MORAL ROBOTIC ALT-AZ MOUNT: PERFORMANCE AND RESULTS OF SATELLITE TRACKING CAMPAIGN

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ABSTRACT

MORAL (Mount robotic alt-azimuth) are a family of alt-az mounts that can be equipped with payloads ranging from 500 to more than 1000 mm in aperture developed by N.P.C. New Production Concept Srl. The project started in 2014 as a direct response for the tracking of fast objects, such as LEO satellites and space debris in the frame of SSA activities.

The goal of the project has been that to minimize mechanical errors and optimize the control in order to achieve excellent performances in pointing and during tracking.

An intense testing campaign in relevant conditions has been scheduled and performed to verify system performances for pointing and tracking at different slew rates and considering different targets (including sidereal targets and artificial objects).

In particular Moral M1000 (suitable for telescopes up to 1 m in diameter) has been recently exploited for the tracking of the reentering uncontrolled Chinese space station Tiangong-1 during January 2018 in the frame of an Italian national campaign for the monitoring of the station, that saw the involvement of a network of different sensors (operated by universities and private observatories).

The space station has been tracked by MORAL during a fast 6 minute passage (at low elevation) using an open loop approach. Retrieved data has been exploited by researchers from University of Rome "La Sapienza" to determine and reconstruct the object attitude, in a synergic collaboration between academy and industry.

The setup adopted to perform the campaign will be addressed: results retrieved during outdoor testing campaign are addressed in the paper. This includes accuracy in sidereal tracking and a focus on main results and figures of merit achieved in the tracking of artificial objects (including Tiangong-1). These aspects will be discussed within the paper along with some details relative to the mount control and in-house developed tracking algorithms.

1 MORAL TELESCOPE MOUNT

Moral (mount robotic Alt-Azimuth) is a class of telescope mounts with performance suitable for SSA and SST applications. The systems are compatible with a wide range of optical instruments, ranging from 300 mm to 1000 mm in diameter.

Different aspects have been optimized during the project in order to achieve the desired level of performance in terms of accuracy, precision, slew rate acceleration [1].

The systems exploit direct drive motors coupled with high resolution absolute optical encoders in order to achieve desired accuracy for pointing and tracking.

An optimization has been carried out on the mechanical design in order to improve the static and dynamic behaviour of the mount in relevant operative conditions, aiming at increasing stiffness and ensuring an overall lightweight structure.

The design of Moral has been maintained flexible with through hole shafts and multiple access points. This allows an easy maintenance avoiding the need to fully disassembly the mount for inspection of critical components.

Moral mounts can have a variable number of power and data signals that can be reach the elevation axis while ensuring the capability of a free rotation around azimuth.

The family of telescope mounts include M1000, M700 and M500 respectively for one meter, 700 mm and 500 mm class telescopes: all the systems share the same level of performance.

The main specifics are listed in Tab.1.

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Safety Programme Office Ed. T. Flohrer, R. Jehn, F. Schmitz (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

Parameter	M500	M700	M1000
Material	Structural Steel with Anti-rust Treatment		
Weight	180 Kg	330 Kg	800 Kg
Mechanical Pointing Accuracy	< 1"		
On sky RMS Pointing Accuracy	<8” after pointing model (proprietary tool)		
Height	1070 mm	1162 mm	2308 mm
Fork Aperture	1000 mm	1212 mm	1925 mm
Distance between plates	603 mm	795 mm	1410 mm
Through hole elevation (Nasmyth)	100 mm	100 mm	100 mm
Through hole Azimuth Axis	30 mm	60 mm	60 mm
Nominal Load	1471 N	2950 N	4900 N
Maximum Load	2950 N	4900 N	9810 N
Acceleration	>80 °/s2	>80 °/s2	>80 °/s2
Slew Rate	60 °/s	60 °/s	60 °/s
Protection	Protective Seals - General System grade IP54		

Table 1.Moral Family specs

Figure 1. Moral M1000

Figure 2. Moral M500 (left) and M700 (right)

Moral has been designed in order to be easily operated by commercial software and user developed software exploiting ASCOM interface and TCP/IP open protocol. It has been however developed a user interface that offer the possibility to exploit specific built-in algorithm for high performance operation. In particular 3 algorithms for optimized star tracking and satellite tracking are present and can be exploited through MORAL interface panel or user defined program.

MORAL is provided with 3 built in alignment models exploiting different mathematical models according to the type of alignment required (fast, intermediate, accurate). The user can however use commercial tool such as Tpoint.

The scope of the system is to provide modular open platform for professional observatories allowing the user to explore the level of customization of the mount operating at different levels with its proper tool and ease the integration of the system in an existing network.

Thanks to consolidated partnership with optics producers, NPC can provide a complete package with required telescope integrated which can be designed and produced according to specific user needs.

2 SIDERAL TRACKING

An outdoor testing campaign has been performed for the M1000 platform in order to assess the performance of the system in relevant conditions (with an actual payload representative of a meter class telescope). The mock-up telescope is characterized by a mass of 500 kg and a MOI (moment of inertia) of 300 kg m2.

A smaller reflector telescope integrated in the mock-up has been exploited for the test.

The main characteristics are listed in Tab.2:

Aperture	200 mm
Focal	2000 mm
FOV	9.9’x7,4’

Pixel scale	0.84”
Pixel size	4.5 µm
Resolution	1280x960

Table 2. Specifics of optical configuration

An open loop tracking has been carried out exploiting a proprietary algorithm that works in an asynchronous way (one of the three built-in star tracking options), i.e. independently from time. The algorithm, starting from initial set of Alt Az coordinates and provided latitude and longitude of the observatory, is capable of propagating the position of the star, following its apparent motion: a linear or polynomial interpolation is performed between points (the current position and the propagated one/s).

Figure 3. Moral M1000 with one meter class telescope mock-up for testing in relevant conditions

Three relevant conditions have been considered for the test, in order to verify the performance for stars characterized by different apparent velocities:

- Star characterized by DEC 0, close to the Meridian (fast);
- Star within 10° from Polaris;
- Star within 10° from local Zenith.

For each star type a five minute tracking has been performed with a sampling 15 Hz.

Each frame is then processed via SW in order to assess the CoM (Center of Mass) of the star. It is possible this way to obtain a graph showing the trend of Azimuth and Elevation error over time and retrieve figures of merit in terms of error (RMS – root mean square - and maximum error).

2.1 “DEC 0” star

The first results are relative to a star characterized by a declination close to 0° and a right ascension close to the local Meridian (star characterized by apparent fast motion).

Object Name	HIP 53907
RA	+11° 02' 43.10"
Dec	-02° 34' 45.53"
Time	23:45:00 STD
Azimuth	161° 10' 28"
Altitude	+41° 23' 53"
Magnitude	4.73

Table 3. Case 1: star with DEC close to 0, close to Meridian

The results in terms of error during a 5 minutes open loop tracking are presented in Tab.4:

El max error [arcsec]	5.1
Az max error [arcsec]	4.6
El RMS deviation wrt median [arcsec]	0.98
Az RMS deviation wrt median [arcsec]	0.73

Table 4. case 1 (star with low DEC, close to Meridian): tracking accuracy

Graphs relative to trend over time of the Azimuth and Elevation error of the CoM of the star relatively to initial coordinate is presented below (Fig.4, Fig.5):

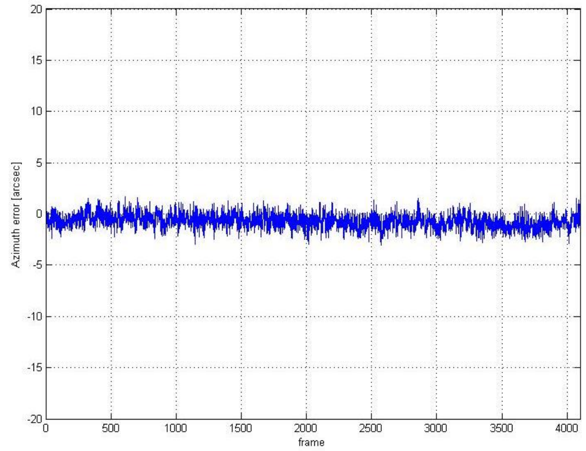

Figure 4. Azimuth error over time during 5 minutes tracking: star DEC close to 0, close to Meridian (fast star)

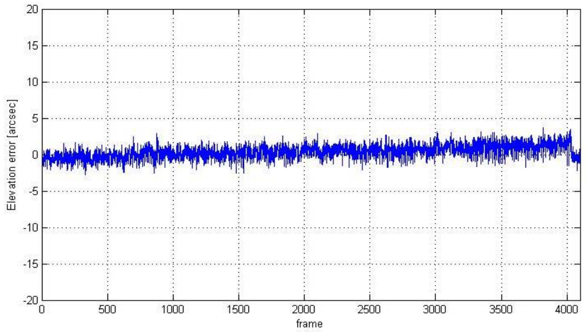

Figure 5. Elevation error over time during 5 minutes tracking: star DEC close to 0, close to Meridian (fast star)

The polar positioning of the CoM of the star is plotted in Fig 6.

The graph displays the motion of the CoM of the star within a subframe of 11 x 11 pixels (9.24" x 9.24").

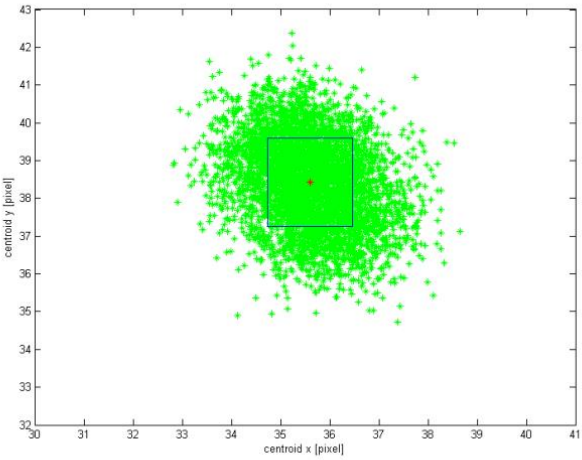

Figure 6. Position of CoM of the star over a 5 minutes open loop tracking: star DEC close to 0, close to Meridian (fast star)

2.2 Star close to Polar

The main parameters relative to a star close to Polaris are displayed in Tab.5: this star is characterized by an apparent slow rate.

Object Name	HIP 47193
RA	09h 39m 28.4s
Dec	+81° 15' 00.234"
Time	22:30:00 STD
Azimuth	359° 13' 58"
Altitude	+53° 06' 43"
Magnitude	4.28

Table 5. Case 2: star close to Polaris

The results in terms of error during a 5 minutes open loop tracking are presented in Tab.6

El max error [arcsec]	6.27
Az max error [arcsec]	4.5
El RMS deviation wrt median [arcsec]	1.11
Az RMS deviation wrt median [arcsec]	0.64

Table 6. case 2 (star close to Polaris): tracking accuracy

Graphs relative to trend over time of the Azimuth and Elevation error of the CoM of the star relatively to initial coordinate is presented below:

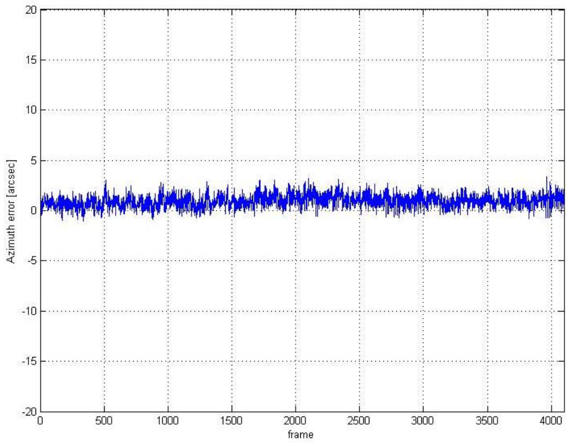

Figure 7. Azimuth error over time during 5 minutes tracking: star close to Polaris (slow star)

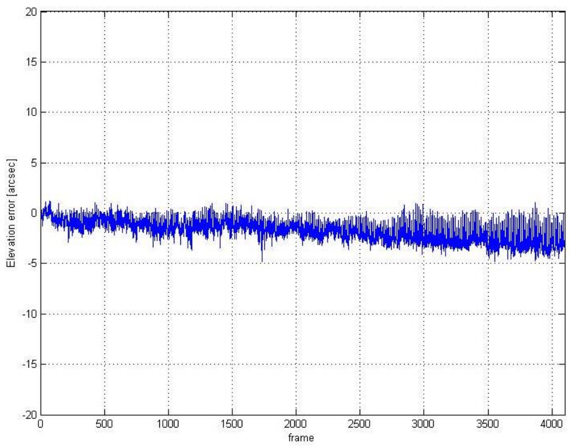

Figure 8. Elevation error over time during 5 minutes tracking: star close to Polaris (slow star)

The polar positioning of the CoM of the star is plotted in Fig 9. A subframe of 11 x 11 pixels (9.24”x9.24”) centered on the star has been used.

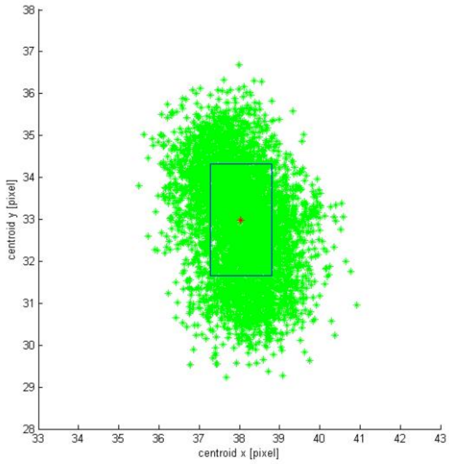

Figure 9. Position of CoM of the star over a 5 minutes open loop tracking: star close to Polaris (slow star)

2.3 Star close to Zenith

The main parameters relative to a star close to Zenith (10° from zenith) are displayed in Tab.7: the relevant condition of this star is the amplification of errors at high elevations.

Object Name	Capella
RA	05h 17m 57.2s
Dec	+46° 00' 56.5''
Time	20:20:00 STD
Azimuth	290° 53' 22''
Altitude	+84° 49' 04''
Magnitude	0.08

Table 7. Case 3: star close to Zenith

This last test has been performed under harsh environmental conditions, in particular in presence of a strong wind at 25 Km/h. This had a relevant impact on the performance in tracking, aspect that has been amplified due to the high value of elevation (84°).

The disturbance is constantly compensated by the motors. This is clearly visible in the peak to peak error for azimuth and for elevation.

The results in terms of error during a 5 minutes open loop tracking are presented in Tab.8.

El max error [arcsec]	36.2
Az max error [arcsec]	5.5
El RMS deviation wrt median [arcsec]	3.36
Az RMS deviation wrt median [arcsec]	0.74

Table 8. case 3 (star close to Zenith): tracking accuracy

Graphs relative to trend over time of the Azimuth and Elevation error of the CoM of the star relatively to initial coordinate is presented below:

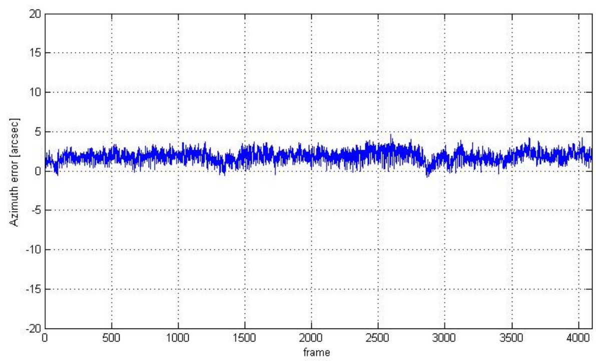

Figure 10. Azimuth error over time during 5 minutes tracking: star close to Zenith

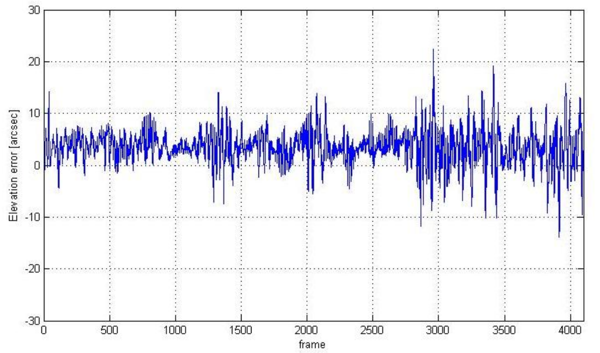

Figure 11. Elevation error over time during 5 minutes tracking: star close to Zenith – strong wind conditions

The polar positioning of the CoM of the star is plotted in Fig 12. A sub-frame of 50 x 50 pixels (42”x 42”) centered on the star has been used. it is clearly visible the elongation along the y direction (elevation) due to the wind disturbances.

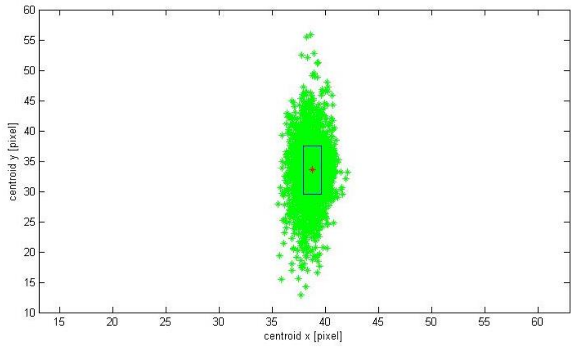

Figure 12. Position of CoM of the star over a 5 minutes open loop tracking: star close to Zenith (strong wind conditions)

3 SATELLITE TRACKING

In the present section the results of open loop tracking satellite performed using M1000 mount is addressed.

A careful tuning of gains relative to motion has been performed in order to achieve the desired dynamic performances during motion, and ensure the desired level of accuracy both in tracking of fast (satellites) and slow objects (sidereal tacking).

Moral SW panel offers an interface specifically designed for tracking of satellites, by generating automatically the sequence of Alt Az coordinates vs time starting from TLE (two line elements).

After importing a set of TLEs the built-in script automatically performs a propagation of the orbit by means of SGP4.

Starting from the satellite state vector the script operates a conversion to Altitude and Azimuth coordinates with respect to the location of the observing site. The script generates a list of coordinates and times that satisfy a imposed constraint on illumination and minimum elevation (i.e. only coordinates and time for which altitude is greater than 20 deg).

All these data are stored inside a generated ‘.txt’ file.

The script can autonomously provide a scheduling of the observations if more than one TLEs are imported.

The ‘txt’ file includes the following data organized in columns:

- Starting date: at which the tracking of the satellite/ object is initiated;
- Time step: expressed in seconds, offset with respect to starting date;
- Azimuth (expressed in degrees);
- Elevation (expressed in degrees);
- Rates (expressed in deg/s).

An extract of the file, only showing the initial time, time step, Azimuth and Azimuth rate is provided in Fig.13:

```
2018;8;28;19;25;22.56516867828395

timestep[s]      AZ [deg]           AZRATE [deg/s]
30;      255.0637137999365;       0.2776062469063874;
1;       255.341320046843;        0.2781383885147193;
1;       255.6194584353576;       0.2786599156231375;
1;       255.8981183509808;       0.2791706953433675;
```

Figure 13. Extract of the automatically generated file from MORAL control panel, used to perform tracking of satellites: starting date of the tracking is indicated, along with coordinates of the object at each time step

At t=start_date the mount automatically slews to a resting position (both for Az and El). This position is calculated as the one that allows to the mount to perform a rendezvous with the first set of Azimuth and Elevation coordinates at the first time-step, so that the mount will reach the desired position at the right time. The process is repeated for each point in the scheduling file. The mount is capable this way to perform an open loop unguided tracking of the object, with the capability to precisely follow the theoretical retrieved trajectory.

As mentioned an extensive phase of gain tuning has been carried out in order to minimize errors during tracking of objects characterized by different rates and accelerations.

The results of a tracking campaign performed on three objects is provided hereafter. A stellar calibration procedure of the mount to model the errors has been carried out prior to performing the tracking, exploiting proprietary built-in in alignment tool.

List of tracked objects is provided in Tab.9.

SERT 2	04327
ENVISAT	27386
ARIANE SRB	21610

Table 9. list with ID of tracked objects

Specifics of the satellites in terms of initial Azimuth and Elevation, maximum Azimuth rate and Elevation rate is provided in Tab.10:

Satellite	AZ_0 [deg]	EL_0 [deg]	Azrate max [deg/s]	Elrate max [deg/s]
SERT 2	222,83	62,79	0,98	-0,24
ENVISAT	255	21,6	0,29	-0,06
ARIANE	243	33	0,45	-0,12

Table 10. satellites initial coordinates and peak rates

The optical setup exploited for the tracking campaign is the same already presented in Tab.2.

The adopted frame rate also in this case has been set to 15 Hz.

As done for the star tracking each frame of the video has been extracted. A subframe of approximately 200 x 200 pixels (2,9' x 2,9') centered on the satellite has been created. An example is provided in Fig. 13 relative to satellite SERT.

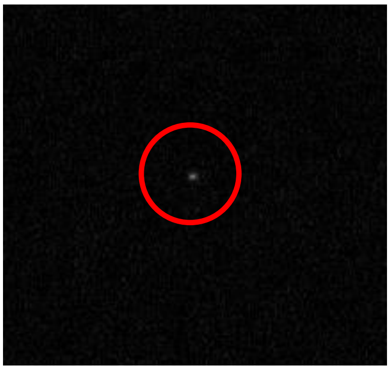

Figure 14. subframe of 200 x 200 pixels relative to satellite SERT2

The CoM of each subframe has been calculated and plotted in a polar diagram to track its motion in terms of Azimuth (x) and Elevation (y) displacement over time.

Results are provided in the following chart for Sert 2 satellite showing computed Az and Alt error in terms of standard deviation with respect to median value.

SERT 2 (04327)	
err_std_y	3.6"
err_std_x	2.7"
# frame	3000
framerate	15 Hz
duration	200 s

Table 11. tracking accuracy for SERT2 satellite, framerate and duration

The polar diagram is portrayed in Fig.15:

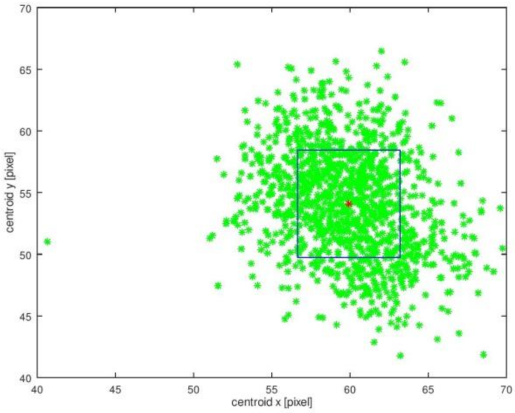

Figure 15. Position of CoM relative to SERT2 satellite during an open loop tracking

Results are provided in the following chart for Envisat satellite showing computed Az and Alt error in terms of standard deviation with respect to median value. A lower number of frames has been exploited due to partial cloud coverage.

ENVISAT (04327)	
err_std_y	1.22"
err_std_x	1.92"
# frame	600
framerate	15 Hz
duration	40 s

Table 12. tracking accuracy for ENVISAT satellite, framerate and duration

The polar diagram is portrayed in Fig.16:

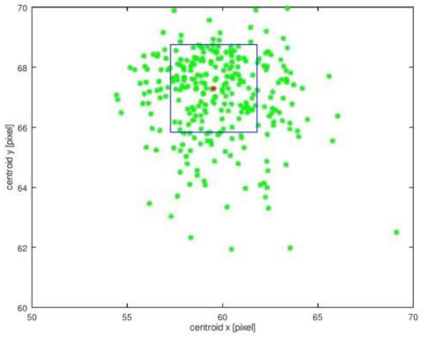

Figure 16. Position of CoM relative to ENVISAT during an open loop tracking

Results are provided in the following chart for Ariane

SRB showing computed Az and Alt error in terms of standard deviation with respect to median value.

ARIANE SRB (21601)	
err_std_y	1,8”
err_std_x	10,5”
# frame	3450
framerate	15 Hz
duration	230 s

Table 13. tracking accuracy for ARIANE SRB, framerate and duration

The polar diagram is portrayed in Fig.17:

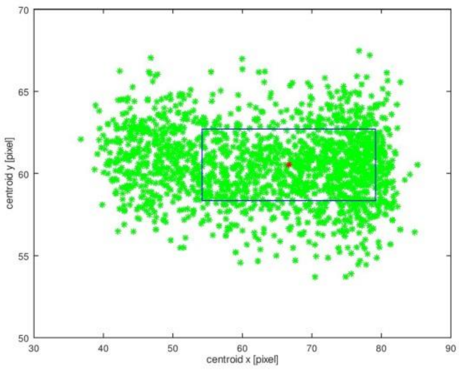

Figure 17. Position of CoM relative to ARIANE SRB during an open loop tracking

As visible in this last case a slight drift in Azimuth has been observed. The entity of the drift is anyway in line with possible errors introduced by the TLE propagation.

3.1 Tiangong-1 reentry: a case study

A relevant case study is represented by the open loop tracking of the re-entering Chinese space station Tiangong-1, which has been performed on January 24rd 2018. The same sequence highlighted in the previous section has been applied to perform the open loop tracking.

The optical setup has been highlighted in Tab.2.

The main features of the object at the time of observation are listed in Tab.14: as shown the tracking has been performed during a low passage of the spacecraft.

Azimuth @ T0	-101°
Elevation @ T0	7.1°
Peak Elevation	18°
Peak Az rate	0.8 °/s
Peak El rate	0.2 °/s
Altitude	220 km

Table 14. TIANGONG-1 coordinated at time of tracking (24th January 2018)

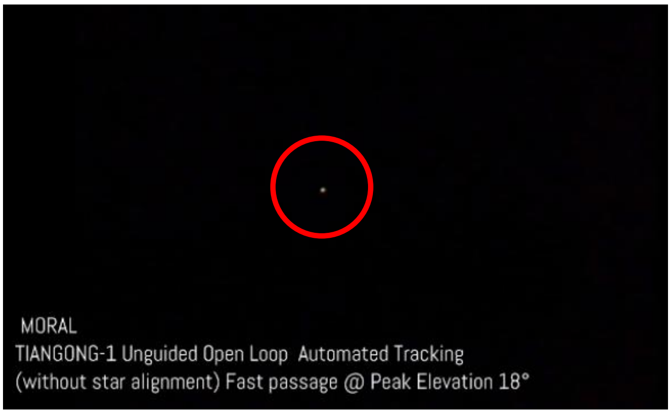

Figure 18. Tracking of Tiangong-1 (extract from acquired data)

The retrieved raw video has been exploited in order to extract light curves of the object and reconstruct its angular velocity. The curves have been extracted and processed by researchers from “Sapienza” University of Rome [2],[3].

In the following the graph of light intensity as a function of time (Fig.19).

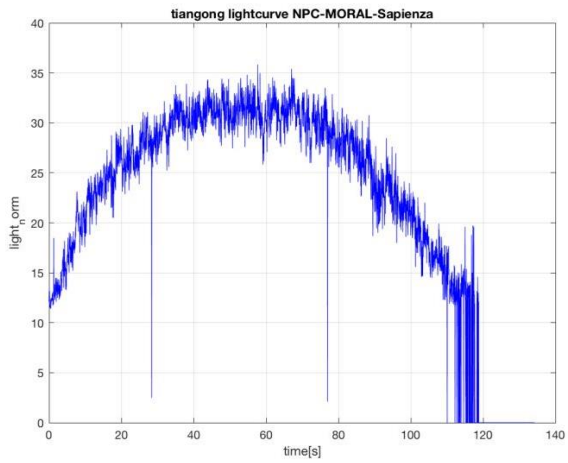

Figure 19. light curve of Tiangong-1 extracted from the tracking video of the object.

The attitude reconstruction is presented in Fig.20, showing angular rate of Tiangong-1 vs time: it is clearly visible that at the time of acquisition the space station was still maintaining a stable attitude, characterized by a slow motion.

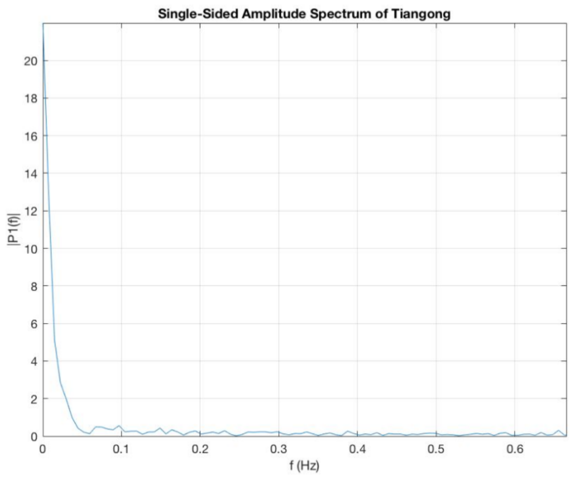

Figure 20. Reconstruction of Tiangong-1 rotation rates

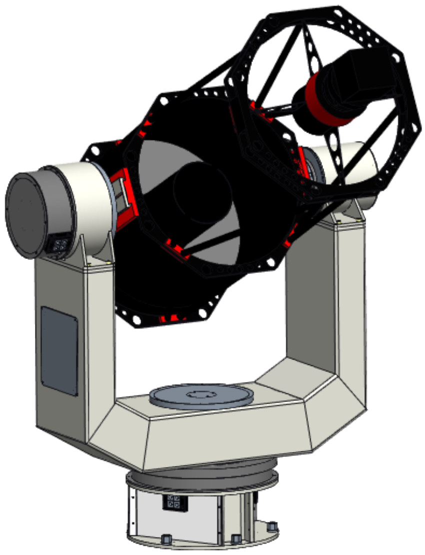

Figure 21. A representation of MORAL M500 SSA system with integrated a 500 mm fast telescope.

4 SST turnkey solution

Moral is currently one of the most interesting trade-off system for high demanding application in SSA activities. Thanks to its flexibility, specific configuration are currently under development in order to identify turnkey solutions.

As relevant aspect it has to be mentioned the partnership of NPC with an important italian company with strong expertise in software development and algorithm/ model implementation for orbit prediction and object tracking. Thanks to the integration with NT-SST software, the capabilities of the system have been increased. Among this a fundamental aspect that it has been introduced consists in the integration of machine learning algorithms upstream to guide operation of satellites tracking, sky survey and identification of flight/orbiting object. A fundamental feature consists in the presence of multiple post processing function that allows to retrieve quick information on the observed object such us classification and attitude data thanks to light curves analysis. All this relevant features as built-in system permits to increase the versatility of possible operations and related performances.

M500 SSA

MORAL M500 version allows the integration of multiple commercial telescope from 350 to 500 mm. The core of MORAL control system combined with NT-SST software combines multiple function for automated sky survey and object tracking.

A layout of the system with is provided in Fig. 21

M1000 Cluster SSA:

MORAL M1000 version allows in fact the integration of telescope cluster in the range of 350-500 mm optics. A steering system has been designed by NPC permitting to independently operate 4 telescopes and allowing thus higher flexibility in terms of Field of view and magnification. A layout of the proposed solution in presented below in Fig. 22:

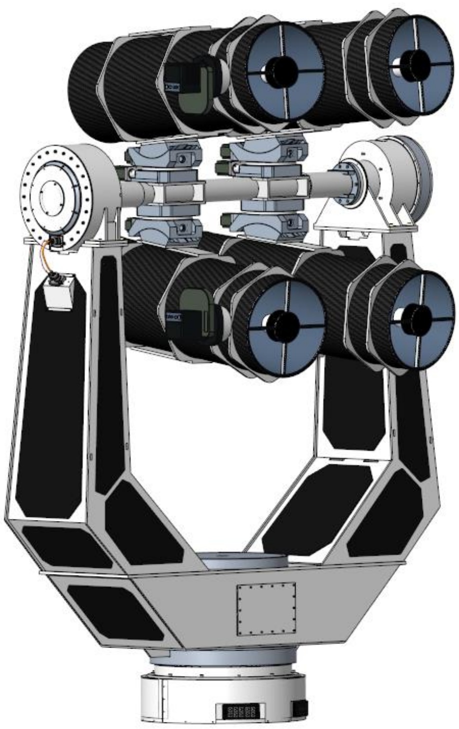

Figure 22. A representation of MORAL M1000 with integrated cluster of 4 fast telescopes for SSA. Additional telescopes can be added to the cluster (8 telescope configuration)

<u>*M500 Survey System*</u>

M500 Survey system is a non-conventional solution for survey and observation of flying objects not orbiting. Among these, air vehicle and drone are comprised. The system exploit the maximum level of performance of MORAL mount permitting high acceleration and slew rate. It is however designed also for satellite and debris re-entering observation.

A layout of the configuration is proposed in Fig.23:

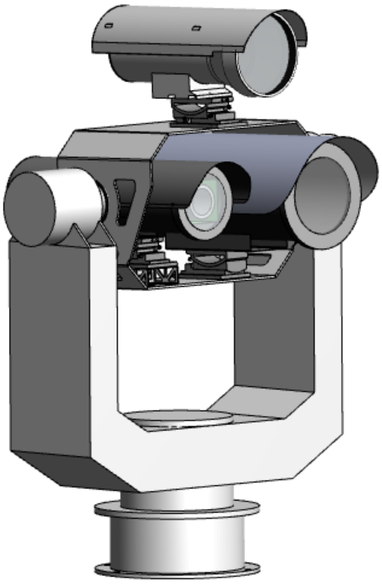

Figure 23. A representation of M500 survey system with integrated cluster of 3 telescopes for survey

5 CONCLUSION

An overview of the main features of Moral family of high performance Alt-Az telescope mounts has been provided. The M1000, compatible with 1 m class telescopes has been extensively tested in relevant conditions to assess its performance.

Main results of the tracking of sidereal and artificial objects has been presented and discussed in the paper: in particular considering satellite tracking an high level description of the built-in algorithm developed has been presented along with results of tracking relative to three satellites, showing the capability of the system to be adopted for SSA and SST applications.

A relevant case study special is represented by the tracking of the re-entering space station Tiangong-1: the retrieved data has been exploited by researchers of "Sapienza" University of Rome to extract light curves and reconstruct the motion of the object in terms of angular rate.

In the end active projects of NPC in the field of SSA/ SST/ survey have been introduced. Each solution is tailored on specific acquisition needs. Strategic partnership have been put in place in order to enhance the offer. Thanks to the integration of NT-SST (developed by Nurjanatech) software, key features such as orbit determination and classification can be performed.

6 REFERENCES

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