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The Sardinia Radio Telescope Metrology System

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Abstract

After the successful finalisation of the performance upgrade, the Sardinia Radio Telescope will be ready to observe at high frequencies up to 116 GHz. To operate at the highest frequencies, improvement in pointing precision and main reflector surface accuracy (RMS, compared to the ideal profile) are required. In order to achieve these goals, the radio telescope has been equipped with a new sophisticated metrology system. This will make possible to optimise the pointing and antenna gain throughout the elevation range in which SRT scans the sky. The purpose of this paper is to provide an overview of all the components of the new metrology system, describing the main features that will make the Sardinia Radio Telescope a state-of-the-art facility.

1 Introduction

Although the Sardinia Radio Telescope has been efficiently observing up to 26.5 GHz, so far the maximum operational frequency, the finalization of the ongoing frequency enhancement will allow to extend its operations up to the highest frequencies which it was designed for [1]. In fact, thanks to a PON (National Operational Program) funding, assigned to INAF from the Italian Ministry of University and Research, new receivers will be installed allowing to receive astronomical radio signals up to 116 GHz, corresponding to a wavelength of 2.6 mm [2]. Large radio telescopes like SRT, a 64-metre fully steerable, need a metrology system, i.e. a set of sensors, instruments and techniques to analyse and describe how the antenna structure behaves when subjected to environmental load [3]. This will make possible to quantify and correct errors in the antenna pointing and reflectors shape, according to the efficiency requirements [4]. The aim of this paper is to describe the design of the new metrology system implemented for SRT (SMS) and its functional scheme. After this brief introduction, a description of the SMS architecture is provided in Section 2. Then, the control and correction of the antenna pointing is described in Section 3. Section 4 presents the metrology system module dedicated to the main reflector (M1) surface RMS monitoring. Finally, concluding remarks are drawn in Section 5.

2 Architecture of the New SRT Metrology System: SMS

Sensitivity to environmental loads depends on many antenna structural factors such as geometry and materials. Since it is impossible to create a non-deformable antenna, solutions must be adopted to compensate for the deformations which affect the antenna pointing and aperture efficiency. On this subject, the SRT is provided of active optics: M1 is composed of 1008 panels which can be moved by means of 1116 actuators, to maintain the M1 shape always close to the ideal one; also, the sub-reflector, M2, can be moved on the optimal position acting the 6 degrees of freedom (DOF) of the kinematic system, which is composed of 6 electro-mechanical actuators. To meet the current observational requirements, i.e. up to K-band frequencies, it has been necessary to ensure that the SRT pointing accuracy is about 5 arcsec and the M1 surface accuracy less than 0.7 mm. These goals have been achieved through the compensation of systematic errors (imperfect rail flatness, assembly imperfections) and gravitational load effects which are variable with the antenna rotations. Furthermore, a parametric astronomical pointing model has been used [5], providing offsets in elevation and azimuth in order to correct appropriately for systematic pointing errors. Also, sub-reflector position adjustments have been performing according to lookup tables (LUTs) data.
Concerning the M1 surface accuracy, the best fit has been achieved by carrying out close-range photogrammetry (CRP) survey campaigns [6] [7]. In order to minimise the primary mirror deflections over the whole elevation range of the antenna, i.e. 0°÷ 90°, the panels were aligned at the 45° elevation angle. In particular, the actuator elongations over the entire elevation range have been interpolated from the displacements measured with the photogrammetric surveys at fixed elevation angles. The acquired data were then stored in LUTs to be used during radio-astronomical observations. Holographic methods have also been implemented. In particular, two different techniques have been used to retrieve the surface deformations from the phase of a microwave signal collected by the antenna reflectors. The first is called Out-Of-Focus (OOF) holography [8]. This procedure is appropriate for characterising large-scale deformations distributed over a wide surface area. However, it is not suitable for identifying panel-to-panel misalignment. Instead, high spatial resolution can be reached by implementing the interferometric microwave holography [9][10]. Unlike the OOF, this approach involves the use of two antennas: the under test antenna (UTA, i.e. SRT) and

a reference antenna (RA), generally smaller than UTA. Up to now, the acquisition system used to study the M1 deflections consisted of two coherent channels, designed to receive a digital Ku-band television signal from geostationary satellites. Applying the resulting correction map to the active surface by means of the LUT, the main reflector surface accuracy RMS turned out to be better than 0.3 mm, enough to efficiently observe at the current SRT maximum frequency (26.5 GHz). However, the limited availability of geosynchronous sources due to the SRT latitude, constrained the elevation range investigated with microwave holography. In fact, this primary focus system allowed mapping only the main reflector surface deformations at the elevation angle of 44°, excluding the contribution of the sub-reflector.
Nevertheless, the new operational maximum frequency of SRT with makes performance requirements more restrictive. As a matter of fact, it must be ensured that the pointing error and the M1 surface accuracy RMS are respectetively still within one-tenth of the Half Power Beam Width (HPBW/10) and one-sixteenth of the smallest wavelength ($\lambda/16$) at W Band. Thus, it is no longer sufficient to only mitigate gravitational effects. Attention must also be paid to those stresses that until now could be neglected, like thermal loads and wind. For this reason, a new metrology system (SMS) for the Sardinia Radio Telescope was designed, also satisfying the interoperability with DISCOS (Development of the Italian Single-dish COntrol System) [11], which is the SRT control software. Its implementation is almost finalised and the advanced tools listed below have been installed to develop an open-loop scheme for the errors control and mitigation:

1. Sensors network;
   - Thermal sensors;
   - Inclinometers;
   - Accelerometers;
   - Anemometres;
2. Etalon Absolute Multiline Technology;
3. Absolute Tracker;
4. Reference Antenna (RA);
5. Data Management and Processing Units.

The system architecture shown in Fig. 1 includes an instrument module for pointing control and correction, and a second module dedicated to M1 deformation analysis. Each of the subsystems will be described in more detail in the following sections.

3 Pointing error correction

Not only gravity causes antenna structural deformation but also thermal load and wind action contribute to pointing error, even if to a smaller extent [12]. For this reason an integrated system of measurement has been implemented to analyse the problem from different points of view.
First, a deformation model (DM) has been designed to complement the corrections provided by the astronomical pointing model. Based on a neural network (NN), it estimates pointing offsets in elevation and azimuth acquiring input data provided by different types of sensors. In particular, the facility has been equipped with 287 thermal sensors distributed among alidade, cruddle and back up structure (BUS). Each thermistor, protected from sunlight with a plastic box, is screwed to a precise alidade girder location singled out after a Finite Element Analysis

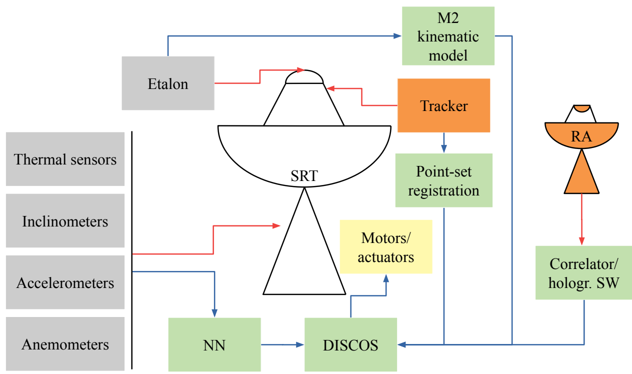

Figure 1. Architecture of the new Sardinia Radio Telescope's metrology system (SMS): In grey are shown the devices used to study pointing effects; in orange is shown the equipment installed to monitor the accuracy of the main reflector. Green are used to identify computer hardware and software dedicated to the management of data collected by the measuring devices. Yellow indicates mechanical drives. In addition, red arrows indicate the active monitoring of the structure, while blue is used to indicate the transmission of collected data to the dedicated management systems.

(FEA) of the SRT thermal behaviour.
Eight inclinometers have also been installed, divided into two categories: four biaxial inclinometers are placed in the alidade girders, close to the elevation axis, to detect the rotations in the ±1° range of the plane where the elevation axis is; four single axis inclinometers are placed in M1 and sub-reflector to measure rotations in the ± 90° range. The first group provide a direct indication of the distortions suffered by the alidade caused by environmental loads and systematic error components. The latter provide the absolute rotations of the reflectors.
Besides, nine accelerometers provide a measure of the dynamic behaviour of the radio telescope. To investigate the relationship between detected oscillatory phenomena and wind intensity and direction, two triaxial anemometers have been installed. The interfacing between the neural network and DISCOS ensures that inputs for antenna movement are transmitted to the mechanical systems.
In order to exploit the potential offered by DM from the beginning, the neural network was trained with a dataset consisting of hundreds of thousands of different load scenarios simulated through FEA [13] [14]. While, the possibility of storing the data continuously acquired by the sensors will allow the neural network to continue training with actual datasets. Since the system takes advantage of the GPUs computational power, offsets resulting from detected load conditions are provided in real time. It is worth to noting that the outputs provided by the NN will be compared with the FEA results before applying the correction offset to the pointing model.
Such a technologically advanced structural monitoring system requires an equally sophisticated management strategy. Modelling the behaviour of SRT using the FE method revealed that thermal effects provide a quasi-additional contribution to gravitational effects. This motivates the choice of using the DM in combination with the pointing model. Therefore, the DM calculation power will be exploited to estimate correction offsets related to time-varying load stresses. On the other hand, the pointing model will be used to correct gravitational influences and systematic errors. This is possible because the observations to calibrate the pointing model are carried out during nighttime,

when the antenna structure is in thermal equilibrium, and in absence of gusts: hence, the analytical formulation does not consider thermal and wind effects on the antenna structure.
In the gregorian focus observations, the position of the sub-reflector also influences the antenna pointing. It should be noted that M2 misalignment is due to the deformations of both its structure and the quadrupod. Since displacements are linked to both antenna elevation angle and load variability, a sensor to measure in real time the sub-reflector offsets with respect to the ideal position was needed. The solution identified is a multilateration system by Etalon Absolute Multiline Technology [1]. In fact, through multiple ranging measurements, which are based on estimating the time-of-flight of the transmitter-reflector path, it is possible to characterise the DOF of M2.
A measurement uncertainty of 0.5 μm per metre for distances between 0.02 m and 30 m and less than 4 arcsec in rotations in normal condition make this instrument suitable for monitoring the position of M2 from the M1 vertex, about 20 m away. Two modules were set up: one for measuring the sub-reflector offsets w.r.t. a reference position and one for evaluating quadrupod deformations. The M2 reference position will set at the elevation angle where SRT has got the best pointing performance. As the elevation angle changes, the sub-reflector moves from the reference position and the offsets are measured by Etalon. In order to facilitate interfacing between collimators and reflectors, LUTs are used to bring the sub-reflector closer to the ideal position.
It should be noted that all the active electronic sensors of the metrology system here described can be remotely controlled. Thus, they can be switched off in case of radio frequency interference (RFI) evidence during low frequency observations.

4 Main reflector surface accuracy monitoring

Environmental loads acting on the back up structure could produce shape variation of M1 [15] [16]. In principle, sensitivity to this kind of loads depends on consistency with the theory of homology that the designer was inspired by [4]. Since reflector deformations could reduce the aperture efficiency, a maximum surface RMS value is defined to ensure no excessive antenna gain loss. It is clear that at high frequencies a more accurate control of M1 deformations is essential.
Generally, photogrammetric surveys are carried out under thermal equilibrium conditions and in the absence of wind gusts. In this way, the effects of time-varying loads are intentionally small and negligible compared to those caused by gravitational action. In fact, dynamic characterisation of effects is required for thermal loads and wind. For this reason, it became necessary to implement other investigation methods.
One of the identified solution is the mapping of the M1 deformations using an absolute tracker [17][18]. The Leica Absolute Tracker ATS600[2] has been placed on one leg of the quadrupod. This position minimises shadow cones throughout the whole elevation range of the antenna. The instrument allows the measurement of a target up to 80 m away, guaranteeing an accuracy of ± 100 μm in length measurement and absolute angular performance of ± 15 μm + 6 μm/m. It also combines the reflector's measurement capability with direct scanning of target surfaces. With this feature it is feasible to locate a point with an accuracy of 300 μm within a maximum distance of 60 m.
In this way it is possible to characterise the M1 deflections remaining after the first alignment of the panels by means of LUTs, due for instance to the diffuse thermal loads on reflector elements and the supporting BUS.
The upgrade also involved the holographic system. A gregorian cryogenic k-band microwave holography system will be soon commissioned to improve the overall surface accuracy RMS up to $\lambda/16$ or better at the SRT maximum operational frequency. In addition, it will provide the deformations map of the antenna aperture field at elevation angles where the geosynchronous satellite signal is not available at the SRT latitude, by alternatively receiving the signal of high flux cosmic radio sources.
Two k-band cryogenic receivers will implement an interferometer able to operate in the frequency range 21-22.5 GHz. The first one, installed on the SRT Gregorian focus, is the k-band 7-feed focal plane array[19][20], of which only the central feed will be used for holographic purposes. The second one, installed on the focus of a 5.3 m-diameter displaced axis dual-reflector antenna, is located about 300 m away from SRT in the south direction. It is worth to point out that mapping the SRT aperture field by holography technique from the gregorian focus, i.e. the focal position from which the high frequency receivers will operate, allows to measure the contribution to the antenna surfaces deformation due also to M2. In this way, one can not distinguish the M1 and M2 contributions to the overall surface accuracy, but they can be all together corrected converting the gregorian holographic deformation map into a new M1 LUT to be applied to the active surface.
The super-heterodyne radio frequency chain of the 5.3 m-diameter antenna, the reference receiver of the interferometer for measuring the phase of the signal incoming, was designed to meet the requirements of robustness, to avoid the receiver saturation (in case of a geosynchronous satellite signal receiving), and high sensitivity (in case of a cosmic source signal receiving). The two receiving chains of the holographic interferometer make available at the input of a digital cross-correlator backend two coherent radio signals having a 200 MHz frequency bandwidth centred at 200 MHz. Then, a dedicated FPGA firmware performs a real-time frequency domain cross-correlation of the two 200 MHz-signals. This digital processing will be also able to adjust the residual time delay between the two incoming signals, in order to maximize the interference fringe, and to change the cross-correlation spectral resolution up to 100 KHz, useful for the cross-correlation of satellite beacon or, alternatively, a cosmic water maser signals.
In theory [21], the overall features of the new holography system would allow reaching an accuracy in the measurement of the surface deformations of about 0.05 mm or better, calculated on a pixel of about one square meter on the main reflector surface, by receiving the signal from a geosynchronous satellite and assuming good environmental conditions for a 22 GHz holographic experiment.

5 Conclusions

So far, SRT has been observing down to wavelengths of about 11 mm for which it is sufficient to correct for the gravitational and systematic effects. But, after the performance upgrade, the facility will be able to extend the observing range to wavelengths of around 2.6 mm. For this reason, a tighter control of both

[1](*https://www.etalonproducts.com/en/products/absolute-multiline-technology/*

[2]*https://hexagon.com/it/products/leica-absolute-tracker-ats600*

pointing and M1 profile accuracy is essential.

This paper offers an overview of the instruments and techniques adopted in order to improve the Sardinia Radio Telescope metrology system to be suitable for high-frequency observations. Thus, the architectural scheme of the project has been presented in Section 2. Besides, a detailed description of the pointing correction module has been given in Section 3, while Section 4 has been focused to the module for the M1 surface accuracy control.

A planned stepwise process will lead to the complete functionality of SMS. To give an example regarding MD, at first, only thermal sensors measurements will be used as input for the NN to mitigate thermal effects. Next, by including the inclinometers detections in the NN inputs, MD will also be able to correct for errors caused by systematic factors and gravitational load, replacing the astronomical pointing model. Then, in the last step, the data provided by the anemometers will also be processed by the NN, to take into account the action of the wind.

A few concluding remarks arise from the above. Achieving functional goals is by no means a foregone conclusion and error control systems are needed to compensate for the effects depending on many sources. Moreover, there is no single approach or technique to meet all requirements. Rather, all components of the metrology system must be used in a complementary way. In addition, an effective metrology system requires multidisciplinary features. Finally, it is important to constantly update in search of better solutions in line with technological advances.

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