low noise figure Monolithic Microwave Integrated Circuits (MMIC) set in parallel. 5 MHz and 10 MHz signals are also provided by the system, generated by division of the 100 MHz reference frequency signal. This state-of-the-art high performing low phase noise divider and distribution board shows improved phase noise characteristics (see Fig. 8) and was developed during the design of the F&T system for DSA3.

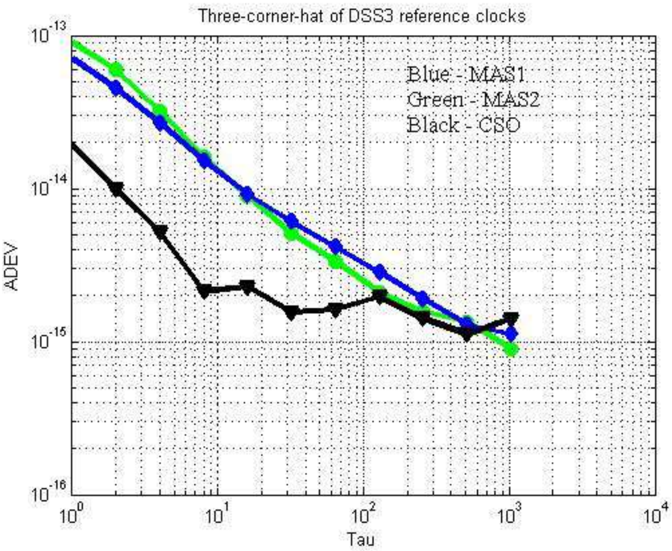

Figure 7. Individual Allan deviation performance of each clock

To assure a successful design, appropriate cables were selected to transmit the 100 MHz signals from the Clocks room to the MER and from the MER to the AER, without degrading the performance of the signal. In fact, implementing a long cross-site link, such as that between MER and AER, at frequencies below 100 MHz would have degraded the maser/CSO performance due to the very high thermal sensitivity of all coaxial cables at low frequencies [3]. Consequently, LDF4 50Ω cables with foam dielectric from Andrew, and presenting an extremely low thermal coefficient (0.6 ppm/K at 100 MHz), were selected for the cross-site link. In addition, cable ducts were buried 80 cm deep to attenuate the temperature variations as much as possible.

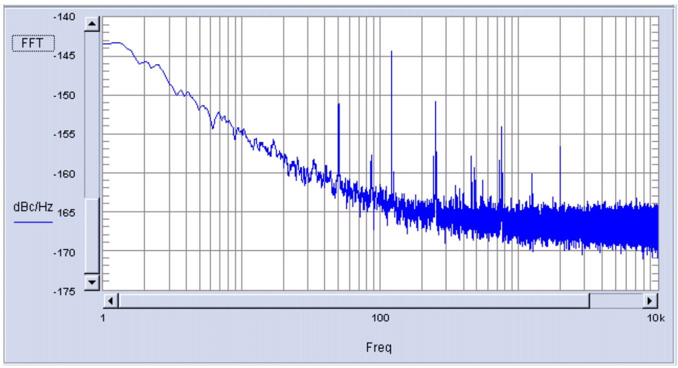

Figure 8. Divider phase noise at 100 MHz (*)

For the transmission of the 100 MHz from the Masers and CSO to the F&T rack inside the MER, and for the cables between the Maser room and the CSO room, FSJ-4 and FSJ-1 cables were used, respectively. These high quality cables have a greater thermal coefficient than LDF-4 50Ω, but, sufficient for adjacent rooms and short distances. A trade-off between thermal characteristics and cost had to be conducted.

Concerning performance at system level, Fig. 9 shows the performance achieved at the furthest point from the clocks (i.e. AER). The setup consisted of using one redundancy chain distributing the signals from one maser, against the second redundancy chain distributing the frequency of the second maser. (3 dB to be subtracted)

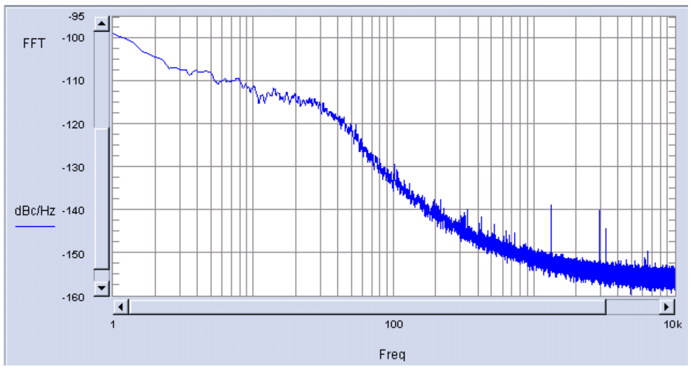

Figure 9. Phase Noise: Maser 1 through chain 1 vs Maser 2 through chain 2 at 100 MHz

* 3 dB to be subtracted to get phase noise of single unit

C. *Timing Distribution System*

Timing signals are generated using the derived 5 MHz signal from the masers (or CSO). The generated 1pps is constantly monitored against UTC (GPS) and maintained within 100ns. Moreover, the GPS comparison also allows long-term frequency accuracy analysis.

There is no distribution of timing signals as such, but regeneration of these signals on the remote side out of a 1pps two-way measurement. An optical link with active delay compensation assures that the remote 1pps signal is aligned to less than 1ns to the transmitted one [4]. IRIG-B timing signals also follow this 1pps and will therefore also appear aligned.

IV. SUMMARY AND CONCLUSIONS

Designing a well-performing F&T subsystem for DSA3 was a challenge. The requirement of locating the clocks at a substantial distance of 100 m from the antenna imposed applying new concepts to the F&T system design. In this paper, we have presented the motivation, architecture, design process, developments and results from the F&T system installed in DSA3, Argentina.

Main differences and new developments with respect to previous stations were, among others:

- Special configuration of the AHM with improved phase noise performance to avoid the use of external clean-ups.
- Design of a 100 MHz distribution system to profit from the reduced temperature coefficient at high frequencies.
- Selection of thermally stable cables running on deep cable ducts to decrease temperature variations.
- Low phase noise, high performing dividers to provide lower frequencies out of the 100 MHz distributed signal.
- Introduction of a third clock with excellent short term performance which could be locked to an AHM at integration times of around 1000 s.
- Improved optical link for time synchronization with active delay compensation and uncertainty below 1ns.

In this paper, we have presented the motivation, architecture, design process, developments and results from the F&T system installed in DSA3, Argentina.

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