TTC 2013
6th ESA International Workshop on Tracking, Telemetry
and Command Systems for Space Applications ESA-ESOC, 10 - 13 September 2013

MEDIA CALIBRATION SYSTEM FOR DEEP SPACE MISSIONS: PRELIMINARY DESIGN AND TECHNICAL ASPECTS

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I. INTRODUCTION

The assessment of Earth troposphere effects on radio frequency links plays a crucial role for deep space navigation as well as for scientific applications as the estimation of planet/satellite gravity fields and general relativity experiments. As a reference, ESA's BepiColombo mission to Mercury will build up on the experience gained with the successful NASA/ESA/ASI Cassini-Huygens mission and will include an advanced accurate Doppler and ranging system based on the use of radio links at X- and Ka-band. This radio frequency system architecture can guarantee an almost complete removal of all dispersive propagation effects accumulated along the radio frequency beam but leaves an uncalibrated contribution due to the Earth's tropospheric path delay. Therefore, dedicated troposphere calibration are needed to accurately measure the signal delay and delay-rate along the time-varying path to the satellite over observation periods which can last up to 40000 s. As a result, the media calibration system (MCS) must be characterized on one side by high sensitivity and accuracy to high frequency fluctuations of the water vapor, on the other side by a very high stability in the long term, usually expressed in terms of Allan Standard Deviation (ADEV) of the residual uncalibrated troposphere noise. The main component of an accurate media calibration system is a steerable and stable K-band microwave radiometer. Microwave radiometer measurements offer a precise estimation of the atmospheric water vapor content and wet path delay along the ground to spacecraft line-of-sight. By studying the instrumental stability it is possible to characterize the expected performance and its capability to calibrate deep space observables.
ESA supported a study focused on the state of the art of microwave radiometers (MWR) to examine their capability to satisfy the stringent radioscience experiment requirements for the future deep space missions.
We present the computation of the error budget to satisfy the stringent radioscience requirements and we also show all the components of a MCS and their possible final deployment configuration at the ESA Deep Space Antenna (DSA) in Cebreros (Spain). General deployment recommendations have been defined in order to correctly install the system at other sites avoiding possible tracking problems.
The work was funded by ESA-ESTEC Contract No. 23127/10/NL/LvH, v1.0, 15/12/11 and further details and study results can be found in [1].

II. ERROR BUDGET COMPUTATION

The deep space navigation and radio science requirements are defined in terms of a two-way tracking ADEV [2] at different observation times. ADEV has been developed for a statistical analysis of the stability of an atomic time oscillator, but It can be used to estimate the standard deviation of data with drifts. Further studies demonstrated that the theory can be applied to other time series, as in the statistical characterization of the stability of a Doppler link [3] and also in the context of other noise processes, such as instrumental radiometric noise [4] [5].

The formulation of the ASD used for this study is:

$$\sigma_x(\tau) = \left(\left\langle \frac{(x(t_k + 2\tau) - 2x(t_k + \tau) + x(t_k))^2}{2\tau^2} \right\rangle \right)^{1/2} \quad \text{[s/s]} \qquad (1)$$

Where: *x(t)* is a generic time series, divided in regular intervals to provide *n* samples at the Δt sampling time in the acquisition time *T*. The series is broken into *m* subgroups of samples where each subgroups have length $\tau = n\Delta t/m$. $t_{k+1} = t_k + \tau$ with $k = 0,1,2,3...$ where the starting point k_0 is arbitrary fixed.

Due to the finite number of data *n*, ADEV presents a limit. In particular as τ increases, the number of subgroups *m* decreases and the ADEV becomes less meaningful. If the considered time series can be modeled as the sum of a bias, a drift and a white Gaussian noise (WGN) of known standard deviation σ_n, Equation (1) can be reduced to:

$$\sigma_x(\tau) = \frac{\sqrt{3} \cdot \sigma_n}{\tau} \text{ [s/s]} \qquad (2)$$

This formulation [6] can be useful to define the deep space mission requirements in terms of TB as follows:

$$\sigma_n = \alpha_\nu \cdot \sigma_n^* \text{ [s/s]} \quad (3)$$

where α is the radiometric sensitivity of the channel ν while the σ_n^* is the radiometric resolution of the same channel expressed in K/s. For example, the radiometric sensitivity of the water vapor channel 23.8 GHz is in the order of $2 \cdot 10^{-11}$ s/K while the σ_n^* is in the order of 0.024 K considering 20s integration time.

Using the ADEV, the error budget of the MCS is computed for the two main components of the troposphere path delay: the wet and the hydrostatic delay. Assuming that the terms of the error budget are not correlated, in order to be conservative it has to be computed as the quadratic sum of the different contributions.

An important aspect of the error budget computation is the satisfactory level: the requirements are met if the error budget results are smaller than the provided values.

The uncertainty terms considered in the error budget calculation are:

- Instrumental Stability: since the instrument used for the estimation of the SWD is a MWR, the characterization of its internal stability represents one of the most important aspects of the MCS error budget. This term dominates the entire budget and it is difficult to predict without any information about the hardware.
- Beam Offset: a crucial aspect is represented by the effect on the retrieval of the different size and configuration of the MWR beam with respect to the DSA one, accentuated in presence of turbulence [7] [8]. A beam offset occurs when the MWR is not mounted on the axis of the DSA. Since generally the MWR is installed next to the DSA basement, this term have to be considered.
- Beam Mismatch: similar to the Beam Offset, another important aspect is represented by the different beam shape. In particular, this effect occurs since the MWR beam is a conic and senses a different volume of troposphere from the cylindrical volume sampled by the DSA [7] [8].
- Water Vapour Emission Model: another issue is represented by the water vapor emission model uncertainty. This contribution can be considered a bias-type error, and it might be difficult to evaluate correctly. Its effect varies according to atmospheric and ground conditions: in particular if there are dry or wet conditions after heavy rain showers. A preliminary value of the water vapor emission model contribution has been obtained by comparing GPS versus MWR measurements of the same atmosphere, as detailed in [5].
- Retrieval Algorithm: a very important aspect of the MCS stability is represented by the retrieval algorithm error model. In particular, it results that the use of different and sophisticated retrieval algorithms may induce a significant ADEV contribution. Preliminary values have been obtained from [9] [10].
- Hydrostatic Fluctuations: this terms represent a small contribution to the error budget. The limited values of this error are due to the stable nature of the hydrostatic component of the atmosphere.
- Hydrostatic Mapping Function: since the hydrostatic component represents the main part of the entire path delay, the definition of the correct mapping function is crucial. In particular, an error in this mapping function scales the path delay at higher magnitude than the wet one. Since an appropriate mapping function is used, (e.g Niell mapping function) [11], this term is not crucial for the error budget.

The computed error budget for the MCS is reported in Table 1 considering three observation times (20s, 1000s and 10000s) and compared with the MORE RSE requirements.

Table 1: Error Budget of the MCS

Error Budget Term	Observation time [s]		
	20	**1000**	**10000**
H/W Stability	2.217E-14	6.483E-16	7.106E-17
Feedhorn Spillover	1.118e-16	5.000e-17	5.000e-17
Pointing Uncertainty	6.182e-17	1.236e-18	1.236e-19
Beam Offset	4.267e-14	9.114e-16	9.106e-17
Beam Mismatch	9.231e-15	7.700e-17	7.700e-18
Emission Model	7.000E-16	3.000e-16	1.300e-16
Retrieval Algorithm	1.386e-14	8.000e-16	2.000e-16
Dry Fluctuations	4.472e-15	2.000e-16	2.000e-17
Dry Mapping Function	1.342e-16	2.600e-16	3.800e-16
Total	5.211E-14	1.294E-15	4.6103E-16
MORE Requirements	3.00E-14	3.00E-14	3.00E-14

III. ARCHITECTURE OF THE MEDIA CALIBRATION SYSTEM

This section presents the list of instruments and ancillary components to be considered for the MCS and to be installed in the vicinity of the DSA.

A. Microwave Radiometers

The main components of the MCS are represented by two MWRs, capable of estimating the path delay along the spacecraft-station line of sight (Slant Path Wet Delay – SWD) with the required accuracy.
Starting from a MWR developed for remote sensing purposes, further aspects have to be considered:

- installation of an antenna with Full Width Half Maximum (FWHM) greater than 1 deg and high side lobe suppression to achieve the requirements for atmospheric beam matching and avoid external contamination;
- use of an ultra-stable receiver in order to achieve the ADEV requirements for both short and long observation times;
- use of a receiver in K-band for the retrieval of the water vapor and Ka-band receiver for the retrieval of the liquid;
- installation of the MWR in a steerable system (azimuth and elevation) capable to track the probe.

A preliminary concept design is presented in Fig. 1 with an 80-cm dish antenna and a radiometer box both mounted on a steerable system with azimuth and elevation tracking capabilities.

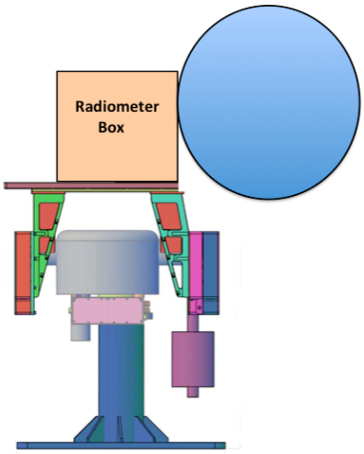

Fig. 1. Setup of the MWR for the MCS: concept design

B. Surface Meteorological Station

An important component of the entire MCS is represented by the surface weather station. It has to include different sensors to estimate the following parameters: surface temperature, surface relative humidity, surface pressure, wind direction and strength, height of the cloud base and rain rate.
Concerning the temperature, humidity, pressure and rain rate parameters, their measurements is necessary for the setup of the MWR retrieval algorithm in order to accurately estimate the Zenith Hydrostatic Delay (ZHD) by using the Saastamoinen model [12]. At present, all the ESA DSA tracking sites are equipped with a meteorological station used for standard troposphere path delay calibration [13].
As far as the wind sensor is concerned, its presence is useful to estimate the possible presence of turbulence and to evaluate its contribution in the MCS error budget. The height of the cloud base can be measured by a ceilometer or inferred by using an infrared radiometer (IRT). Because IRTs are rather low cost instruments it might be installed in different configurations: on the Tracking MWR, in a stand-alone system or in the radiometer profiler.
Finally, an important aspect of the meteorological station is its automation, where flexible instrumentation can transmit their data using Wi-Fi or dedicated connections to a remote control computer in the station control room.

C. Atmospheric Profiler

A dedicated instrument should be included in the MCS in order to satisfy some aspects of the requirements not sufficiently satisfied with the meteorological station. In particular, the missing aspects are the estimation of the air temperature and humidity vertical profiles to be used for the accurate retrieval of the path delay along the probe line-of-sight [14]. To satisfy this aspect, a microwave profiler should be included in the MCS. As an example, the possible instrument to be included is the RPG-HATPRO MWR (Humidity and Temperature Profiler) for the air temperature and water vapor profile, Fig. 2. This instrument is equipped with a selection of 7 channels in the water vapor line from 22 GHz to 27 GHz, a channel in the liquid water line at 31.4 GHz and a selection of 7 channels in the Oxygen line between 51 GHz to 58 GHz.
This instrument for the profiling assessment is capable of perform autonomously scan pattern of the atmosphere. It is important to point out that this solution does not limit the MWR's tracking activity. Instead, while the MWR will be synchronized to track in parallel with the DSA, the profiler can continuously perform boundary layer scans and provide information on high accurate atmospheric profiles.

Fig. 2. RPG-HATPRO MWR capable to estimate both air temperature and water vapor vertical profile.

D. Global Navigation Satellite System Receiver

An optional component of the MCS is a ground-based GNSS receiver. It can serve as a backup instrument for different applications: estimation of atmospheric turbulence, time reference, monitoring of Zenith Total Delay (ZTD). Provided that accurate observations of the ground pressure are acquired, the equivalent Zenith Wet Delay (ZWD) can be inferred as a reference in order to validate the performance of the MWRs.
A geodetic dual–frequency receiver is required in order to reduce and suppress error sources of the GNSS. The dual frequencies are for example needed to estimate and remove the dispersive effect on the propagation delay of the signal caused by the free electrons in the ionosphere. This kind of receivers are usually installed on concrete monuments in order to provide high position stability and equipped with a choke ring antenna, to suppress the multipath effects from the ground and nearby objects.
At present, DSA sites are already equipped with dual-frequency GNSS receivers for timing purposes and monitoring of the site stability. Fig. 3 shows the GNSS receiver installed at the Cebreros (S) DSA site. Similar receivers are installed in all the ESA DSA sites and they can be considered in the MCS.
Another important application of the GNSS receiver is its use to characterize the atmospheric behavior and even estimate the turbulence strength parameter C_n^2, [15].

Fig. 3. Cebreros (CEBR) GNSS receiver installed in its monument.

E. Data Acquisition And Processing System

Another important component is represented by the data acquisition and processing system. This system is crucial to collect data from all the instruments of the MCS and to process them in order to obtain accurate calibration. This system provides the connection of the MCS data directly to the spacecraft control center. Fig. 4 shows the layout of the entire MCS data acquisition and processing system: starting from the instruments to the ESA European Space Operation Centre (ESOC) monitor and control process.

Some MCS instruments, as the MWRs, are able to operate independently using its embedded computer. Once MWRs have been set up, they are capable to perform the tracking activity synchronized with the DSA. Then, thanks to an external connection, data are sent to an external computer which interfaces with all the other MCS instruments and processes all the data in order to provide the troposphere calibration.
The data acquisition and processing system software needs to control the activity of all the instruments. Concerning the MWRs the software has to manage automatic tipping curve procedure and to avoid tipping curve calibrations during tracking passages.
At the same time the SW has to manage the scanning activity of the profiler as well as to monitor the acquisition activity of the other instruments.

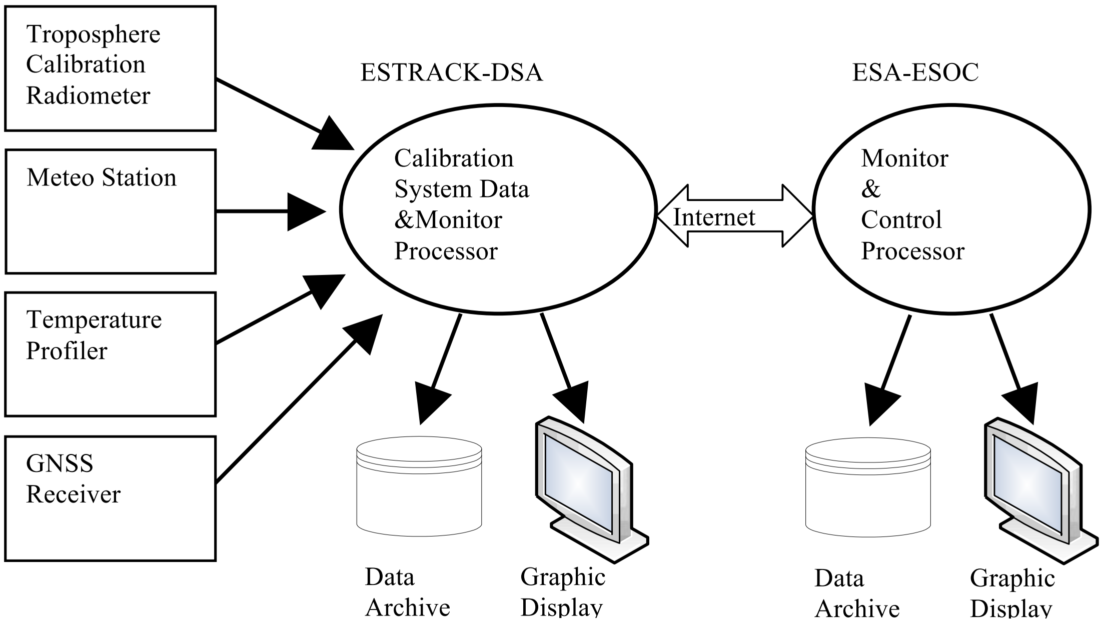

Fig. 4. Layout of the MCS data acquisition and processing system

IV. DEPLOYMENT ASPECT OF THE MEDIA CALIBRATION SYSTEM

Following the list of equipment described in the previous Section it is important to mention the deployment configuration of the entire system with respect to the DSA. A crucial aspect is that the instruments have to be installed in a correct position to avoid blockage of their field of view from the DSA dish or other instruments and installations in the complex.
The following proposed configuration considers the ESA DSA site at Cebreros (S) but the same considerations apply to other sites.
Among all the possible configurations, some aspects have to be fixed for a correct deployment of the MCS, in order to avoid blockage of the field of view of the MWRs due to the DSA dish and to mitigate the effects of the atmosphere fluctuations. Since the DSA tracks deep space S/C along ecliptic plane and the MWR has to be installed as close as possible to the DSA (to reduce atmospheric fluctuations noise), the MWR has to be installed in a free of obstacle position with respect to the antenna dish. In particular, the radiometer would be southward if the DSA site is in the northern hemisphere or northward if the DSA site is in the southern hemisphere.
Generally speaking, installing a MWR in the DSA subreflector would provide the most accurate estimation of the real path delay observed by the DSA [7], but following the results of the study this solution has been discarded due to complexity in the installation and maintenance.
In order to mitigate the effects of the atmospheric fluctuations, previous experience has shown that the deployment distance between the MWRs and the DSA basement should be limited up to 25 m [1].
The proposed configuration is the most accurate and reliable and considers two identical MWR instruments and the possibility to combine their measurements to mitigate external sources (e.g. Sun and atmosphere fluctuations). Moreover the configuration considers an atmospheric profiler, a meteorological station, a GNSS receiver and a data acquisition and processing system.
Fig. 5 shows a possible deployment of this TCS configuration in Cebreros, where the two MWRs have been installed southward of the DSA antenna dish at a distance of about 25 m from the center of the DSA basement.

The distance between the two MWRs has been fixed to 20 m. This distance is crucial to guarantee a redundancy without loss of tracking data in case of failure. In particular, the distance between the two MWRs could be reduced without limitations but if it would increase possible blockage of the field of view of the instruments at low elevation angles. In case of failure, this means that calibration data would not be available for the entire tracking time, and the reduced performance would be similar to the one obtained with the single MWR configuration.
In order to better characterize the atmosphere status, an additional radiometer profiler has been deployed between the two MWRs. The meteorological station is not shown, since that one already available at the site is used. Finally the IGS Cebreros GNSS receiver (CEBR) is also shown.

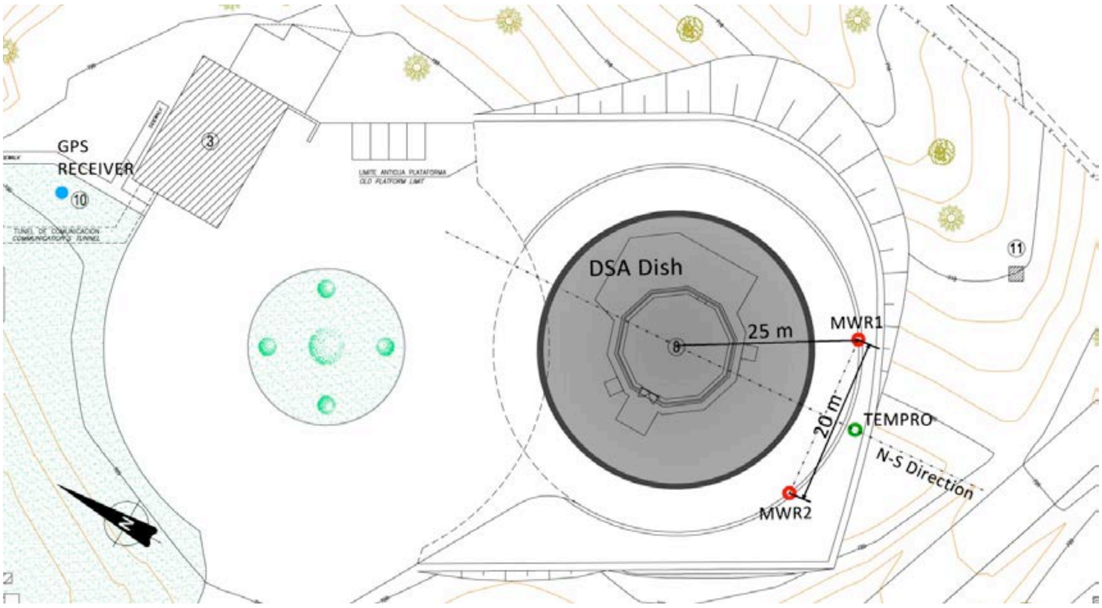

Fig. 5. Overview of a possible deployment of the TCS twin MWR configuration in Cebreros

V. CONCLUSIONS

In this paper we shows the main configuration of a MCS for the estimation of the troposphere path delay to calibrate deep space observables obtained combining meteorological data acquired by different instruments.
The proposed configuration has been based in the ESA/ESTRACK ground station site of Cebreros (S) and it is based on two MWRs capable to track the probe in parallel with the DSA.
An important aspect of the MCS is the computation of the error budget to satisfy the RSE requirements. In this work, all the components of the error budget has been presented.

VI. REFERENCES

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