OBSERVATIONS BY SHOT AT TEPLICE OBSERVATORY

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ABSTRACT

Sand Hill Optical Telescope (SHOT) is a new optical sensor dedicated for space debris observations and satellite tracking. The SHOT sensor is operated by the Teplice Observatory located 80 km north of Prague, Czech Republic. In the paper, we present observing methods and the results of astrometric observations from the last campaign. We focus on accuracy of time measurement and epoch determination, which is crucial for precise orbit determination. The time bias is mainly contributed by the CCD shutter's latency. Another source of error is the duration of the opening and closing of the shutter. The behaviour of the CCD shutter has been analysed and evaluated epoch correction will be applied to measurements.

1 INTRODUCTION

In this paper we present a new optical sensor dedicated mainly for Space Surveillance and Tracking (SST) activities, but also suitable for NEO follow-up observations. Teplice Observatory is located 80 km north of Prague, Czech Republic, on the small hill called Sand Hill in the southeast part of the North-Bohemian town Teplice. It is a part of North-Bohemian Observatory and Planetarium in Teplice, a non-profit organisation with focus on the popularisation of astronomy and science. The SHOT started its observation in 2015, shortly after Teplice Observatory was equipped with a new 43-cm f/6.8 reflector on a precise German equatorial mount. In 2016, the sensor became involved in the European Space Agency (ESA) activity P2-SST-X "Support Observations and Sensor Qualification" within the Space Situational Awareness (SSA) programme as a sub-contractor of Italian company e-GEOS. The SHOT sensor was successfully qualified for SST observations during this activity. The observations were interrupted from June 2017 to August 2018 during the general reconstruction of the main building of the observatory. From September 2018, the sensor is involved in the ESA project P3-SST-III "Robotic Telescopes Demonstration" with the aim to fully automate its operation.

2 SHOT SENSOR

The SHOT sensor consists of 0,43-m f/6.8 reflector, high-precision German equatorial mount with absolute encoders and a CCD camera (Fig. 1).

Figure 1. The SHOT sensor (Teplice Observatory, southeast dome)

The SHOT parameters are specified in the Tab. 1.

The telescope is used in conjunction with the 0,66× focal reducer for the resulting focal ratio of f/4.4.

Two CCD cameras are available for observations. For the first campaign, a front-illuminated CCD camera Apogee Aspen CG9000 with field-of-view (FOV) of 65′×65′ was used. Pixel binning 2×2 is preferred for faster download of images acquired by this camera. The second CCD camera is a back-illuminated CCD camera Apogee Aspen CG230 with FOV 55′×55′. This camera has smaller FOV, but it reaches higher quantum efficiency (Q.E.) and its performance is being tested.

The sensor is located inside a classical 5,5-m dome with 2-m shutter opening. All objects more than 10° above the horizon are observable by SHOT.

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Table 1: SHOT sensor specification.

Sensor location	
Name	Teplice Observatory, southeast dome
Latitude	50°38'18.0"N (50.63833°)
Longitude	13°50'48.3"E (13.84675°)
Elevation	275 m
Datum	WGS-84
Telescope	
Model	Planewave CDK17
Optical design	corrected Dall-Kirkham with 0.66× focal reducer
Aperture	432 mm
Focal length	1915 mm (with 0.66× focal reducer)
CCD camera #1	
Model	Apogee Aspen CG9000
Sensor	KAF-09000 (ON Semi), front-illuminated, Q.E. 64% @550 nm
CCD array size	3056×3056 pixels
Pixel size	12 µm
CCD sensor size	36.7 × 36.7 mm (51.6 mm diagonal)
FOV	65′×65′
Pixel scale	2.58 arcsec/pixel (binning 2×2)
Readout time	4 s (binning 2×2)
CCD camera #2	
Model	Apogee Aspen CG230
Sensor	CCD230-42 (E2V), back-illuminated, Q.E. 96% @550 nm
CCD array size	2048×2048 pixels
Pixel size	15 µm
CCD sensor size	30.7 × 30.7 mm (43.4 mm diagonal)
FOV	55′×55′
Pixel scale	1.62 arcsec/pixel
Readout time	5 s
Mount	
Model	10micron GM3000 HPS
Design	German equatorial mount
Pointing accuracy	20 arcsec
Tracking capabilities	Sidereal tracking or custom tracking up to 1°/s. Tracking accuracy about 1 arcsec in 5 min. Slew rate up to 12°/s.
Dome	
Diameter	5,5-m
Rotation speed	3°/s
Control	MaxDome II

3 TIME ACCURACY AND BIAS

The typical accuracy of astrometric position (i.e. the accuracy of the angle measurement of right ascension and declination) from SHOT observations is better than 1 arcsec in most cases for NEO observations. For faster moving objects like satellites and space debris, with sky motion over 15 arcsec/s, the accurate time is crucial for the precise orbit determination. If we request the 1 arcsec accuracy of the astrometric measurement also for SST observations, and the time accuracy shall not compromise the astrometric accuracy, the corresponding accuracy of time determination for the GEO satellites is about 50 ms. For MEO satellites with sky motion typically about 1 ′/s, the necessary accuracy increases to 15 ms and for LEO observations with motion up to 30 ′/s, the accuracy much better than 1 ms has to be reached.

During the observational campaigns, several timing issues have been solved. We found that the synchronization of the PC's system clock with external Network Time Protocol (NTP) [1] server exhibited large delays and led to larger errors in the time determination. Therefore, a new NTP server with GPS receiver with internal accuracy better than 1 ms was installed in the observatory and operating system time was synchronized prior to each exposure.

The computer for image acquisition is equipped with Windows 7 operating system. This system poses another limitation for time determination, the system time is stepped by 15 ms which causes a random error of the observation epoch. Another issue arose from Maxim DL 6 software which prints the DATE-OBS keyword into FITS file header with precision of only two decimal digits. This caused an additional random error of ±5 ms for the epoch determination.

To solve all the above issues, we acquire time before each exposure by direct call to internal NTP server. The time accuracy is verified again by querying the time server after the exposure command has been sent to the CCD camera. The network communication with the server is fast and the command roundtrip delay is usually less than 4 ms. Even if the network communication is not symmetric, the expected accuracy of the time determination is better than 2 ms.

Another serious problem is the CCD shutter latency, which affects the time bias of the measurement. The time delay between the instant when the computer sent the exposure command, and the instant when the shutter is opened depends mainly on the CCD camera hardware, connection to the computer, operating system and software for image acquisition.

The shutter latency can be determined in two ways: by laboratory measurement, or by analysis of the data for satellites with high precision orbits. We measured the shutter latency with an ultra-high speed camera with the frame rate of 2000 fps and we determined a delay of 53 ± 5 ms prior to the start of CCD camera shutter opening. The ESA performance analysis of the SHOT observations shows that the time bias for LEO observations relative to the reference SP3 orbit is 56.71±0.15 ms for Sentinel-2A satellites, which is in agreement with the laboratory measurement.

To cope with the time bias in future we plan to observe GNSS satellites prior, possibly after the observation of the target objects. We plan to use the precise reference orbit of a GNSS satellite at the times of frame exposures for determination of the time bias.

An additional bias is caused by the shutter opening and closing itself which lasts 13 and 18 ms, respectively, for the CCD camera #1 (Aspen CG9000). The typical course of the 200 ms exposure for CCD camera #1 is:

- T_0 – the start of the shutter opening
- T_0 + 13 ms – the end of the shutter opening
- T_0 + 201 ms – the start of the shutter closing
- T_0 + 219 ms – the end of the shutter closing

We speculate that under certain circumstances this behaviour could contribute to the satellite along-track error for LEO targets positioned off-centre in the CCD frame. If a certain XY position in the CCD frame is preferred, then the satellite streak can be shifted due to the non-instantaneous opening/closing only in one direction.

4 OBSERVATION AND DATA PROCESSING

SHOT data acquisition process has been mostly automated, but some levels of the automation (e.g. scheduling of targets, streak detection) are still under development (Fig. 2).

Real-time tracking of the selected target is based on simultaneous pointing and tracking of the telescope, dome slewing and CCD image capture control. Simple scripts have been developed for batch acquisition of scheduled targets. Images acquired with the CCD camera are calibrated for dark frame and flat field and saved in the FITS format.

Methodology and observing strategy varies depending on the target tracking speed. At the end of the processing chain there is a formatted message in the TDM or MPC standard format.

4.1 GEO/MEO Observations

For "slow" targets (e.g. MEO and GEO satellites) with tracking speed less than 60 arcsec per second the Automatic Satellite and Asteroid Processor (ASAP) for data processing can be used. ASAP is a software developed by Iguassu Software Systems in the frame of the ESA project "Demonstration Test-Bed for the Remote Control of an Automated Follow-Up Telescope" and its development continues in the present ESA SST activities P2-SST-X and P3-SST-III, in which the SHOT sensor is involved.

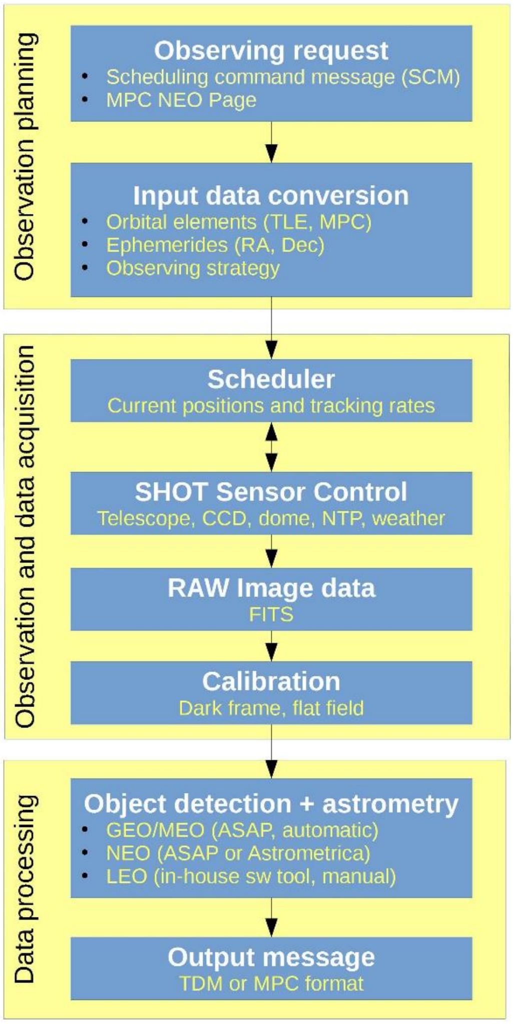

Figure 2. SHOT observation and data processing

The observing strategy required for processing images by ASAP is based on the telescope tracking with the satellite speed (in both axes) and the telescope moving back to the same coordinates after each exposure, resulting in all images having the same right ascension and declination. Finally, a reference frame with sidereal tracking of the same field is acquired.

We need at least 5 positions for a successful automatic detection of the target. Therefore, the transit time across the SHOT sensor's FOV has to be less than 60 seconds, because after each exposure (when the target is tracked), we need typically 15 seconds to move the telescope back to the exact initial position to keep the original star field. The typical exposure for these targets is 2 seconds. For fainter space debris objects we used exposures 5 or 10 seconds.

4.2 LEO Observations

For "fast" targets (LEO) it is impossible to use ASAP strategy. In this case the telescope follows the sidereal motion and the target is captured as a streak even for short exposures of 200 milliseconds used in our campaigns. Typically, we have only one position of the object at the given star field, because during the image download the object leaves the FOV. The celestial coordinates of the target are measured manually by the LEOAstrometry tool developed at Teplice Observatory. The tool can be used also for manual measurements of very faint debris targets that cannot be recognized automatically by ASAP.

4.3 NEO Observations

Observations of NEOs can be processed automatically with ASAP or manually using Astrometrica [2]. So far all minor planet astrometry was performed by Astrometrica. We have successfully used the "Track and Stack" method implemented by Astrometrica for fast moving objects detection, and the detection limit for such objects was increased up to 20^m. The automatic NEO processing with ASAP will be tested during 2019.

5 RESULTS

5.1 SST Observations

In the last campaign performed from May 20 to May 29 2017, the SHOT sensor performance has been verified by ESA. We observed intensively 6 different MEO and GEO targets (satellites and debris objects). In total, 270 tracklets in the standard TDM format (Tracking Data Message) and 3173 astrometric positions were obtained. Analysis of GPS data shows that the standard deviation of residuals relative to the reference SP3 orbit is about 1 arcsec after accounting for the time bias of 54.4 ± 3.6 ms due to the shutter latency.

During the same campaign we observed also LEO targets (two NOAA 11 space debris objects and Sentinel 2A and 2B satellites). In total 30 passes/tracklets and 318 astrometric positions were obtained. The comparison of Sentinel 2A batch orbit relative to the reference SP3 orbit shows, that after accounting for the time bias of 56.71 ± 0.15 ms, and the elevation bias of $-0.002273°$, the results are well within the accuracy envelope for LEO orbits defined in the SST System Requirements Document (i.e. 40 m radial, 200 m along track, 100 m cross track).

5.2 NEO Observations

In March 2015 we started CCD astrometry of minor planets and comets, and we received the observatory code K62 from the Minor Planet Center. In 2015 we published 103 astrometric positions of Near Earth Asteroids (NEAs), comets and other unusual objects in 21 Minor Planet Electronic Circulars (M.P.E.C.). With a 4-min exposure we are able to measure precise positions of objects as faint as 20^m. Using the method of CCD images stacking, we can reach this limit also for faster moving asteroids. We detected small (5-m in diameter) asteroid 2015 GL13 in the distance of about 500,000 km from Earth and a space debris object with the designation WT1190F a day before it entered the Earth's atmosphere on 13th November 2015. The total residuals of our published observations show that the accuracy of astrometric positions is better than 1 arcsec in 92% of cases and that it is not worse than 2.1 arcsec for all published positions (103 astrometric positions).

6 FUTURE DEVELOPEMENT

There is a continuous development of the SHOT sensor. The dome shutter opening will be driven electrically by the end of January 2019, so an assistance of the observer will not be necessary and the shutter will automatically close in the case of bad weather conditions. A new SHOT control software has been developed and tested. It includes the accurate time determination, a better graphical user interface and increased autonomy of the observation. The future development of the software will focus on automatic processing of scheduling messages, automated LEO and NEO astrometry and automatical handling with output messages.

7 CONCLUSIONS

The SHOT sensor is intended mainly for satellite and space debris observations, but it can be used also for NEO follow-up observations. It allows observation up to 20 different fast moving objects per hour. The target brightness limit for MEO/GEO observations and their automated processing using ASAP is approximately 16^m. Weaker MEO/GEO objects up to approximately 18^m can be processed manually with our astrometric tool. For LEO targets the limiting magnitude is about 12^m, for NEOs about 20^m. The sensor's hardware and software is under continuous development and many improvements are planned in the near future. The SHOT sensor is now in permanent operation, available anytime the weather conditions allow observations.

8 REFERENCES

1. Network Time Protocol Documentation, http://www.ntp.org

2. Raab, H.: http//www.astrometrica.at