Surveying control of the structure of a telescope for observing cosmic very-high-energy gamma rays

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Abstract. It has always been an engineering challenge to analyze the behavior of new, unique structures. Examples of the structures that must maintain strict operating parameters at all times, regardless of the conditions, include the prototypes of astronomical telescopes intended to work in observatory arrays. A structure analyzed in this publication is a single-mirror small-size (SST-1M) Davies-Cotton telescope with a dish diameter of 4 meters, built for the southern observatory of the Cherenkov Telescope Array – CTA [1],[2].
This paper presents the results and analysis of the measurements of its structure. The subject of the analysis are the measurement method and error models for both the foundations and the steel structure. The results show that the prototype design satisfies the CTA assumptions and can be included in the observations. Structure deflection, its deformation, stability of its foundation and damping of dynamic vibration allow for the astronomical observations, independent of the angle of elevation and azimuth of observations, even during adverse weather conditions.

Keywords. Deformation monitoring, radar interferometry, CTA

1 Introduction

The small-size telescopes (SSTs) are intended to receive the highest energy band of all the telescopes planned for the Cherenkov Telescope Array (CTA), which means that they work in the energy range from single TeV up to 300 TeV. The studied structure, based on the Davies-Cotton design, was proposed by the Polish-Swiss consortium. The presented SST-M has a focal length of 5.6 meters and the diameter of the canopy is planned to reach 4 meters. The theoretical area of data collection is 9.42 m²[1]. The 18-ton prototype structure has been located on the premises of the Institute of Nuclear Physics in Krakow, in order to test its drive, repeatability of work and for structural tests.

The direct field of research of the team of industrial surveyors from AGH University of Science and Technology was surveying control of the structure of the prototype telescope for static deflection, stability and dynamic characteristics.

The works were implemented by being divided into four research tasks:

- Measurement of the deformation of the telescope mast structure according to the angle of elevation in the range of -13° to +95° (four positions) for the angle of 0° in azimuth,
- Measurement of the deformation of the telescope structure, depending on the azimuthal angle in the range of -270° to +270° (six positions) for the angle 0° in elevation,
- Checking the telescope setting repeatability,
- Checking the frequency of the telescope natural vibration using interferometric radar.

In order to properly fulfill the research objectives, the following measurement and calculation technologies were adopted, which were carried out in several stages:

- Development of observation network for the performance of angular and linear observations.
- Carrying out observations using precision electronic total stations. Geodetic control points and the points representing the telescope structure were subject to the measurements.
- Adjustment of the observations using the method of least squares.
- Determination of the coordinates representing the test object.
- Determination of potential deflections using spatial transformations.

The repeatability of the telescope settings was checked based on these calculations, by comparing the coordinates for the corresponding settings in pairs. Control of the telescope foundation, the study of its subsidence, was performed by determining height of the points representing the foundation in

four settings of the telescope. Precision leveling technique was used for the measurements.
The analysis of the dynamic behavior of structure was performed subject to the measurements carried out based on ground radar interferometry. The recorded time series were analyzed to give a free vibration amplitude spectrum of the structure.

2 Adjustment of the observations

2.1 Monitored and controlled elements

For the purpose of determining deformations of the telescope structure, 20 points were selected on its surface, which were marked with reflective tape enabling precise measurement in all positions determined in the measurement plan. The points were arranged symmetrically on both sides of the structure. The points 1-4 and 21-24 were located in the least deformable part; at a later stage they will be used for analyzing the behavior of the rest of the structure, whose behavior is illustrated by the points 5-10 and 25-30. The arrangement of all the points is presented on the diagram of the controlled points distribution (Fig. 1).

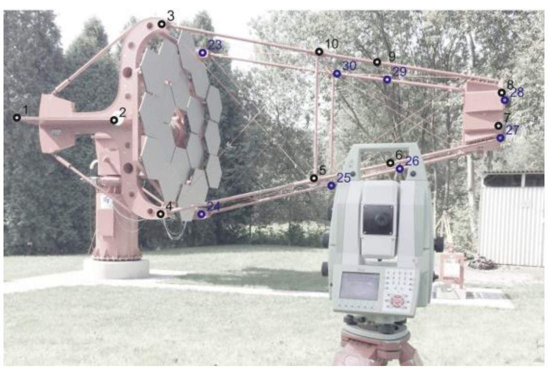

Fig. 1 Diagram of the points distribution [2].

2.2 Control network

In order to perform the measurements of the steel structure deformation, it was necessary to establish a special measurement control consisting of 8 points. The reference between the points was established through the measurement of 27 horizontal directions, slope distances and zenith angles (in two series each). Taking into account the small number of unknowns of the network, such a set of observations ensures high rigidity and reliability of the measurement structure, which is necessary to support the measurements of the telescope deformations. Thanks to the use of the precision electronic total station Leica MS50, as well as precise EDM prisms, high accuracy of determining the coordinates was possible. A set of observations was adjusted by the method of least squares. For the purpose of weighting the normal equation system, the following mean errors of the measured values were adopted: 15^{cc} for horizontal directions; 20^{cc} for zenith angles; 0.3 mm for slope distances. Based on the adjustments, spatial position of all the reference points with a standard deviation of ±0.58 mm were determined.

2.3 Observations and adjustment result

Based on the established control network, the deformation of the structure was measured by the method of angular intersection from the four positions of the instrument simultaneously. Based on the analysis of multiple observations, the mean measurement error of the horizontal direction and the vertical angle was estimated at $\pm 20^{cc}$. The adopted assumptions were verified during the adjustment of the measurements using local variance estimators. The measurement was performed at a total of 13 telescope settings, each time determining the positions of 20 points of the structure. The mean error of determining the positions of the points was approximately ±0.5 mm.

3 Telescope mast deflection analysis

Coordinates of the points measured at various angles of elevation of the telescope were transformed to the reference coordinate system (elevation 90º – probably the least loaded setting of the mast), and compared. A potential deformation of the object was obtained therefrom, induced by a variable angle of elevation.
Due to the fact that the reference coordinates were observed with an average accuracy of 0.5 mm, only the differences of the coordinates three times exceeding that value may have been considered to represent deformation of the structure. The presumed deflection of the structure, due to its weight, should occur in the vertical plane, thus the results represented by the vertical component are particularly interesting (Fig. 2).

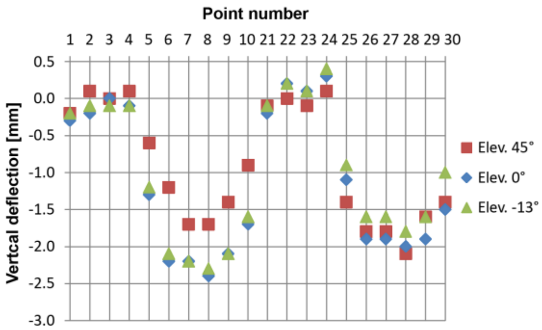

Fig. 2 Vertical defections of the mast structure [2].

As it can be seen, for the points 6 to 10 and 25 to 30, there was a deflection of the mast structure.

In the control of the structure, resulting from the changes in the azimuth of the telescope setting, coordinates of the points representing the object were measured in different azimuths of the telescope setting, and then transformed to the reference coordinate system (azimuth 0).

Table 1. Example of structure defamation – azimuth 270°

Differences in coordinates [mm]		
dX	dY	dH
0,2	0,0	0,1
0,1	0,1	-0,2
0,0	0,1	-0,1
-0,1	0,1	0,2
-0,2	0,6	0,0
0,1	0,5	-0,1
0,0	1,0	0,4
0,6	1,0	-0,2
-0,1	0,7	0,2
-0,2	0,4	-0,2
0,0	-0,2	0,1
0,1	0,0	0,0
-0,2	0,1	-0,3
-0,1	-0,1	0,2
-0,2	0,0	0,0
-0,2	0,1	0,1
0,0	-0,2	0,4
-0,3	0,1	-0,1
-0,2	-0,1	0,0
-0,3	0,0	-0,4

The points, together with the differences in coordinates, representing the potential deflection of the object, have been analyzed (Tab. 1).

As it was in the case of studying deflections caused by variable elevation, due to the fact that the reference coordinates were observed with an average accuracy of 0.5 mm, only the differences in the coordinates three times exceeding that value may be considered to represent deformation of the structure. The presumed deflection of the structure, due to its weight, should occur in the vertical plane, thus the results represented by the vertical component are particularly interesting.

Based on these results, it can be stated that there are no deformations of the construction occurring with the azimuth change of the telescope settings. It is fully in line with the expectations, since the moment of the forces acting on the structure of the telescope is the same, regardless of the azimuth.

4 Results of subsidence measurement

The aim of the task was to assess the stability of the telescope foundation at a given angle of elevation and various azimuth settings. To achieve it, measurements were performed by the method of precise leveling, allowing to determine the subsidence and rotation of the foundation. The measurements were carried out in four azimuth settings (epochs) of the telescope of 0°, 90°, 180° and -90° at the angle of elevation of 0°. Six screws (controlled benchmarks) were subject to the observations, bonding the core of the mast with the foundation (Fig. 3). The observed screws were anchored directly to the foundation, and therefore it was assumed that their potential vertical movement during the various settings will reflect the displacement of the foundation.

To ensure maximum accuracy of the measurement, the work was carried out using two Leica DNA03 precise levels with invar bar code staffs, with the expected reading accuracy of ±0.05 mm. The levels were set appropriately low, and on both sides of the telescope, so that each of them observed three controlled benchmarks. One invar leveling staff with a bar code of the length of 1 meter was used for the measurement. The reading in the level was carried out by a triple measurement and averaging the result.

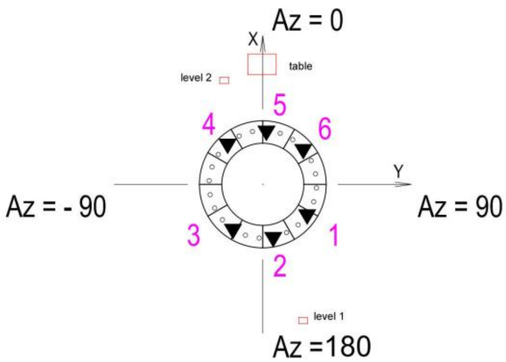

Fig. 3 Diagram of the distribution of the foundation controlled points.

In order to determine the actual accuracy of the height of the controlled benchmarks, in every measurement epoch, the leveling staff was two times placed on two of the three observed benchmarks, and independent readings were made. Based on these observations, the mean errors were determined: of the reading from the staff (±0.03 mm), of the height (±0.04 mm), and then of the displacement (±0.06 mm).

In order to determine the average subsidence and rotation of the foundation on the basis of vertical displacements of the points of the object, they were approximated using the following equation:

$$\Delta z_i = \Delta z_0 + x_i e_x + y_i e_y \qquad (1)$$

where: Δz_i – subsidence of the point; e_x – inclination of the foundation along the X axis; e_y – inclination of the foundation along the Y axis; Δz_0 – the mean value of the subsidence. The calculated values are summarized in Table 2.

Table 2. Analysis of vertical displacements of the foundation

Azimuth settings [°]	e_x [mm/m]	e_y [mm/m]	z_0 [mm]
90	0,04	0,07	0,03
180	0,07	0,06	0,00
-90	0,00	-0,02	0,00

The obtained values of vertical displacements and determined displacement parameters of the foundation are smaller than the accuracy of their determination. Based on these values it should be stated that the telescope does not exhibit positional changes at different azimuth settings.

5 Interferometric measurement results

To verify the hypothesis of dynamic sensitivity of the mast, 18 measurements were performed using ground-based interferometric radar. Figure 3 illustrates exemplary data and their spectral analysis.

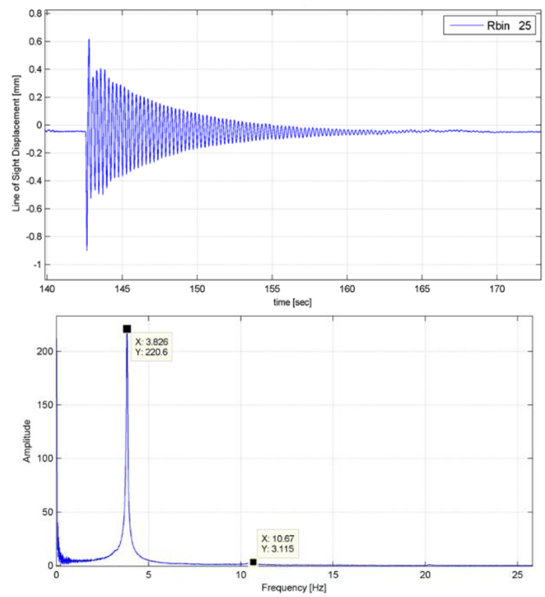

Fig. 4 Example of time series based on line of sight displacement recorded by IBIS radar (upper) as well as corresponding FFT analysis (bottom).

The excitations were carried out in five of the telescope settings (the “mast setting” column in Table 3). The individual excitations differed in strength and direction in relation to the telescope setting (column number 3). The mast set in positions S2 and S3 was not loaded by a mass substituting the camera. Therefore, the results of dynamic measurements performed during the excitations 4–12 did not allow for a reliable determination of the vibration frequency. These measurements repeated in positions S2’ and S3’ with the installed mass (excitations 13–18) gave the proper results.

The results of the spectral analysis in all mast settings did not give a clear information about the structure eigenfrequency. These values were different depending on the type of excitation. It can be assumed that this effect was caused by a complex mounting of the structure.

Table 3. Summary of dynamic test results

No.	Mast setting	Excitation	Vibration frequencies [Hz]
1	S1 Az = 0 El = +90	weak A ⊥	**3.32**, 3.89, 33.42
2		strong A ⊥	**3.83**, 10.67
3		strong B ‖	**3.02**, 3.33, 3.85
4	S2 Az = +135 El = –13	medium C ⊥	**2.86**, 3.57
5		strong C ⊥	**1.84**, 2.55
6		strong C ⊥	**2.10**, 2.96
7		weak C ⊥	**3.09**, 3.64, 22.67
8	S3 Az = +135 El = +10	strong D ‖	–
9		medium D ‖	–
10		strong D ‖	–
11		strong D ‖	–
12		strong D ‖	25.12, 51.23
13	S2' Az = +135 El = –13	medium C ⊥	**2.57**, 3.33, 52.76
14		medium C ⊥	**2.44**, 3.33, 52.71
15	S3' Az = +135 El = +10	strong D ‖	**2.68**, 19.48
16		strong D ‖	**2.68**, 19.45
17		medium E ‖	**2.76**, 26.87, 32.58, 43.60, 52.55
18		medium E ‖	**2.80**, 26.86, 32.58, 43.60, 52.54

6. Summary

Base on geodetic measurements several important information's have been captured [1]:

1. Relative deformations between the camera and the mirror dish in the full elevation range reach 2.5 mm.
2. Relative deflections between 45^0 and 95^0 elevation angles are in the range from -2.1 mm to -1.7 mm, in good agreement with a 1.5 mm value estimated through FEM calculations.
3. Within the accuracy of the measurements, the telescope structure does not suffer any deformations with the change of the azimuth angle.
4. The angle between the azimuth and the elevation planes is equal to 90^0 04'50" and the tilt angle of the azimuth axis with respect to zenith is 0^0 05'55".
5. Natural modes identified for the telescope are in Table 3, and they only slightly depend on the type and strength of the excitation. They are in good agreement with the results of the full spectral analysis performed with the use of accelerometers, and also in line with FEM calculations.

References

[1] J. Niemiec, et al., Prototype of the SST-1M Telescope Structure for the Cherenkov Telescope Array, The 34th International Cosmic Ray Conference, 30 July- 6 August, 2015 The Hague, The Netherlands

[2] J. Niemiec, et al., Single-mirror Small-Size telescope structure for the Cherenkov Telescope Array, in proceedings of 33rd International Cosmic-Ray Conference, Rio de Janeiro, Brazil, 2013