IAC-07-A6.I.11

OPTICAL OBSERVATIONS AT THE ZIMMERWALD OBSERVATORY

Tim Flohrer

Astronomical Institute, University of Bern, CH-3012 Bern, Switzerland
tim.flohrer@aiub.unibe.ch

Thomas Schildknecht, Carolin Früh, Reto Musci, Martin Ploner

Astronomical Institute, University of Bern, CH-3012 Bern, Switzerland
thomas.schildknecht@aiub.unibe.ch
carolin.frueh@aiub.unibe.ch
reto.musci@aiub.unibe.ch
martin.ploner@aiub.unibe.ch

ABSTRACT

The Zimmerwald Observatory, located 10 km south of Bern, belongs to the Astronomical Institute of the University of Bern (AIUB). The main instrument is the 1 m Zimmerwald Laser and Astrometry Telescope (ZIMLAT) that is used for satellite laser ranging observations (SLR) and for optical observations of Earth-orbiting satellites, in particular of space debris in high altitude orbits. Astrometric and photometric measurements, as well as light-curves are acquired while performing optical observations. Additionally, minor planets and Near-Earth objects (NEOs) are in the observation schedule. ZIMLAT is operated every night if weather permits.

With the observations acquired at Zimmerwald AIUB ensures the necessary follow-up observations of space debris objects discovered during the ESA surveys performed at the ESA Space Debris Telescope (ESASDT) on Tenerife. Beside this, the AIUB provides observations from the Zimmerwald Observatory to the Pulkovo cooperation of optical observers (PULCOO).

In this paper we present the optical facilities at Zimmerwald, discuss their capabilities and the instrumental constraints. We further give a brief overview of the processing steps and outline the procedures of planning follow-up observations. Special attention is paid to the high degree of automation that is reflected in the statistics of the observations of the recent years.

By exemplary cases we show results from typical observations. One example is the determination the orbital elements of objects with high area-to-mass ratios that are kept in a catalogue at AIUB. Those objects are usually discovered with the ESASDT and the immediate use of the Zimmerwald facilities is mandatory in order to secure the first orbits and to maintain the catalogue. For the acquisition of light-curves and photometric observations ZIMLAT is well suited, but due to the narrow field-of-view accurate a priori orbit information is needed. We show light-curves of a high area-to-mass ratio objects as second example.

FULL TEXT

1. Introduction

In this paper we present the optical facilities at the Zimmerwald observatory. Starting with a very brief history of the observatory, we discuss capabilities of the current main optical instruments. We outline the planning-observation-processing loop that is executed daily, present the current status of the routine observation campaigns, and introduce the monitoring of the operation performance. Exemplary results from typical observations are shown at the end of the work.

2. History

The Zimmerwald observatory is located at an altitude of about 950 m at 46.9 deg North, 7.5 deg West, which is about 10 km south of Bern, Switzerland. The Zimmerwald observatory belongs to the Astronomical Institute of the University of Bern (AIUB).

Zimmerwald observatory was built for optical observations, such as surveys for supernovae, novae, minor planets, and variable stars. The 50th anniversary of the observatory was celebrated in 2006.

The first major milestones in its history is set in 1959 by the installation of the “old” main instruments, a combined 40/62 cm Schmidt and a 60 cm Cassegrain telescope. The surveys carried out in the following decades, utilizing the 6 deg field-of-view Schmidt telescope were highly successful. The discoveries list contains 49 supernovae, 3 novae, 97 minor planets, and 7 comets (including comet Wild-2, the target of NASA’s Stardust mission).

In the mid 1960s the work in the field of satellite geodesy was established to contribute to the optical observations of passive Earth-orbiting satellites.

Since 1970 satellite laser ranging (SLR) has been carried out at Zimmerwald. For these observations a new building was erected, housing a dedicated 50-cm Cassegrain instrument. The Swiss Federal Office of Topography (swisstopo) has been supporting the SLR observations in Zimmerwald since 1992.

Between 1995 and 1997 a new telescope was installed at Zimmerwald, replacing the 50-cm Cassegrain. This new 1-m multipurpose instrument (Zimmerwald Laser and Astrometry Telescope, ZIMLAT) is unique in the world, as it allows both, SLR observations as well as optical observations. Today’s optical observations have their main focus on acquiring astrometric measurements and photometric light curves of Earth-orbiting satellites and objects in the solar system.

2006 a new annex to the observatory for atmospheric research could be inaugurated. A robotic small aperture telescope (Zimmerwald Small Aperture Robotic Telescope, ZimSMART) was installed on the roof of the new annex, complementing the optical observation capabilities of ZIMLAT.

3. Optical facilities at Zimmerwald observatory

Todays optical facilities at Zimmerwald comprise two telescopes, ZIMLAT and ZimSMART. We discuss their capabilities and instrumental constraints in this section. The telescopes are used for different purposes and thus show significantly different designs.

Both telescopes are controlled by the same software package (“ZimControl”) developed at AIUB. This software is also used to process the acquired exposures and to extract the positions of detected objects.

Figure 1: Zimmerwald observatory during installation of ZimSMART in Spring 2006.

3.1. ZIMLAT

ZIMLAT (see Figure 2) is a Ritchey-Chrétien telescope on horizontal mount. The telescope is equipped with a derotator platform, which allows using 4 optical detectors. A so-called derotator mirror directs the light path to one of the detectors. Switching between the individual detectors can be done within a few seconds. The primary focal length of ZIMLAT is reduced by optical systems mounted in front of the detectors. For optical observations a system with a focal length of about 4 m and a field of view of 40 arcmin is used.

The optical detector used most of the time is a backside-illuminated CCD Camera with an e2v 4240 Chip. The chip size is about 27 x 27 mm, which corresponds to an effective field of view of 21 arcmin. The pixel size is 13.5 µm, equivalent to a pixel scale of about 0.7 arcsec/pixel. The detector is read out in about 40 s. Applying 2 x 2 binning can significantly reduce this time. The resulting degradation of the astrometric accuracy is usually negligible, due to the seeing conditions. A filter wheel allows observations in different wavelengths reaching from blue to infrared. Switching of the filter can be done within a few seconds controlled by the telescope software. A special shuttering mode ("smear mode") was developed to register the exposure epoch with an accuracy of about 1 ms. An error of about 7 ms corresponds to an along-track error of 0.1 arcsec for objects in geostationary orbits.

A Proline 16803 CCD Camera (PL16803) from Finger Lakes Instrumentation (FLI) is installed at another derotator port, mainly used for test purposes. The focal length of this optical configuration is 8 m and the resulting field of view is about 15 arcmin. The CCD Camera has a Kodak KAF-16803 chip with a size of 37 x 37 mm and a pixel size of 9 µm. The CCD chip is frontside-illuminated and has micro-lensing implemented, with a quantum efficiency of about 60%. The whole 4 k x 4 k frame can be read out within 3 to 16 seconds depending on the selected readout speed. Currently, no exact epoch registration is available due to the fact that no "smear mode" is implemented in the camera. Tests of the accuracy of the epoch registration show that the epoch registration accuracy is better than 10 ms. This result was obtained by comparing the optical observations to microwave observations of GNSS satellites.

To control SLR operation during nighttime one port of the derotator platform with a focal length of 1.2 m is used. At this port a PCO 2000 CCD Camera with 1280 x 1024 pixel and a pixel size of 6 µm is used. This camera allows very fast exposure times and can operate in a quasi video mode with an frequency of about 5 Hz.

With the ZIMLAT telescope and the e2v camera the astrometric accuracy is about 0.1 arcsec depending on the brightness of the object and seeing conditions. This value will decrease to about 0.5 arcsec at the limiting magnitude of the optical system (20.5 mag). We use reference stars of the catalogues Hipparcos, Tycho2, UCAC2 and USNOB1.0 for the astrometric reduction, where we determine pointing direction, scale and orientation using a least square adjustment. Higher-order terms of the mapping function are estimated using special mapping series. The obtained parameters are then applied to all exposures during processing.

ZIMLAT provides a high pointing and tracking accuracy of the instrument's (1-2 arcsec absolute), primarily to ensure a high number of "returns" during the SLR operation, even for slow objects. If weather permits, ZIMLAT can be operated 24 h, during daytime for SLR-observations exclusively. Nighttime operation is shared between SLR and optical observations based on selectable priorities. The switch from SLR configuration to the configuration for optical observations takes about 30 s, so that both modes may be used nearly in parallel. ZIMLAT is considered as being quasi-operational system.

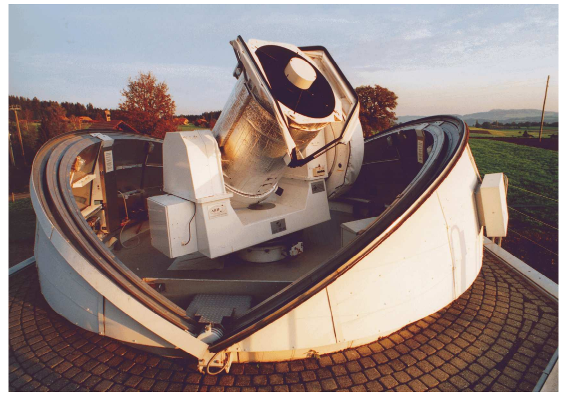

Figure 2: 1 m ZIMLAT telescope

3.2. ZimSMART

ZimSMART (see Figure 2) was built-up from commercially available components (COTS). The telescope is a Takahashi Epsilon-180 (hyperbolic astrograph), mounted on a Paramount ME (German-equatorial) from SoftwareBisque. The camera is a PL09000 camera from FLI. The 3056 x 3056 pixel resolution Kodak KAP-09000 chip is a front-illuminated device with micro-lensing technology. The high quantum efficiency of about 65% is a result of this new technology. The pixel size of 12 µm corresponds to a pixel scale of about 5 arcsec. The maximum data rate for full frame exposures images is 8 MHz. To reduce the readout noise to about 10 electrons the camera is operated with a readout speed of 1 MHz normally, with readout within 12 s. For focusing the telescope is equipped with a Precision Digital Focuser (PDF) manufactured by FLI. Currently no filter wheels are available. The accuracy of the pointing of the telescope is about 20 arcsec. A more accurate mount model could potentially improve this value. All components (telescope, focuser, camera and dome) are controlled by the software package "ZimControl". Additional data (temperature, pressure and humidity) are received from the central meteo sensors of the observatory. A rain sensor ensures that the clamshell dome manufactured by Astrohaven closes if rain appears. ZimSMART has its limiting magnitude around 16. In summer 2007 we consider ZimSMART as nearly operational, as we are able to acquire and process pre-planned observations automatically.

Due to the quite large pixel scale of ZimSMART of about 5 arcsec the obtained astrometric positions cannot be compared with the ones from ZIMLAT. After processing, positions of reference stars are usually better than 1 arcsec, but we still observe systematic errors at the periphery of the image. Future improvements of the mapping model should result in a astrometric position accuracy of about 1/10 of the pixel scale. However, it must be kept in mind that the main tasks of ZimSMART are the search for unknown bright objects, and the acquisition of follow up observations for building up and maintaining a catalogue of space objects. For these tasks it is not necessary to reach an astrometric performance level better than a few arcsec.

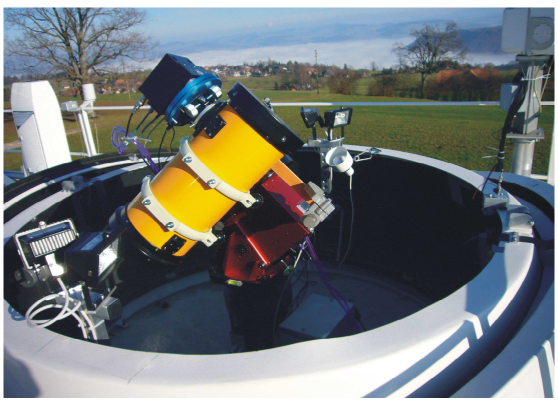

Figure 3: 0.2 m ZimSMART telescope in completely opened dome

The current aims of the optical observations at Zimmerwald are:

- Acquisition of observations of artificial space satellites and natural bodies in the solar system allowing orbit determination and orbit improvement
- Support of the build-up and maintenance of a catalogue of orbital elements for selected objects
- Timely re-acquisition of selected objects newly detected during the ESA space debris surveys at the Observatorio del Teide, Tenerife, in order to secure the orbits
- Characterization of selected objects by obtaining light curves (high-resolution variations of the apparent brightness) and by acquiring observations with color filters
- Maintenance of the high level of automation, extension of the automated performance monitoring
- Consolidation of ZimSMART as test-bed for the development, test and validation of algorithms, survey techniques, and real-time follow-up procedures

4. Planning, observation and processing outline

Planning, acquisition, and processing of the optical observations at Zimmerwald form a closed continuously executed loop. In this section we give a brief overview of this loop. The outline of the process flow for the routine optical observations at Zimmerwald observatory is presented in Figure 4.

Let us start with the orange box, representing the data acquisition at Zimmerwald observatory. Both telescopes acquire data automatically according to a defined prioritization scheme. For ZIMLAT the observation time is shared with the SLR observations. The prioritization scheme is dynamical, which allows to insert or delete objects into the schedule during the observations, or to change the priority levels.

Processing of the night data (violet box) is widely automated and executed during nighttime in the background. More than 90% of the planned GEO objects larger than about 40 cm are detected automatically. Normally, position, exposition epoch, and apparent brightness are extracted from the raw data and are archived. For the faintest 10% of the objects, a manual control of the object detection is carried out, usually during the next working day.

The extracted observations are used internally to maintain the AIUB catalogues of orbital elements (pink box in Figure 4), or – if acquired in the context of collaborations – are exchanged with external partners (yellow box in Figure 4).

The updated orbital elements from the catalogues, provided from internal work or from external sources, are used to plan the observations of the next observation night (green box). In the planning we used knowledge from past observations to improve the observation schedule. In particular we pay attention to ephemeris quality, determined brightness, or whether objects were not found. Planning is usually made before the nightly observations start, but may be run during night as well (or again), if changes in the observations schedule are needed. The planning has to ensure that all data for the nightly work are in place at Zimmerwald observatory and that the observer is instructed if special actions are required.

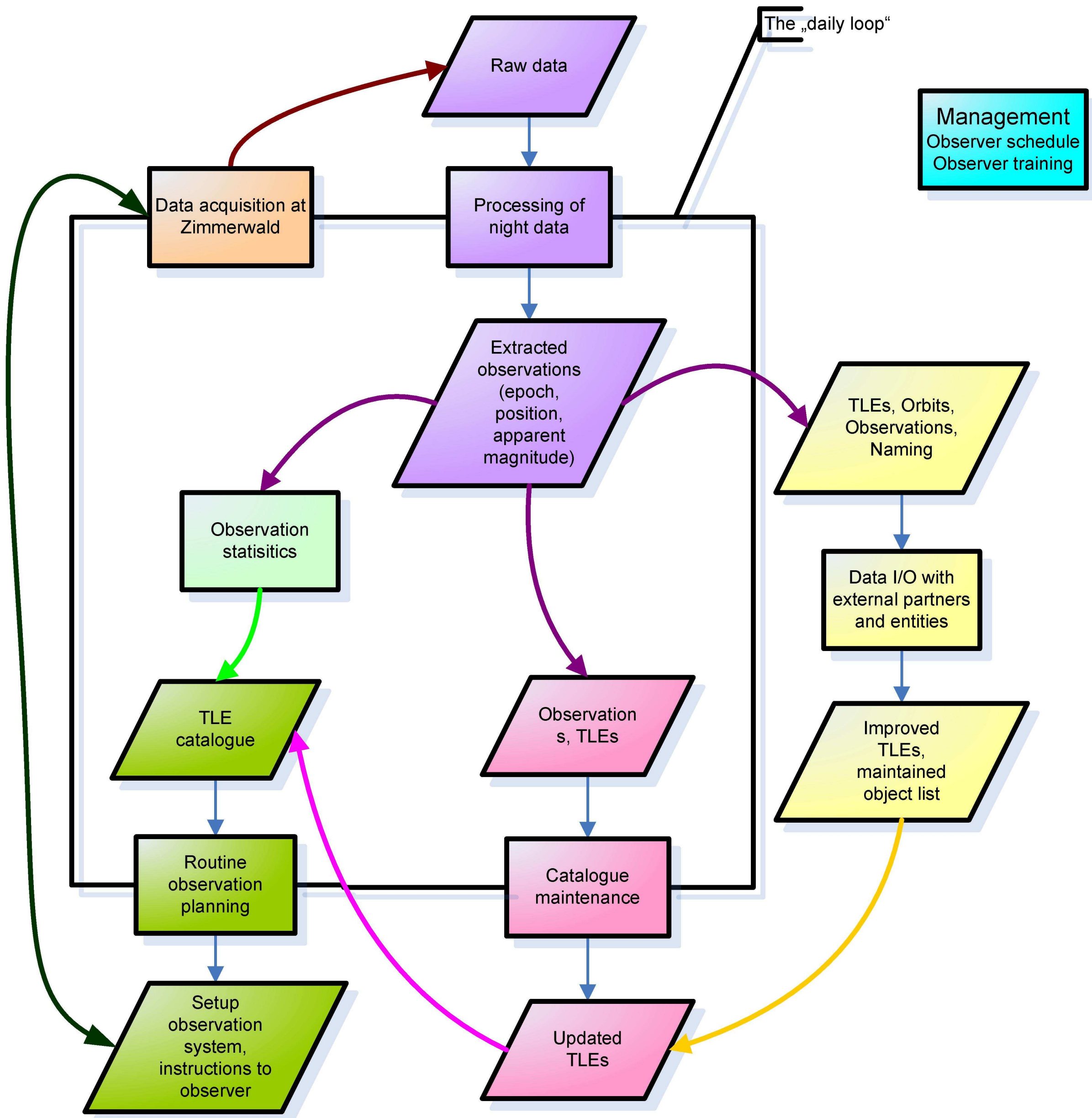

Figure 4: Process flow for the routine optical observations at Zimmerwald observatory

5. Routine observations

We may structure the current operations in Zimmerwald according to their contributions to AIUB research projects. Currently, the main work includes

- Modeling and study of space debris objects with high area-to-mass ratio in high altitudes
- Long-term monitoring and modeling of orbits of objects in GEO
- Techniques and algorithms for build-up and maintenance of catalogues
- Combination of optical and microwave observations of GNSS satellites
- Surveys for unknown objects in high altitudes
- Study of the relation between apparent magnitude and phase function
- Observation of natural bodies in the solar system (minor planets, comets, NEOs).

Students in bachelor and master courses may use the facilities in Zimmerwald in the scope of their educational projects.

A significant part of the routine observations at the Zimmerwald observatory is carried out in the framework of international collaborations. These collaborations aim to jointly monitor objects orbiting at high altitudes, in particular to study objects with high area-to-mass ratios. Collaborative observation and data exchange is needed to ensure the frequent re-observation of catalogued objects to keep the orbital elements up-to-date. Up-to-date orbital information is mandatory for further studies characterizing these newly found population (see [1]) utilizing narrow field-of-view technologies, such as radar, or spectroscopy, as well as for the acquisition of light-curves.

Collaborations exist in particular with Keldysh Institute of Applied Mathematics (KIAM) of the Russian Academy of Sciences [2], [3]. See in particular the “High Geocentric Orbit Space Debris Circulars” published by KIAM [4] for the significant contributions from the Zimmerwald observatory.

Observations from Zimmerwald are used in the framework of IADC (Inter-Agency Space Debris Coordination Committee) campaigns.

In the scope of AIUB contracts with ESA, Zimmerwald observations are used to support the ESA Tenerife surveys.

6. Performance monitoring

The performance of the Zimmerwald observations is monitored routinely. The monitoring comprises the daily check of the acquired data and the status of the installations at the observatory, but also includes post-processing analyses, allowing to (among other analyses) extract valuable information of the processing and detection performance, e.g. the allocation of telescope time, and the estimate of the probability of object loss from the catalogue if follow-ups are not carried out. As the objects observed in Zimmerwald are usually arranged in so-called campaigns according to the AIUB research projects, it is possible to break down the performance analyses campaign-wise.

The telescope time allocated to optical observations is only relevant for ZIMLAT, where the observation time is shared with SLR. Figure 5 gives the telescope time used for optical observations per night since July 2006. This plot shows that in more than 50% of all nights observations are acquired (the telescope is in “optical observation mode”). Unfortunately, due to weather conditions not all nights are so-called “full nights”, where observations are possible from dusk till dawn. In full nights, about 25% of the total nighttime is spent for optical observations in batches, which sums up to 4 h in winter and 1 h in summer. By the horizontal spacing of the impulses in Figure 5 the periods with good weather conditions (June/July 2006, November 2006, April 2007) and the periods with bad weather conditions (January 2007, June/July 2007) are indicated. In addition, periods with system outage (July/August

2006) or SLR unavailability (the 8 in March 2007) can be seen in the plot.

Figure 6 gives the number of position measurements per month, which is the second important performance figure. It is possible, but not shown here, to classify this parameter per observation campaign or per object class, or even for different time intervals than one month. A detailed analysis of Figure 6 must, however, always take into account the actual observation time. We may conclude from the plot that the very high degree of automation allows an average of more than 1300 position measurements per months. This estimated average number of position measurements has to be interpreted carefully, as it is a function of object selection, summed telescope time, and weather conditions. Faint or difficult to search for objects result in less position measurements compared to bright or easy to find re-acquisition objects. In summer the available telescope time is shorter than in winter. Weather conditions (thin clouds, etc.) or the Moon (phase and appearance) may significantly raise the detection threshold. In March 2005 the prominent peak is partly due to the mentioned SLR outage.

The impact of available telescope time, which cannot be discriminated from the prioritizations scheme and observation schedule, and the effect of the weather conditions on the observation statistic is difficult to assess. Computing a “hit ratio” of all or a subset of objects can, however, be used to monitor the effect of the object selection. An example is given in Figure 7, where the ratio between the number of successfully processed exposures and the number of exposures with identified objects is plotted for the routinely observed GNSS satellites. GNSS satellites are observed because they have accurately known ephemerides and are perfectly suited to calibrate some parts of the observation system. We use final orbits from the Center of Orbit Determination in Europe (CODE) [5], provided in an inertial frame. With one exception the hit ratio is always higher than 85%. It does not reach 100%, as objects may interfere with a star in the exposure, which prevents from measuring the object coordinates, or (thin) clouds may corrupt the exposure, which seems to happen more often in summer.

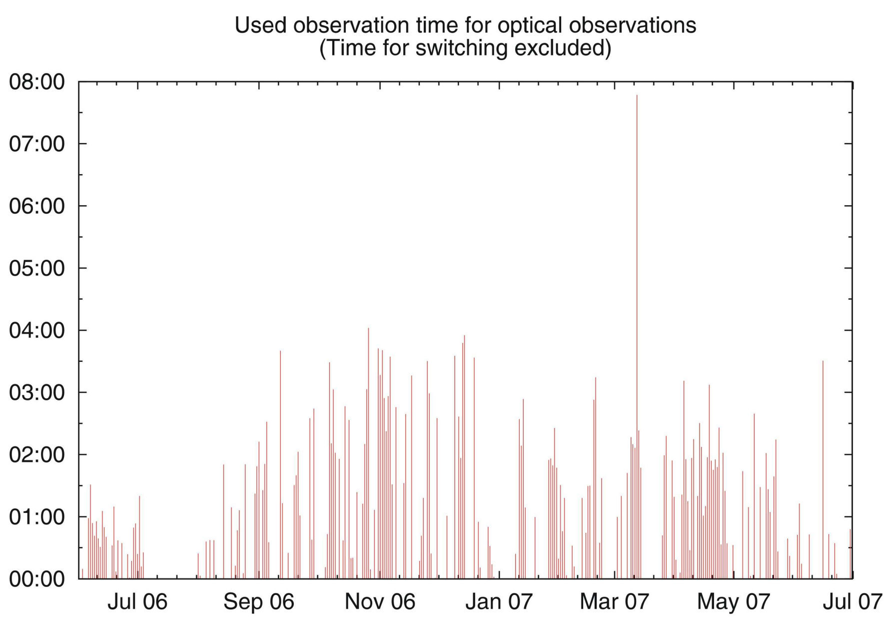

Figure 5: ZIMLAT time used for optical observations (hours per night in Zimmerwald)

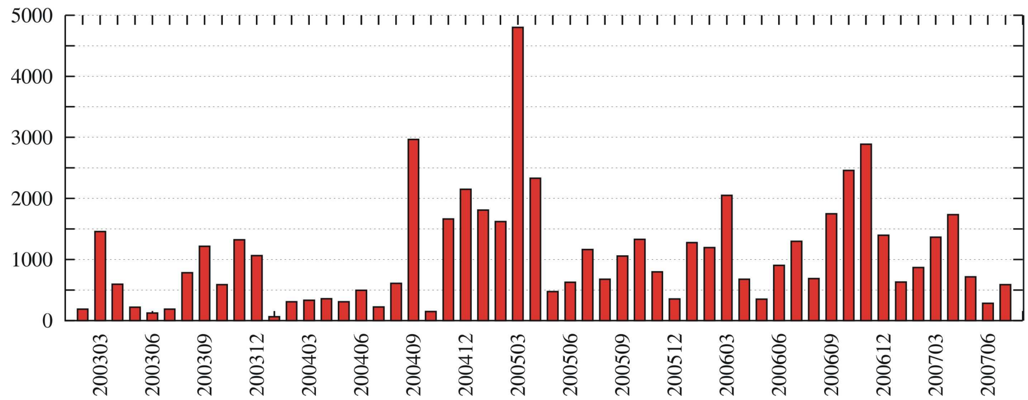

Figure 6: Successful position measurements per month, ZIMLAT only

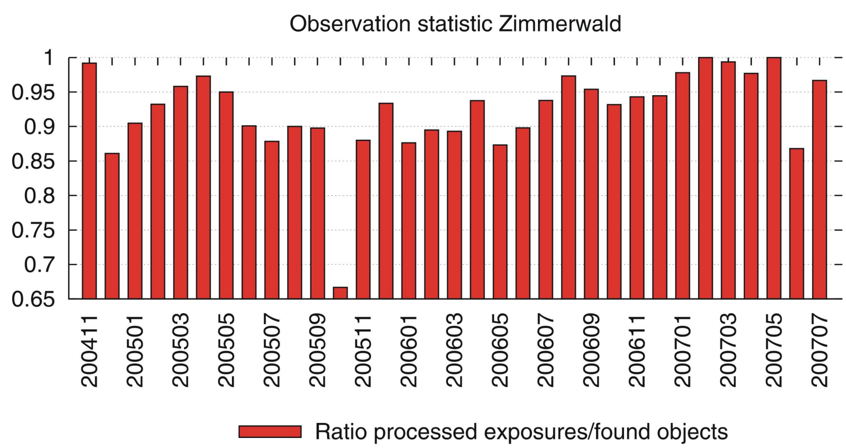

Figure 7: Hit ratio for GNSS satellites with ZIMLAT

7. Examples

By exemplary cases we show results from typical observations.

The first example is the process of determining the orbital elements of objects with high area-to-mass ratios that are kept in a catalogue at AIUB, which is one of the main goals of the acquisition of optical observations performed at the Zimmerwald observatory. Highly accurate orbits are needed for such objects in order to perform photometric observations.

The process flow of the routinely operated catalogue maintenance procedure is shown in Figure 8. The processes performed at the Observatorio del Teide, Tenerife, are indicated with blue boxes, those performed at AIUB in Bern with green boxes, while the processes performed at the Zimmerwald observatory are in red boxes. 'Semi-automated' means that a few manual interactions are necessary, e.g., to start a script, while 'automated jobs' are operated fully autonomously.

High area-to-mass objects in high altitudes are usually discovered during the surveys with the ESASDT or by facilities of collaborating partners. In this paper we focus on discoveries made with the ESASDT. The observations are processed on-site at the Observatorio del Teide and a first orbit is determined. Follow-up observations of these objects are already performed during the night of the discovery with the ESASDT. The used follow-up concept is described in [6]. All processed observations are sent to AIUB in less than one hour after the end of the observation night. The observations are extracted using a software system developed by AIUB (the same software system is used to perform the observations with the ESASDT) and are stored in the appropriate directories.

The main loop for the Zimmerwald observations is indicated in Figure 8 by bold arrows. First, an orbit determination and/or improvement is performed for all objects with new observations. Then, all available orbits in the AIUB catalogue are propagated to 0:00 UT of the following night and TLEs generated from the propagated orbits. The propagation is needed to take care of the effects related to the high area-to-mass ratio. The TLEs can be used to plan further observations with the ESASDT, with one of the Zimmerwald instruments, or with collaborating sensors.

Ephemerides have to be determined using the TLEs for the Zimmerwald observations. ZIMLAT or ZimSMART can either use these ephemerides. The observations from both instruments are automatically processed at the observatory and sent to AIUB in Bern. Merging these observations with all available observations of a specific object closes the loop.

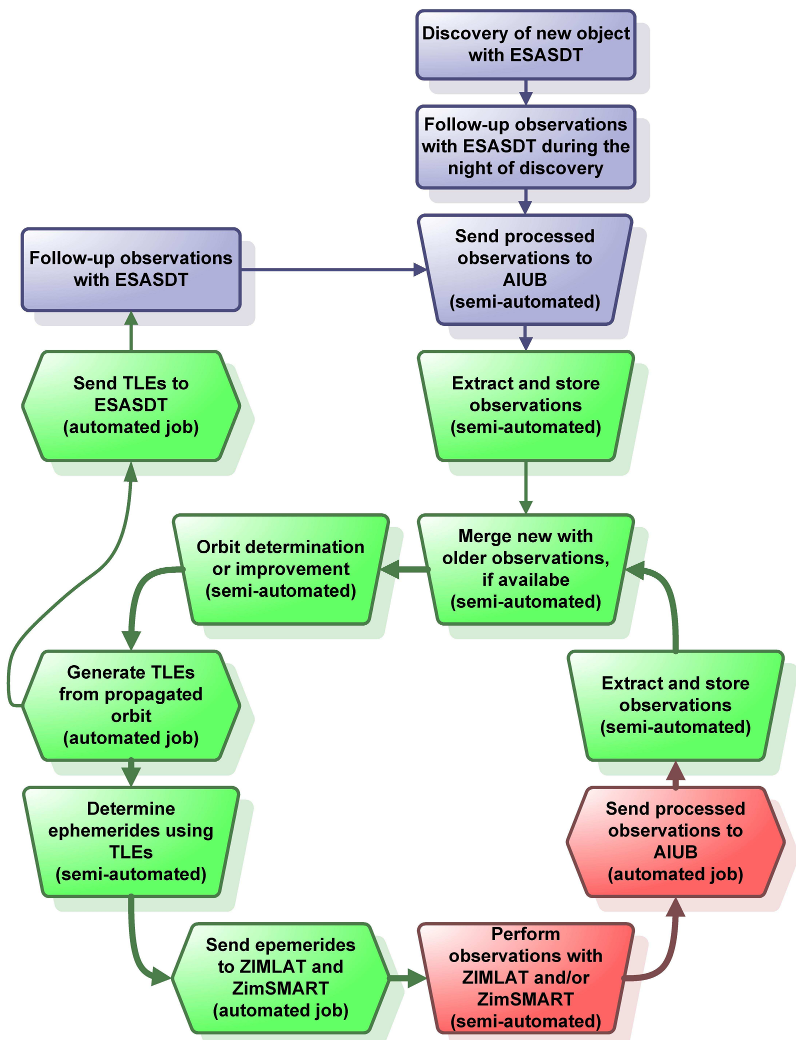

Figure 8: Process flow for the orbital catalogue maintenance procedure. The blue parts are performed at the OGS, the green parts at AIUB, and the red parts at the Zimmerwald observatory). The bold arrows indicate the main loop for the Zimmerwald observations.

In order to acquire more information on the sizes, shapes and possibly the material of the debris objects with high area-to-mass ratios, light curves are acquired with ZIMLAT. The light curves show a wide variety of signatures, ranging from periodic or random variations of several magnitudes over time spans of a few minutes to constant brightness over 10 minutes. Moreover, the behavior may change completely for one and the same object from one observation to the next. All this is indicative of randomly tumbling objects with complicated shapes.

Figure 9 shows two light curves of the object 'EGEO21'. Both light curves show significant periodic variations. However, the amplitudes and the periods of these variations are very different. The peak-to-peak variations range from 1 to 2 magnitudes and the periods from 50 to 250 seconds. The apparent magnitude of this object is highly variable – although showing distinct periodic signatures over short time spans of a few minutes - indicating an object in a random tumbling motion with a rather complex shape and probably including some highly reflective surfaces.

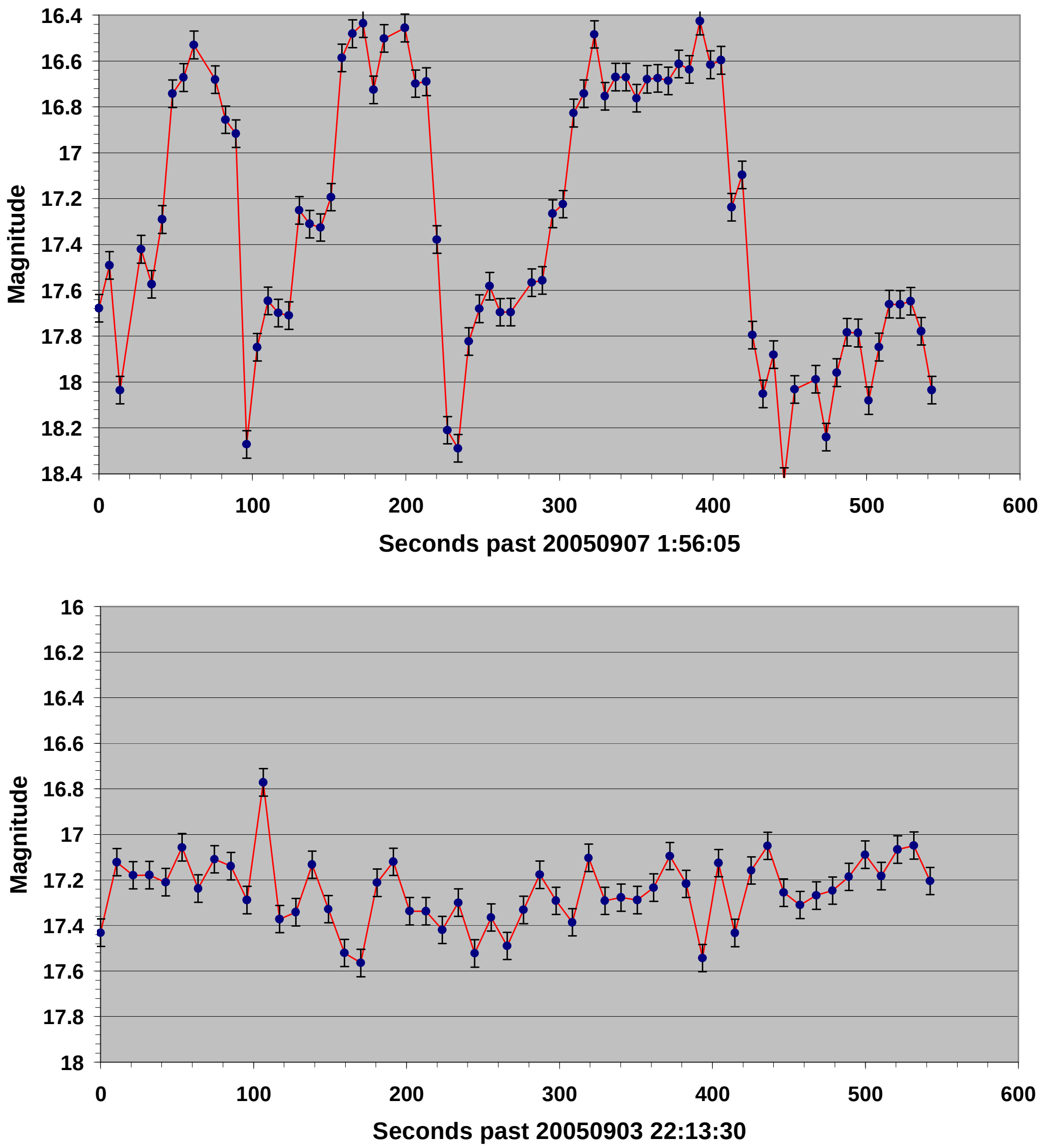

Figure 9: Two light curves of the object 'EGEO21' which has an area-to-mass ratio of 4.6 m^2/kg.

8. Conclusions

We outlined the current status of the optical observations at AIUB's Zimmerwald observatory. The capabilities and utilization of the two main instruments (the 1-m ZIMLAT and the 0.2m-ZimSMART telescopes) for optical observations were presented. Today these observations are mainly acquired to determine orbits and physical characteristics of artificial space satellites and natural bodies in the solar system. A major part of these optical observations is devoted to the necessary follow-up observations of space debris objects discovered during the ESA surveys performed at Tenerife and is also devoted to the participation in international collaborations, such as with KIAM. An outline of the planning and processing procedures was given. Special attention was paid to the high degree of automation. The attempt to highly automate the observation, planning and processing loop requires the establishment of a reliable performance monitoring. Some aspects of the assessment of the post-processing performance were presented. Exemplary cases of typical observations complete the work. The process of the determination of orbital elements of objects with high area-to-mass ratios, which are kept in a catalogue at AIUB, was presented, as well as the acquisition of light-curves and photometric observations with ZIMLAT.

9. Acknowledgements

The Swiss National Science Foundation through grant 200020-109527 supports the optical observations at the Zimmerwald observatory.

References

[1] Schildknecht, T., Optical surveys for space debris, Astronomy and Astrophysics Review, Vol. 14, pp. 41-111, 2007, doi: 10.1007/s00159-006-0003-9.

[2] Agapov, V., T. Schildknecht, E. Akim, I. Molotov, V. Titenko, and V. Yurasov, Results of GEO space debris studies in 2004-2005, 57th International Astronautical Congress, October 2 – 6, 2006, Valencia, Spain, IAC-06-B6.1.12.

[3] Molotov, I., V. Agapov, V. Titenko, Z. Khutorovsky, Yu. Burtsev, I. Guseva, V. Rumyantsev, M. Ibrahimov, G. Kornienko, A. Erofeeva, V. Biryukov, V. Vlasjuk, R. Kiladze, R. Zalles, P. Sukhov, R. Inasaridze, G. Abdullaeva, V. Rychalsky, V. Kouprianov, O. Rusakov, E. Litvinenko and E. Filippov, International scientific optical network for space debris research, Advances in Space Research, In Press, 2007 doi:10.1016/j.asr.2007.04.048.

[4] Akim E. L., V. M. Agapov, I. Ye. Molotov, High Geocentric Orbit Space Debris Circular, Issue 1-4, 2007, see http://lfvn.astronomer.ru/main/report.htm.

[5] Hugentobler, U., S. Schaer, G. Beutler, H. Bock, R. Dach, A. Jäggi, M. Meindl, C. Urschl, L. Mervart, M. Rothacher, U. Wild, A. Wiget, E. Brockmann, D. Ineichen, G. Weber, H. Habrich, C. Boucher, CODE IGS Analysis Center Technical Report 2002, Bern 2002.

[6] Musci, R., Identification and Recovery of Objects in GEO and GTO to Maintain a Catalogue of Orbits, PhD thesis, 2006.