PHOTOMETRY OF SPACE DEBRIS AT THE ASTRONOMICAL OBSERVATORY OF CASTELGRANDE IN 2019–2021

Sergei Schmalz(1), Filippo Graziani(2), Riccardo di Roberto(2), Vladimir Kouprianov(3, 4), Vladimir Lopachenko(1), Viktor Voropaev(1)

(1) Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences, Miusskaya Sq. 4, Moscow, 125047, Russian Federation, Email: sergiuspro77@gmail.com
(2) GAUSS Srl, Via Sambuca Pistoiese 70, Rome, 00138, Italy, Email: info@gaussteam.com
(3) University of North Carolina, Department of Physics and Astronomy, 120 E. Cameron Ave., Phillips Hall CB3255, Chapell Hill, NC 27599, United States, Email: v.kouprianov@gmail.com
(4) Central Astronomical Observatory of the Russian Academy of Sciences, Pulkovskoye Chaussee 65, Saint-Petersberg, 196140, Russian Federation

ABSTRACT

We present recent results of and current work on photometry of artificial satellites at the Astronomical Observatory of Castelgrande (Italy) in 2019–2021. Results of Falcon 9 R/B and Atlas 5 Centaur R/B long-term photometry. Preliminary results of Intelsat 29E long-term photometry. On-going photometry of decaying space debris. Development of photometry software for analysis of rotation period and rotation axis orientation. Development of a new database for artificial satellite photometry. Theory of a light curve modelling method with Blender 3D.

1 CASTELGAUSS PROJECT / ISON-CASTELGRANDE OBSERVATORY

Upon the installation of the observatory in the end of 2014 in a rural area at 1250 meters altitude, rougly 7 km north-east from the Comune of Castelgrande within the Province of Potenza in the South Italian Region Basilicata, the regular work of the observatory had been started in September 2017 as CastelGauss Project, which is a collaboration of an Italian private company GAUSS Srl (*Group of Astrodynamics for the Use of Space Systems*) [1, 2], of the Castelgrande municipality and of the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences (KIAM RAS).

The observatory site, its equipment, the telescope control and image processing software as well as the first observation results had been described in [3]. Since then an new 2-m Scopedome cupola (Fig. 1) has been installed in October 2019, and since November 2020 the former CCD camera had to be replaced by a FLI CCD PL16803 (CCD size – 4096×4096 pixel, pixel size – 9 micron, FOV – 4×4 degrees); the planned installation of a new 35-cm telescope for observations of faint space debris is still pending due to the current pandemic situation; the planned installation of a Starlight Xpress Oculus 180 all-sky camera for observations of meteors and space debris re-entry is scheduled to be finished in May 2021.

Figure 1. View of the ISON-Castelgrande Observatory (top, front) with its 2-m and 3-m domes together, and of the 22-cm telescope (bottom) of the observatory.

2 PHOTOMETRY SOFTWARE

2.1 APEX

In order to address the needs of photometric observations, a new Python script *apex_geo_lightcurve* has been written and added to the APEX software package [4, 5], which is in use at the observatory for

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image processing and analysis. Since its first version in December 2018 the script has undergone a substantial development. Its current version provides the user with the following functionality:

- plotting of apparent brightness light curves (data input in APEX XML format) with an auxiliary phase angle axis and with optional magnitude errors
- user choice for phase angle calculation based either on topocentric equatorial coordinates of the target and of the Sun (assuming co-linearity of the Sun-target and Sun-observer vectors), or on the target orbit (including TLE orbit format)
- calculation of absolute brightness reduced to arbitrary target phase angle and observer-target distance
- automated search of brightness periodicity either by the Lomb-Scargle Periodogram (LSP) [6, 7] (imported from the Astropy package [8]) or by the Phase Dispersion Minimization (PDM) (imported from the PyAstronomy package [9]) with a full user control over input parameters required by the both algorithms, including the period search range
- plotting of reduced brightness light curves folded to a period either found automatically or set by the user
- manual interactive period search directly in the folded light curve plot (the plot is being immediately updated while using a slider to change the period within a selected period range)
- user choice of a factor for automated calculation of the rotation period when its value is a multiple of the light curve period
- manual interactive deletion/restoration of data points directly in apparent and reduced light curve plots
- customization of plot features (title string, brightness axis range, filter designation, tick step size on phase angle and time axis, image resolution, phase angle and period value precision)

Photometric image processing by APEX gives the user a variety of options: choice of photometry flux type (PSF, aperture, full, pixel), several aperture shapes (circular, elliptic, rectangular), different reference star catalogues (e.g. UCAC, APASS, GAIA, USNO), some reference star selection criteria (saturation, SNR, brightness).

On-going improvement of the APEX package will include:

- trail photometry (currently we use AstroImageJ [10] for this purpose)
- wavelet analysis
- selection of photometric GAIA DR3 reference stars by their BP-RP color index (selection of solar type reference stars)
- automated calculation of the period error
- processing log file output with full details, including min/max/mean of the SNR and brightness error, etc.

2.2 Blender 3D

In support of real data acquisition through photometric observations we intend to develop and implement a method of light curve modelling by using the Blender 3D software [11]. The idea of the method consists in: creation of a 3D model of an artificial satellite, illumination of its surface by the source of simulated sunlight (already available in Blender 3D), application of arbitrary rotation period and attitude of the 3D model and, finally, read-out of instrumental brightness of the 3D model at arbitrary temporal resolution (time steps) on the basis of pixel values of the observed surface of the 3D model from any observer position in relation to the 3D model and to the source of light. Since Blender 3D is entirelly written in Python, it is supposed to use a custom written Python script to read out the pixel value data. Light curve modelling will assist analysis of observed real data and help to better determine the real attitude of observed objects.

2.3 Axis orientation

Another approach to determine the attitude of an artificial satellite is a custom written software in development which uses real data measurements in XML format produced by the APEX package in combination with orbital data and object shape model (Fig. 2).

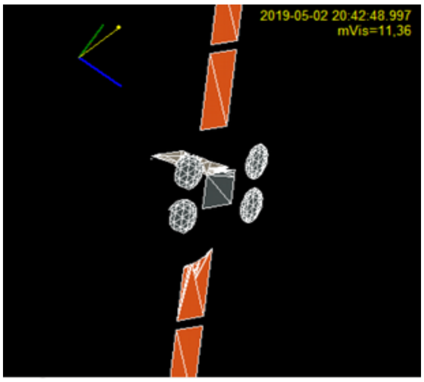

Figure 2. Model of the Intelsat 29E satellite.

3 PHOTOMETRIC OBSERVATIONS (CASE STUDIES)

Regular photometric observations of artificial satellites mostly in HEO/MEO/GEO have been started at the Astronomical Observatory of Castelgrande in February 2019. All observations so far have always been performed without any filters; installation of the second telescope will make colour photometry possible. The majority of observed objects belong to three categories: defunct satellites in GEO, upper stages in HEO and decaying objects in HEO. Other object families, e.g. ARIANE 5 DEB (SYLDA), are under way.

3.1 Defunct GEO objects

During April 7–18, 2019 the geostationary communication satellite Intelsat 29E (NORAD 41308) suffered a major anomaly and its control has gone lost. From April 24, 2019 onwards we've started a photometric observation campaign which still continues. Thanks to the collaboration between the Astronomical Observatory of Castelgrande with other observatories (particularly of the ISON network and of the Arkhyz observatory of the Research and Production Corporation Precision Systems and Instruments) we have finally managed to organize and conduct temporally dense follow-up observations with a full GEO coverage worldwide.

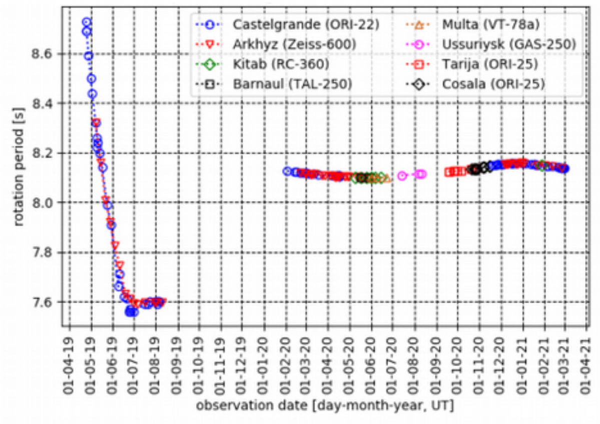

Figure 3. Rotation period change of Intelsat 29E (NORAD 41308).

The major goal of the campaign for Intelsat 29E is to keep track of how its rotation period changes (Fig. 3) and to analyze the influence of the GEO environment on this change, specifically, to investigate further the possible YORP effect which had been previously shown in [12, 13].

A dedicated publication with a full scale analysis is in preparation. Similar campaigns have already been started or are planned for other defunct object in GEO (including sub- and super-synchronous altitudes as well as the graveyard orbit), e.g. Galaxy satellites, Chinasat 9A, etc.

3.2 Upper stages

So far, three families of upper stages have been extensively observed at the ISON-Castelgrande observatory: Falcon 9 R/B, Atlas V Centaur R/B and Ariane 5 R/B. Each of these families has demonstrated its own features such as average rotation period and signatures of folded light curves.

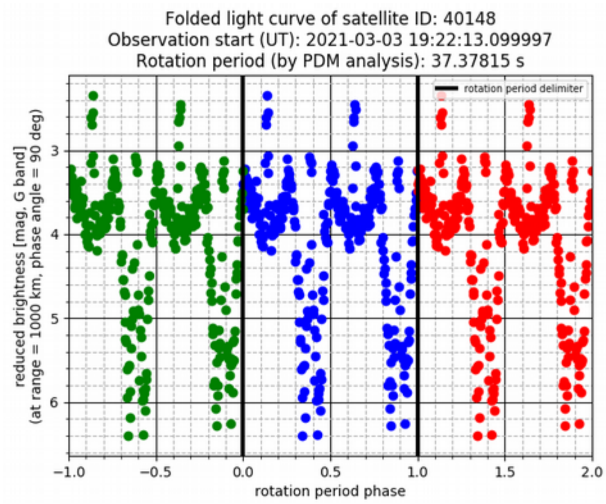

Figure 5. Folded light curve of Ariane 5 R/B (NORAD 40148).

For example, as far as rotation periods are concerned, we have determined that there are no fast rotators among Falcon 9 upper stages – rotation periods range from 40 sec to 25 min (roughly 75% of them with periods more than 2 min); most of their rotation periods grow with time, but a few ones have decreasing rotation periods. Ariane 5 R/B family on the contrary consists mostly of fast rotators – 1/3 of them with rotation periods less than 3 sec, 2/3 of them with rotation periods less than 10 sec (Fig. 4); all of them exhibit almost linear growth of rotation periods.

As for the signatures in folded light curves, we've found very distinctive features in Ariane 5 R/B. The maxima of brightness regularly show a relatively small deep, which sometimes exhibits a sharp flash (Fig. 5). This complex curve shape is entirely absent in folded light curves of Falcon 9 R/B and Atlas 5 Centaur R/B which mostly have a rather simple sinusoidal shape. The only common feature for all three families is a very short flash at the global minima of brightness.

A publication with a full-detailed comparative analysis is in preparation. Other upper stage families, such as

Fregat R/B, Ariane 4 R/B and others, are planned for photometric observations soon.

3.3 Decaying objects

First observations of decaying objects started at the Astronomical Observatory of Castelgrande with Tiangong-1 on March 31, 2018 as descibed in [3], but were limited to acquisition of astrometric data only. By gradual growth of competence and skills more and more interest for decaing objects evolved, as indicated through the participation in the 5th ESA International Space Re-entry Workshop. Currently, we attempt to regularly observe those medium/large size objects which have received a 60-day decay prediction message status in the Space Track database [14], as well as object with perigee height below 200 km. The above mentioned worldwide collaboration with other observatories makes it possible to follow-up object until a few days before the actual re-entry burn.

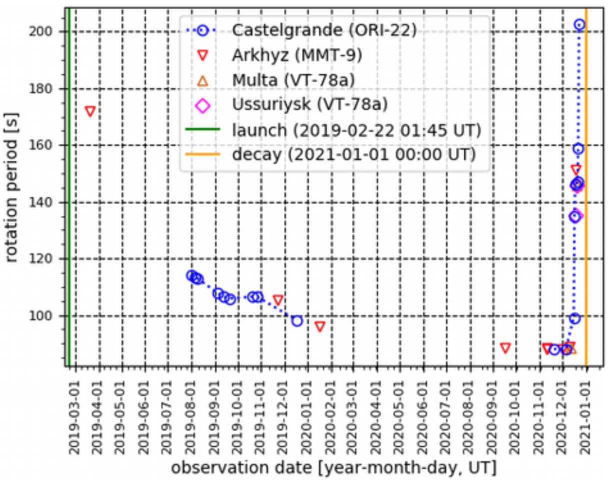

Figure 6a. Rotation period change of Falcon 9 R/B (NORAD 44050).

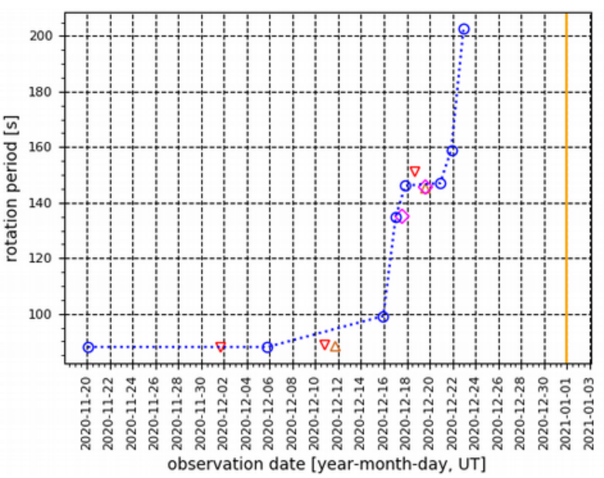

Figure 6b. Scaled view of the later part of Fig. 6a.

For example, a Falcon 9 R/B (NORAD 44050) in HEO had been observed at four observatories over a period of almost two years between the launch and decay dates. This upper stage demonstrated a rather rare decrease (speeding up) of its rotation period (Fig. 6a) during its initial orbital life, which is an inverse behaviour compared to the majority of upper stages of this family. Only after its perigee height dropped below 200 km it showed a typical strong increase (slowing down) of the rotation period (Fig. 6b).

A dedicated publication on observed decaying objects is in preparation.

4 PHOTOMETRIC DATABASE WASP DB

Since February 2019 photometric data for over 250 artificial satellites and space debris in LEO/MEO/HEO/GEO has been collected at the Astronomical Observatory of Castelgrande. To share this data with the international scientific community a new open & free for use photometric database WASP DB (World Artificial Satellite Photometry Database) is being developed at KIAM RAS.

To make WASP DB compatible with the software already in use and in development, it will be based on PostgreSQL/Python. At the current stage, the entity-relation structure of the database (Fig. 7) has already been finished, and the user web-interface is being prepared.

The user-interface will provide immediate access to the database but with limited functionality. Each DB query will be customizable by a set of different criteria: object ID, rotation period, telescope/observatory ID, orbital parameters, etc.

To use the full range of functions a user will have to accomplish a free user account registration which will technically allow additional features such as custom search in the database, automated notifications by email, data ingestion, etc. Specifically email notifications are supposed to be used by observers who need to be notified when some object of interest has to be re-observed according to the use-specified criteria. Also, email notifications will alert a user about new objects/observations added to the database.

Each object entry in WASP DB will include: object data (name, orbital information, last known rotation period, etc.); a list of single observations; a web-link to the same object in other open photometric databases (e.g. MMT DB [15, 16]), if available.

Each observation entry will include: information on observation method, observation processing, observation equipment, observation quality, processing results, raw data, etc.

The first data release DR1 for over 200 objects is planned by the end of the second quartal in 2021.

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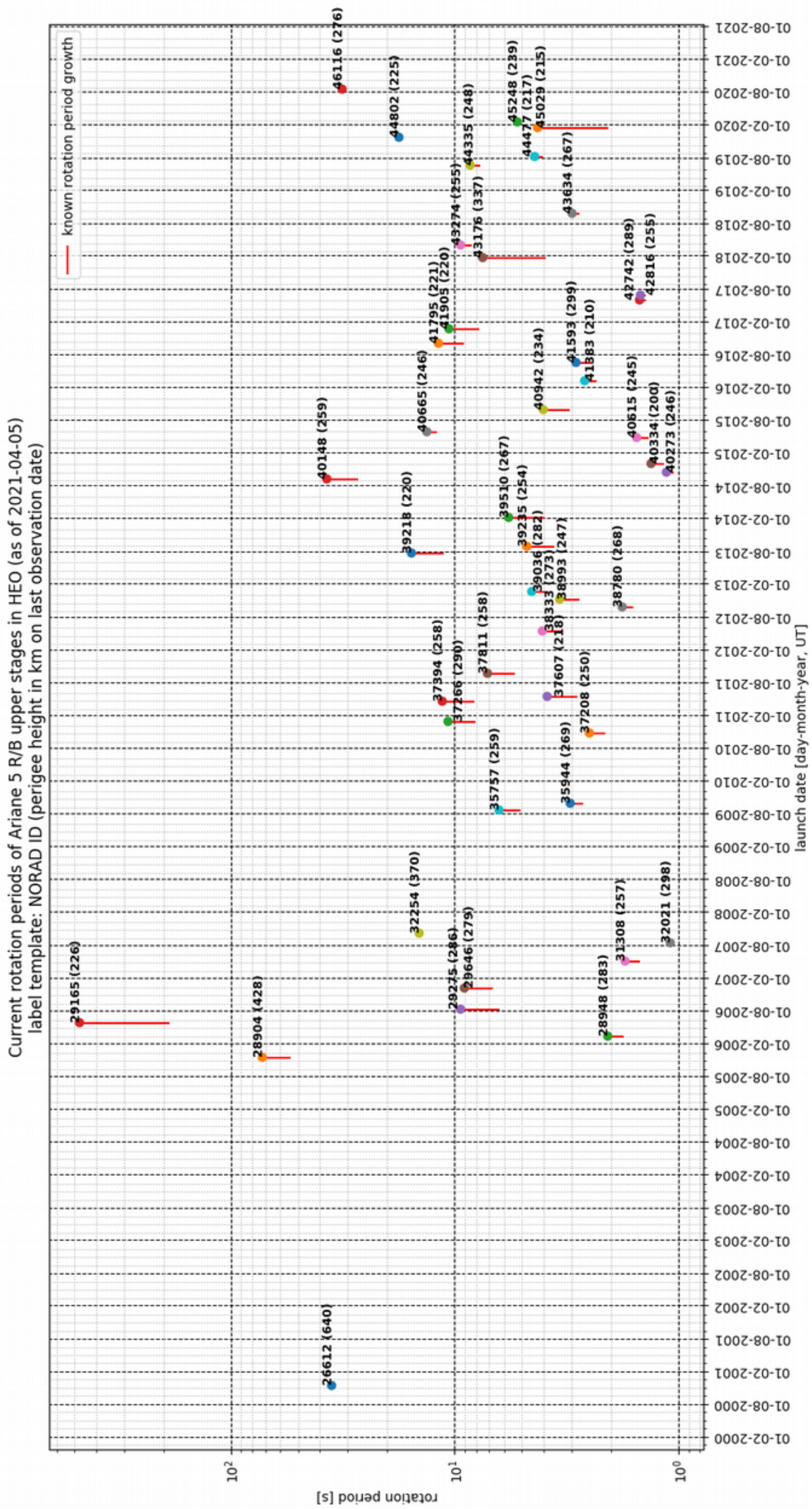

Figure 4. Rotation periods of 44 Ariane 5 R/B.

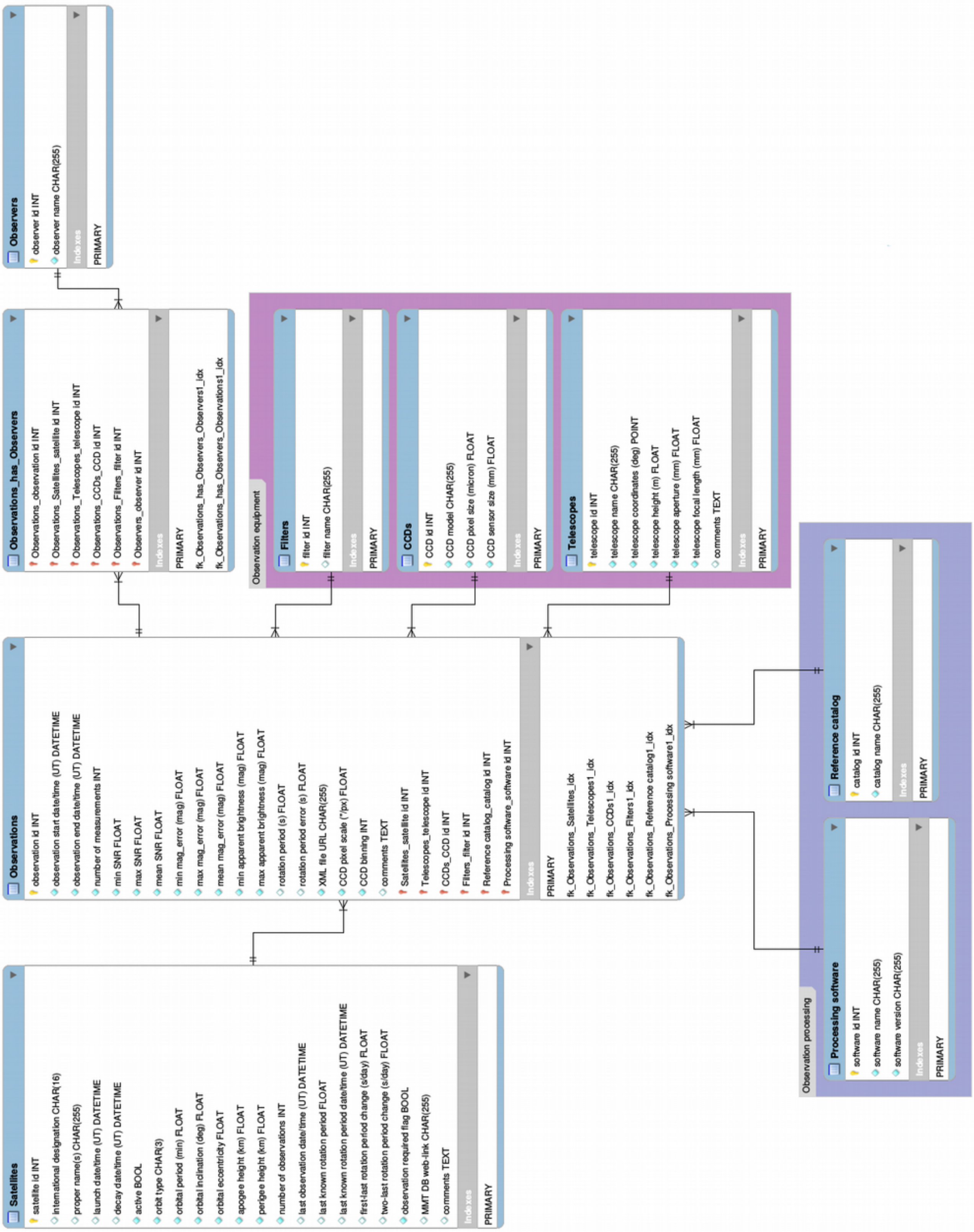

Figure 7. Entity-relation diagram of WASP DB.