The DAG Project, a 4m class telescope: the telescope main structure performance

G. Marchiori*[a], A. Busatta[a], L. Ghedin[a], E. Marcuzzi[a], C. Manfrin[a], C. Battistel[a], O. Pirnay[b], Carlo Flebus[b], C. Yeşiliaprak[c], O. Keskin[d], S. Yerli[e]

[a]European Industrial Engineering s.r.l., via Torino 151A, Venezia, Italy 30172; [b]AMOS, rue des Chasseurs Ardennais, 2, Liege, Belgium 4031; [c]Atatürk University, Erzurum, Turkey, 25030; [d]Işik University, University Street 2 Istanbul, Turkey 34980; [e]Middle East Technical University, Universiteler Mahallesi, Dumlupinar Bulvari 1, Ankara, Turkey 06800.

ABSTRACT

Dogu Anatolu Gözlemevi (DAG-Eastern Anatolia Observatory) Project is a 4m class optical, near-infrared Telescope and suitable enclosure which will be located at an altitude of ~3.170m in Erzurum, Turkey.

The DAG telescope is a project fully funded by Turkish Ministry of Development and the Atatürk University of Astrophysics Research Telescope - ATASAM.

The Project is being developed by the Belgian company AMOS (project leader), which is also the optics supplier and EIE GROUP, the Telescope Main Structure supplier and responsible for the final site integration.

The design of the Telescope Main Structure fits in the EIE TBO Program which aims at developing a Dome/Telescope systemic optimization process for both performances and competitive costs based on previous project commitments like NTT, VLT, VST and ASTRI.

The optical Configuration of the DAG Telescope is a Ritchey-Chretien with two Nasmyth foci and a 4m primary thin mirror controlled in shape and position by an Active Optic System.

The main characteristics of the Telescope Main Structure are an Altitude-Azimuth light and rigid structure system with Direct Drive Systems for both axis, AZ Hydrostatic Bearing System and Altitude standard bearing system; both axes are equipped with Tape Encoder System.

An innovative Control System characterizes the telescope performance.

Keywords: 4m class Telescope, Direct Drive System, Hydrostatic Bearing System, Control System, Tape Encoder.

1. INTRODUCTION

The DAG Project Telescope performance have been studied during design by means of:

- Finite Element Analysis,
- Servo Analysis and
- Pointing/Tracking error budget.

The workflow presented here, is a standard process during a telescope design phase as it permits to understand the structural behavior (and thus, telescope stiffness), the dynamic performance of the telescope controlled by the motion control systems (accuracy of the servo) and the overall accuracy of the telescope mount when it is observing the sky.

The Finite Element Analyses results will be presented along with a brief model description showing all the configurations analyzed.

Before outlining the analysis and results obtained by a servo system simulation, a brief description of the components involved in the control of the main axes is given; in particular, drive motors, encoders and hardware (industrial PC and drive inverters).

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Finally, the list of factors involved in the sky pointing and tracking will be listed giving the global view of the performance of the telescope.

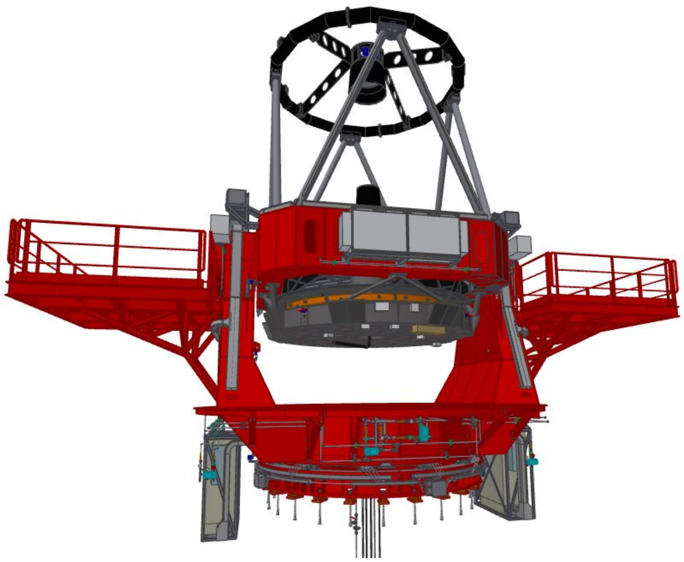

Figure 1. DAG telescope

2. STRUCTURE PERFORMANCE

2.1 Telescope Finite Element Model

The telescope global model and its components are described in this section.

Most of the telescope structure is composed by box girders and they have been represented by using shell elements. Top Ring, Serrurier and platforms have been represented by using beam elements.

The Telescope Main Structure is divided into two separated structures: the Azimuth Structure and the Altitude Structure.

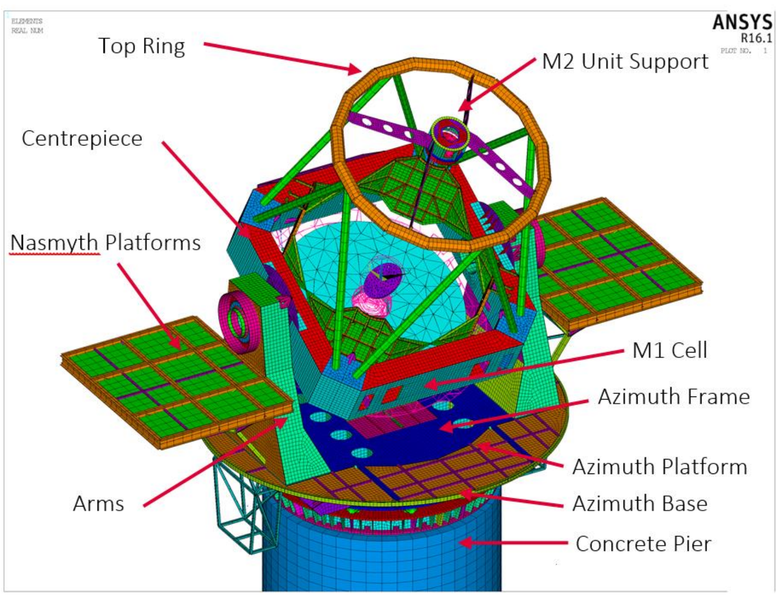

Figure 2. DAG telescope FEM

The dynamic behavior of the telescope has been investigated by performing the modal analysis of the structure, also in this case throughout the entire functional motion range of the telescope (from 0 deg to 90 deg altitude positions): four different zenith angle positions (namely: 0°, 30°, 75° and 90°) have been considered in performing the analyses.

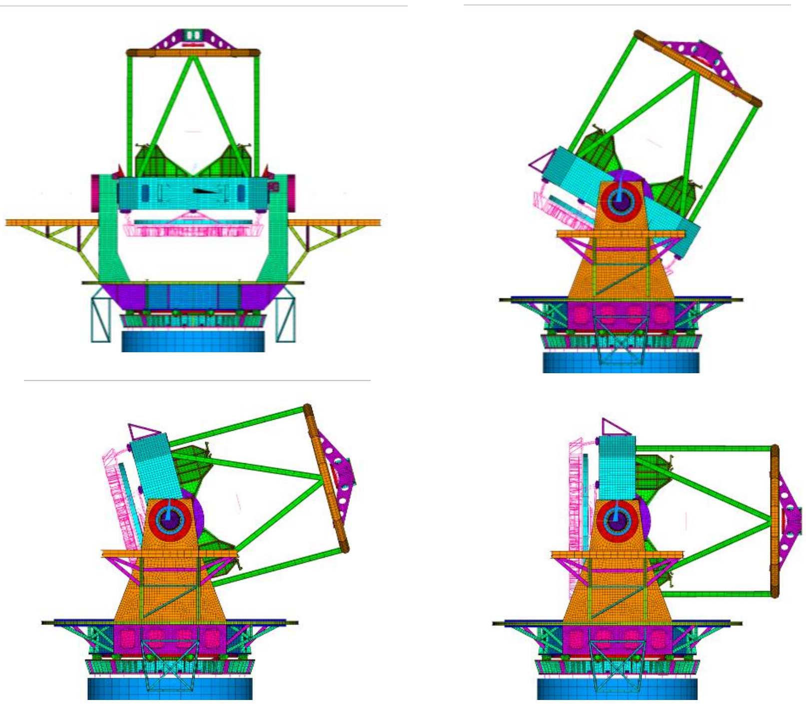

Figure 3. DAG telescope FEM positions

2.2 Finite Element Analysis: modal behavior results

The locked rotor analyses in all altitude configurations highlight a first eigenfrequency always above 8Hz as required by specifications.

Here, are presented the results for all the altitude angle configurations:

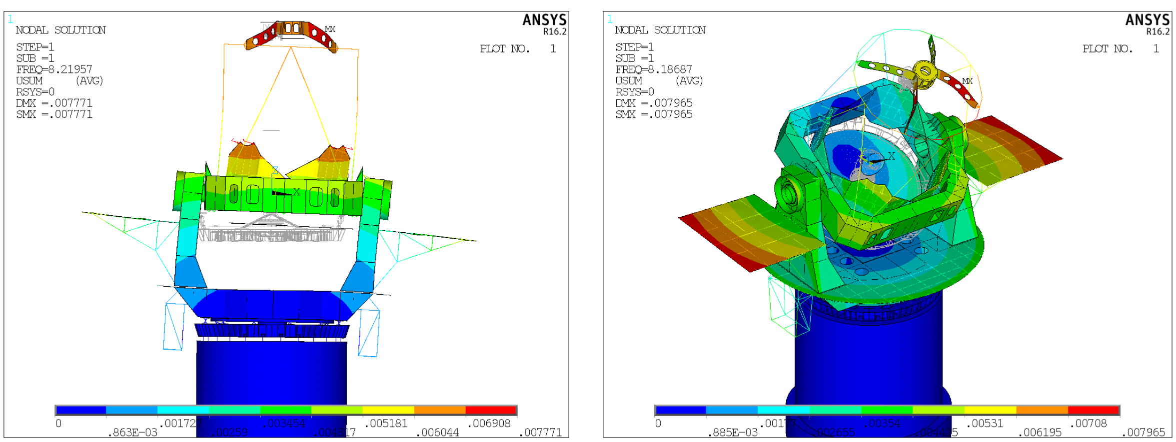

Figure 4. DAG telescope FEA results for 0° and 30° zenith altitude angle

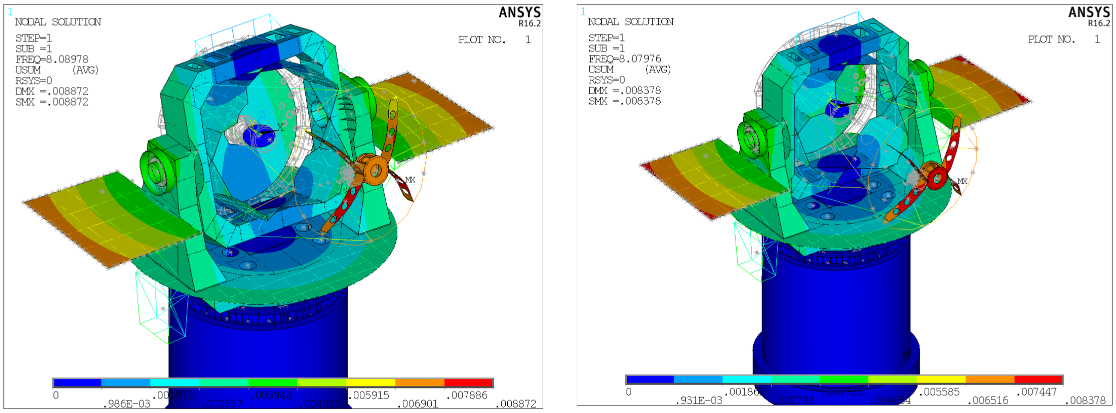

Figure 5. DAG telescope FEA results for 75° and 90° zenith altitude angle

3. CONTROL SYSTEM PERFORMANCE

3.1 Drive motors

It is foreseen to install one direct drive torque motor on azimuth axis placed in the central bearing shaft of the Azimuth base. To avoid unwanted torsional response of the altitude structure a motor is installed on both arms shafts. So, the motors are two in order to have the best response of the tube. This type of motors are very efficient in terms of motion smoothness as friction is not present to transmit the torque.

Figure 6. DAG telescope drive motors

The motor is equipped with a stator with windings and a rotor provided with permanent magnets. In particular, for the Azimuth axis, the stator is installed in the Azimuth frame, which rotates and the rotor is installed in the Azimuth base structure. For Altitude axis, the stator is installed in the Arm, which is fixed and the rotor which is installed in the Altitude shafts. In this way, the cables necessary for power supply and signal are passing through Azimuth cable drapes but not Altitude cable wraps.

The drive internal position feedback is given by the same encoder responsible for the axis position control. The torque and speed are congruent with a slewing speed of 2deg/s and accelerations up to 1deg/s2.

Motor phasing is granted by hall sensors installed on motors. This allows the drive to move the motor safely during encoder initialization (small movement performed at the beginning of motor motion which permits to estimate absolute position from encoder).

The present motor is equipped with water cooling jacket having a water glycol mixture (water/mono-ethylene glycol mixture with respectively 55/45%). Some probes measure the superficial temperature value and operate on a three way mixing valve so to maintain temperatures within the tolerance limits.

3.2 Encoders

The main axes position will be retrieved by angle encoders with graduation on steel scale tape (by Heidenhain) and 8 scanning heads to compensate possible misalignment due to mounting errors and enhance the axes absolute position accuracy below 2arcsec for 360° excursion and 0.1arcsec for small offsets of 10arcmin. The gap between tape and head needs to correspond to 0.75±0.1mm.

The graduated scale read by the scanning heads is a metallic tape fixed in a dedicated groove present in central bearing shaft. The sampling rate of the graduation is 73000 subdivisions of the full circle for Azimuth and 53000 subdivisions for Altitude. The Azimuth encoder is accessible in a dedicated pit in center of the Azimuth frame and it is mounted in the central shaft of the Azimuth base structure; reading heads are located on the Azimuth frame and will rotate according to it. The Altitude encoder, is accessible on the top of the right Arm. The tape is mounted in the altitude axis shaft so it will rotate according to it; reading heads are located on the Arm.

It is essential to mention that this type of encoder is incremental with absolute reference marks; this leads to have an initialization procedure before starting to move the axis. The initialization consists in reading at least 2 reference marks to get the absolute position; so it will entail a brief axis motion dedicated to this scope. In the case that, during the initialization the range limits are engaged, the axis stops and the initialization process start over again towards opposite direction.

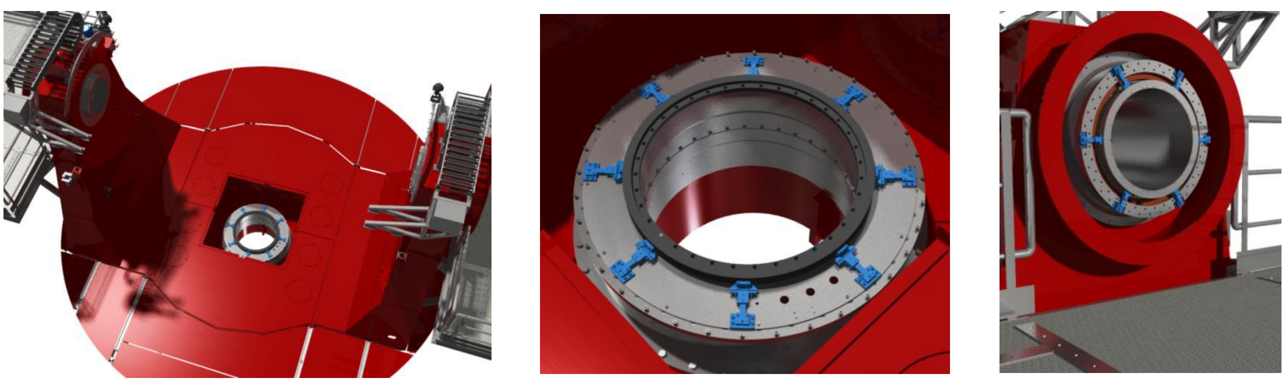

Figure 7. DAG telescope encoders (left & central: azimuth, right: altitude)

The scanning heads on supports are adjustable in 5 degree of freedom to achieve the best configuration during the motion of the Azimuth bearing. The supports stiffness have been analyzed through modal response of their Finite Element Model in order to have the adequate stability for such precise measurement, as shown in Figure 8.

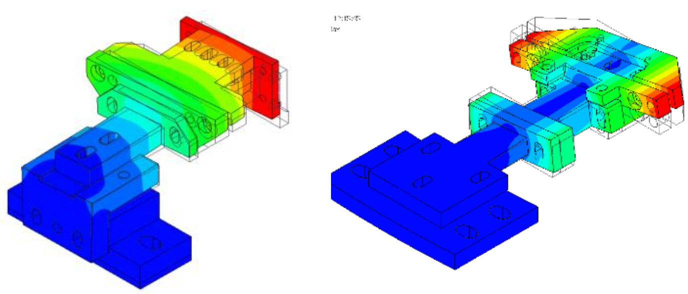

Figure 8. DAG telescope example of encoder supports modal behaviour

3.3 Telescope Control System Architecture and Hardware

The Telescope Control System (TCS) is organized in three main units:

- the Telescopes Supervisor (TSV) that provides the commands interface between the Observatory Control System (OCS) and the telescope system including all the subsystems, practically translating “macro” commands received from the OCS in “micro” commands for the subsystems. It also coordinates the activities of the subsystems.
- the Mount Control System (MCS) which has direct access to the low level functionalities of the hardware controllers and drivers and implements the control loops of the telescope motion, so is the responsible of the telescope dynamic performances
- the Telescope Auxiliary and Monitoring System (TAMS), which has to control the Hydrostatic Bearing System, the M1 cover, communicates in real time with the Telescope Safety System by the EtherCAT fieldbus, acquires the measurements of the temperature sensors and commands the motorized valves.

The MCS and TAMS, which have to execute all the hard real time functionalities, are equipped with Beckhoff hardware. The chosen automation hardware makes it possible to employ different state-of-the-art technologies.

In particular, the following technologies will be used:

- TWINCAT (The Windows Control and Automation Technology), that is a software system developed by Beckhoff that turns almost any PC-based system into a real-time control system
- EtherCAT (Ethernet for Control Automation Technology) fieldbus, which is a protocol standardized in IEC 61158, suitable for both hard and soft real-time requirements in automation technology. The key functional principle of EtherCAT is the processing modality of the Ethernet frames: each node reads the data addressed to it and writes its data back to the frame all while the frame is moving downstream. This leads to improved bandwidth utilization (one frame per cycle is often sufficient for communication) while also eliminating the need for switches or hubs.
- EtherCAT Automation Protocol (EAP), which defines interfaces and services for the exchange of information between controllers (master/master communication) or for interfacing with a central master computer. The EAP communication can be handled directly in the user data of an Ethernet telegram, without the need for an additional transport or backup protocol. An important feature is that the EtherCAT Automation Protocol uses a standard Ethernet infrastructure and can therefore be transferred via any Ethernet medium, including wireless communication.

  The cyclic data exchange can be based on the “pushed” or “polled” principle. In particular, in “pushed” mode, the devices are divided in “publisher” and “subscriber”: each publisher device sends its data cyclically or in a multiple of its own cycle. The subscriber can be configured to receive specific data from the senders. The sender and the data are configured via an object directory and process data mapping from inside of TwinCAT.
- OPC-UA (OPC Unified Architecture), which is a communication protocol developed by the OPC Foundation. Its scope is to provide a technology agnostic Machine to Machine (M2M) communication. The protocol is suitable for real time and low latency systems, because it defines a binary protocol that doesn’t need the overhead of parser, HTTP headers or XML protocols.

  Also OPC UA provides the “Subscription” functionality: an OPC-UA Client can subscribe to a selection of variables of interest that the server makes available. Only in case of changes, e.g. to their values, the server notifies the client about such changes. The sampling interval can be individually defined for each monitored variable in the subscription.

  Since OPC-UA is technology agnostic, server and clients can be implemented using any programming language.

The complete network architecture including the TSV and the Observatory Control System can be compared to a classic communication network in automation technology, as shown in Figure 9.

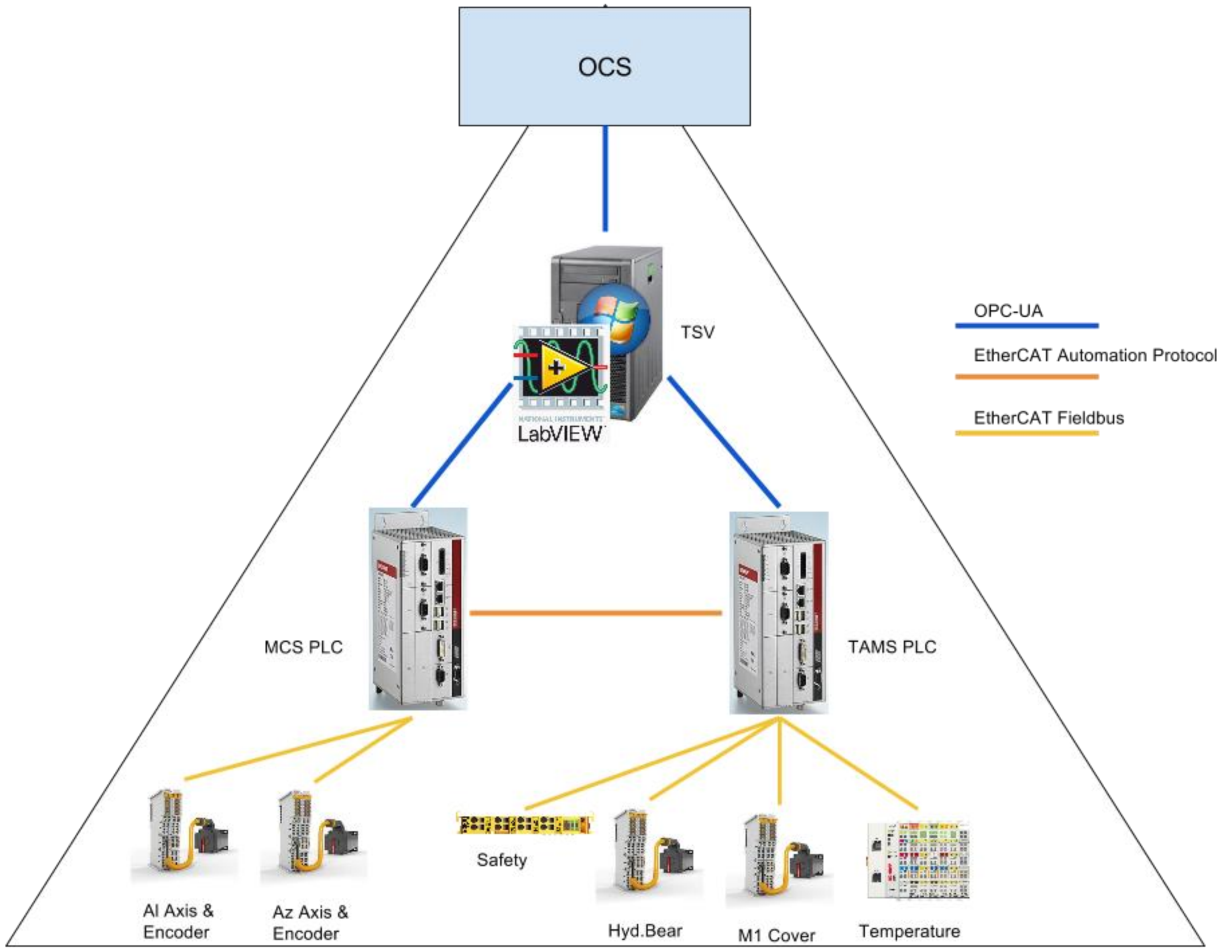

Figure 9. TCS network configuration

The OPC-UA is responsible of the highest communication level between the TSV, the OCS and the subsystems.

At the lowest level, the EtherCAT fieldbus guarantees the hard real time performances and precise synchronization.

In between, the factory network implemented using EtherCAT Automation Protocol can guarantee connection to configuration/diagnosis system, wireless connection, master-master communication

Following the configuration suggested by Beckhoff to optimize the network bandwidth usage, each Industrial PC will be modeled as an independent OPC-UA server.

3.4 Main axes servo-analyses

The telescope dynamic performances have been studied developing a model to simulate the behavior of the structure [2]. In particular, the modal analysis estimated from the FEM model in the free rotor configuration contains the information about the flexible modes. In this case, the modal analysis has extracted 120 eigenmodes up to 55.211 Hz eigenfrequency, then the model order has been reduced considering 40 modes to estimate the State Space Matrix [3].

The so obtained State Space Model of the structure is based on 40 flexible modes, of which two are the rigid modes (Altitude and Azimuth rotation).

As an example, in Figure 10, two input-output transfer functions are shown, where it is possible to evaluate the behavior of the reduced model (big red dots) respect to the original complete model (black line): it is quite evident that the reduced model contains most of the information needed to assess the behavior of the structure. Of course this evaluation has to be done considering all the significant input-output relations.

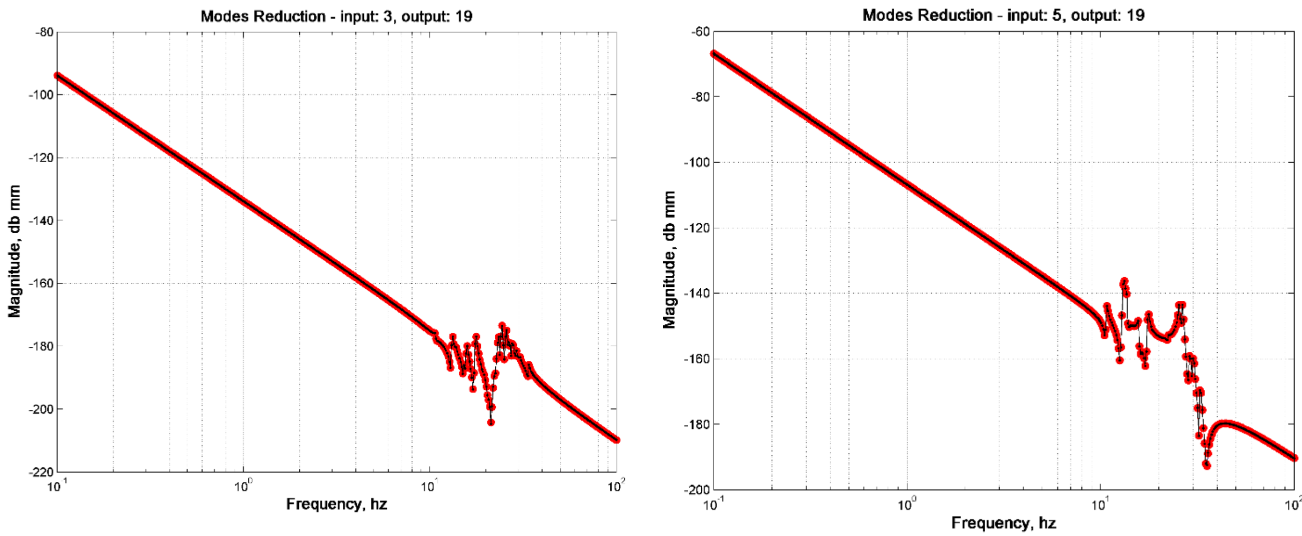

Figure 10. Model reduction: Bode diagram of two transfer functions

The dynamic model has included the wind load, described by the Von Karman spectrum as requested in the specifications, and the following internal disturbances [4][5]:

- motor torque ripple and cogging,
- the viscous friction caused by the hydrostatic bearing system,
- the static friction caused by the rolling elements of the AZ central bearing,
- the dynamic friction caused by the rolling elements of the AZ central bearing,
- the static friction caused by the rolling elements of the AL bearings,
- the dynamic friction caused by the rolling elements of the AL central bearing

The model has been discretized considering the encoder systems resolutions, the servo loop sampling and loop latencies.

The controller design has initially been performed in the continuous time domain. The velocity controllers have been developed before of the position controllers for both axes with the main objective to guarantee the robustness and performances. Then the position controllers have been developed considering mainly the robustness, the closed loop transfer function bandwidth to avoid the excitation of the structural modes, and the tracking requirements.

A particular effort has been dedicated to tune the Altitude axis control loops to reach the desired performances in wind disturbances condition.

After the iterative process of tuning the control loops, several simulations have been done to evaluate the complete behavior of the telescope with different tracking velocities. In Figure 11 is shown a tracking trajectory of the AZ axis in wind condition moving at 100 arcsec/s and Figure 12 shows a tracking trajectory of the AL axis in wind condition moving at 5 arcsec/s.

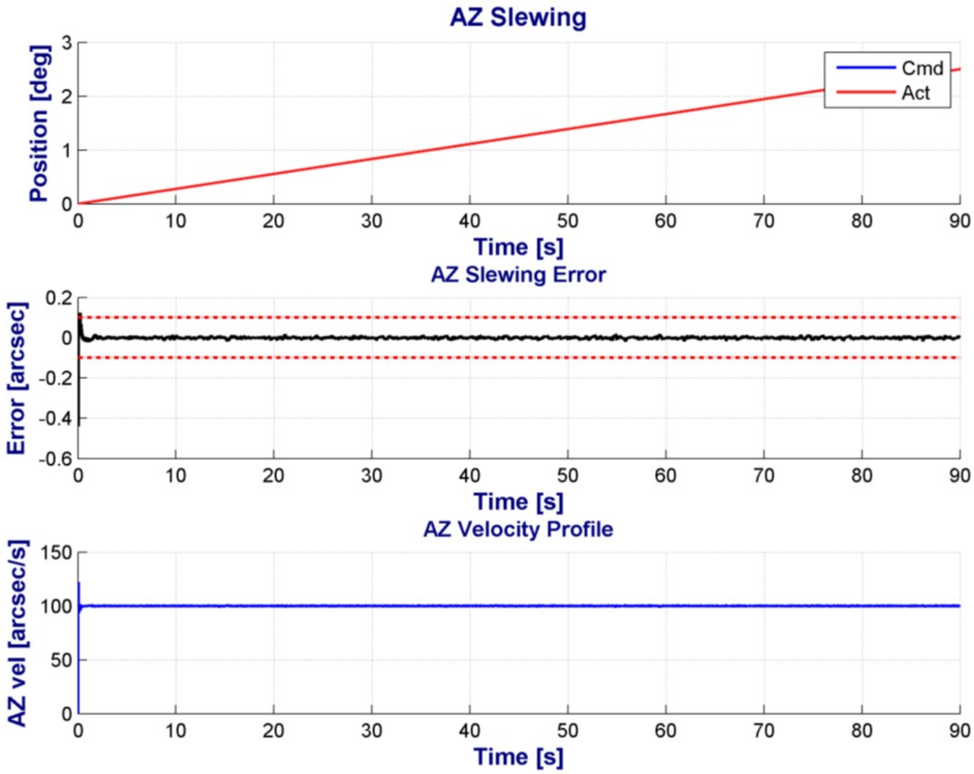

Figure 11. Azimuth tracking with wind at 100 arcsec/s

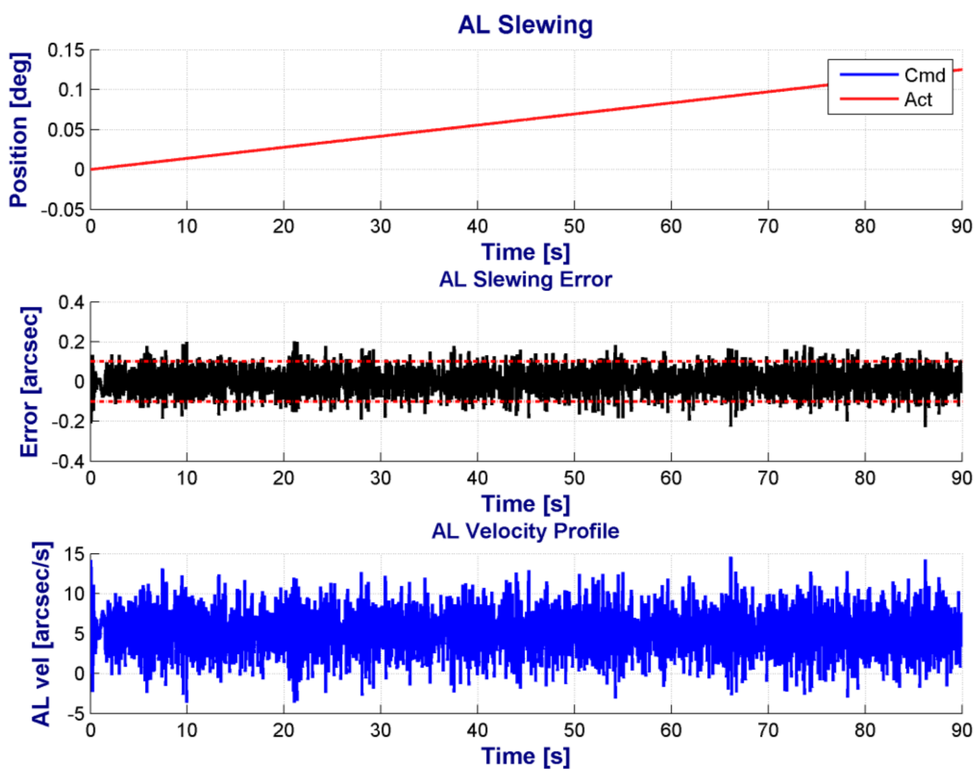

Figure 12. Altitude tracking with wind at 5 arcsec/s

The data obtained from the simulations have been analyzed in the frequency domain to carefully evaluate the behavior of the structure and understand the impacts of each vibration mode on the performances. In Figure 13 is shown the original signal and the FFT of one point of the structure.

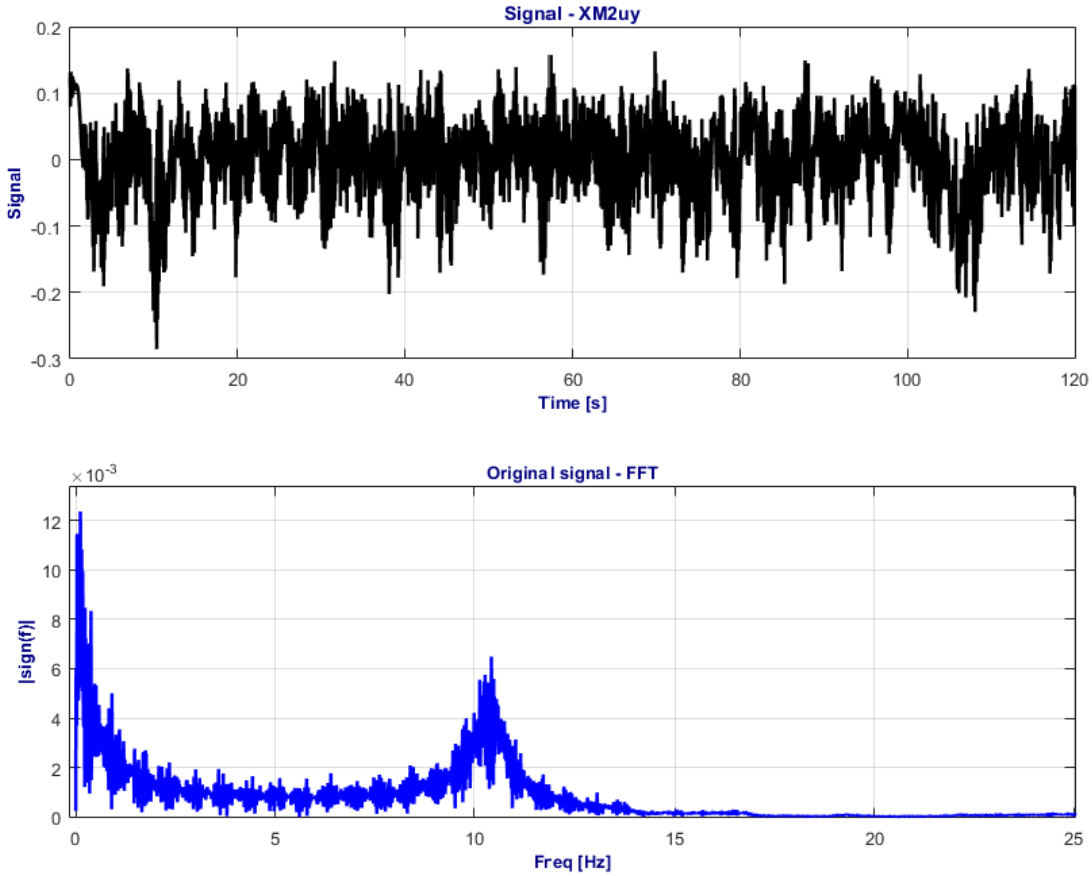

Figure 13. Original signal in the first plot and its FFT in the second plot

4. TELESCOPE MOUNT PERFORMANCE

The error budget assessment for telescope pointing and tracking involves many factors which can be listed here below:

- Foundation subsidence
- Gravity
- Temperature effects
- Wind effects
- Assembly tolerances and Hysteresis
- Servo-control accuracy
- Encoder accuracy
- Optics accuracy
- Autoguide accuracy

The analysis of each of these factors has been done in order to be able to address the overall telescope performance in pointing and tracking:

- Absolute pointing accuracy (blind pointing error): < 2arcsec for any point in the sky with Zenith angle < 70°.
- Offset pointing accuracy: < 0.1arcsec for a 10arcmin offset in any direction.
- Closed loop tracking accuracy: < 0.1arcsec rms for one hour.

5. CONCLUSION

The DAG telescope performance have been analyzed deeply in order to comply with the specifications. In particular, the dynamic behavior of the structure has been successfully analyzed via FEM and servo-analysis to guarantee the correct telescope response during pointing and tracking on the sky.

A great effort has been put especially to achieve the 100marcsec of accuracy during one hour observation with the help of autoguide. It is worth saying that, autoguide contribution is essential to satisfy the specification request as in open loop, the accuracy with only 1 minute observation is slightly above 100marcsec.

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