Deliverable 5.6

H2020 COMPET-05-2015 project "Small Bodies: Near And Far (SBNAF)"

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Lead Author	Pablo Santos-Sanz, IAA-CSIC, psantos@iaa.es

WP5 Ground based observations
Objectives: To obtain auxiliary ground-based observations for the SBNAF sample objects: time series (lightcurves), astrometric measurements, occultations and absolute photometry.

Description of deliverable

Very brief description of the different observational techniques used to obtain auxiliary data of the SBNAF targets and applications of all these observational data. A list of works (published or in preparation) related to each observational technique within the SBNAF project is provided. This list will be updated for the subsequent deliverables: “D5.7 Observational publications 2” and “D5.8 Observational publications 3”.

Contents

1 Time series observations

Time series observations are designed to obtain the brightness variability of any target with time. In the particular case of solar system atmosphereless objects this brightness variability is directly related to the rotation of the body and can be due to an irregular shape of the object or to regions with different albedo on the object's surface. From these kinds of time series observations it is possible to derive the rotational period of the object and the peak-to-peak amplitude of the lightcurve. Many high-quality, densely sampled lightcurves obtained at different epochs combined will lead to shape and spin-vector solutions for the object. In the framework of the solar system minor bodies these time series are usually referred as rotational lightcurves, or simply 'lightcurves'. This technique is working for NEAs, MBAs, Centaurs and TNOs (see Fig. 1 in Müller et al. 2017).

1.1 Brief description of the technique

This observational technique needs one or several dedicated telescopes to observe the target enough time to determine its rotational period (lightcurve). The minimum observing time required is equal to the whole rotational period, but times larger than this are usually needed in order to avoid technical problems or other issues due to bad meteorology, changes in the sky conditions, etc. The telescopes observe the target one or various nights then the images are processed and analyzed to obtain object flux variation with time. The measure of the object fluxes are usually obtained relative to several (non-variable) background stars located in the same field of view (FOV) of the target (i.e. relative photometry) in order to correct for sky transparency and seeing fluctuations that could ruin the photometry. Subsequent analysis of these data allow to obtain a rotational period by means of different period searching techniques. For a more detailed description of this technique see Warner (2006) and Pravec et al. (2002).

1.2 Applications

As has been described, time series observations are used to obtain time series photometry (lightcurves) from which we can obtain the rotational period of the object. These rotational periods, together with the amplitudes and "features" of the lightcurves, are used as input to obtain shape models via lightcurve inversion techniques (WP6, Durech et al. 2015, Santana-Ros et al. 2017 and references therein). Apart of the lightcurves obtained from ground-based facilities we are also working with lightcurves obtained from space-based observatories, like the thermal lightcurves of a few TNOs and Centaurs obtained with Herschel and, most recently, we are obtaining long-time sampled (uninterrupted) lightcurves with Kepler K2 mission for some small bodies of special interest for SBNAF project.

These observational lightcurves are used in all SBNAF works that include new shape model determinations or improvements in former shape models. These data are also included in dedicated lightcurve papers (e.g. the particular case of TNOs or Centaurs, or other small bodies with lightcurves of special interest). Results derived from time series observations are, then, published within research papers, or presented in international conferences. We also try to make the data available in various public data bases like PDS[1], MPC[2], CDS[3]… e.g. for Müller et al. (2016) we provided the data also to CDS on request from Astronomy & Astrophysics (see last sentence in the next section).

1.3 List of related works

List of works related to time series measurements acquired in the SBNAF context at date 31-March-2017. A list of SBNAF-related measurements is included for

[1] PDS: The Planetary Data System https://pds.nasa.gov/
[2] MPC: Minor Planet Center http://www.minorplanetcenter.net/iau/mpc.html
[3] CDS: Centre de Données astronomiques de Strasbourg: http://cdsweb.u-strasbg.fr/

each work (other publicly available data sets not related to SBNAF are often used within these publications).

- Large Halloween Asteroid at Lunar Distance, by Müller et al. 2016, A&A 598, A63
    - *3-band mid-infrared observations with ESO VLT/VISIR*
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN, La Hita)*
    - *Absolute magnitudes in V and R-bands*
- 2008 OG19: a highly elongated Trans-Neptunian object, by Fernandez-Valenzuela et al. 2016, MNRAS 456, 2354
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN)*
    - *Absolute magnitude in R-band*
- Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations, by Kiss et al. 2016, MNRAS 457, 2908
    - *Long-term optical lightcurve observations from K2, Campaign 3*
    - *Astrometric K2 measurements*
- The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids, by Szabó et al. 2017, A&A, 599, A44
    - *Long-term optical lightcurve observations from K2, Campaign 6*
    - *Astrometric K2 measurements*
- Uninterrupted optical lightcurves of main-belt asteroids from the K2 Mission, by Szabó et al. 2016, A&A, 596, A40
    - *Long-term optical lightcurve observations from K2*
    - *Astrometric K2 measurements*
- Large Size and Slow Rotation of the Trans-Neptunian Object (225088) 2007 OR10 Discovered from Herschel and K2 Observations, by Pál et al. 2016, AJ 151, 117
    - *Long-term optical lightcurve observations from K2*
    - *Astrometric K2 measurements*
- Physical properties of centaur (54598) Bienor from photometry, by Fernandez-Valenzuela et al. 2017, MNRAS, accepted
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN, NOT)*
    - *Absolute magnitude in V and R-bands*
- Hayabusa-2 Mission Target Asteroid 162173 Ryugu (1999 JU3): Searching for the Object's Spin-Axis Orientation, by Müller et al. 2016, A&A 599, A103
    - *Optical observations from ESO La Silla MPI 2.2m / GROND*
- Spectral and rotational properties of near-Earth asteroid (162173) Ryugu, target of the Hayabusa2 sample return mission, by Perna et al. 2017, A&A 599, L1
    - *Optical lightcurve observations with ESO VLT/VISIR*
    - *Absolute magnitude in V-band*
- "TNOs are Cool": A Survey of the Transneptunian Region. XII. Thermal lightcurves of Haumea, 2003 VS2 and 2003 AZ84 with Herschel Space Observatory-PACS, by Santos-Sanz et al., A&A, submitted Dec 24, 2016
    - *Thermal lightcurve observations with Herschel/PACS*
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN)*
- Several other publications related to this technique are in preparation.

It is important to note that part of the SBNAF observational data on which are based these (and next chapters) publications are accessible via CDS database.

2 Astrometric measurements

Astrometric measurements are the measurements of the positions (Right Ascension and Declination) of any astronomical source. In the particular case of solar system moving objects these coordinates only can be obtained from relative comparison with star catalogue coordinates located in the same FOV where the object is. That is also applicable for any other astronomical source not included in astrometric catalogues.

2.1 Brief description of the technique

To measure good astrometric positions of solar system objects it is needed to obtain CCD images of the object within an enough large FOV to include sufficient catalogue stars to derive the object coordinates from comparison with the star coordinates. Ideally, observations must be done when the target is near the meridian to minimize differential chromatic refraction issues. The object must have enough signal-to-noise-ratio in the images (ideally > 20) to get a good determination of its position in the image via centroid fitting. As has been stated, this position in the image is compared with star catalogue positions in the same FOV. Until relatively few months ago the most precise star catalogues were UCAC4 (astrometric uncertainties ~ 15-100 milliarcseconds –mas– depending on star magnitudes, Zacharias et al. 2013) and the incomplete URAT1 catalogue (astrometric uncertainties ~ 2-3 times better than UCAC4, Zacharias et al. 2015). The situation has improved with the first release of the GAIA star catalogue (GAIA-DR1) with uncertainties in the star positions ~ 0.3 mas for stars down to 11.5 magnitude and ~ 10 mas for the remaining stars (Lindegren et al. 2016) and it will be even better from April-2018 when it is expected the second GAIA data release[4], and with the subsequent releases. In some special cases, as for TNOs or Centaurs, relative astrometry can considerably improve the precision in astrometric measurements of these distant bodies. A more detailed description of this technique is included in Jedicke et al. (2015), Farnocchia et al. (2015) and references therein.

2.2 Applications

Astrometric measurements are pivotal to predict stellar occultations produced by TNOs and Centaurs. The orbits of these icy and distant objects are not known with enough accuracy and precise astrometric updates of their positions, few month/weeks prior to the occultation, are needed to obtain reliable path shadow predictions. For other closer small bodies like main belt asteroids (MBAs), with less uncertain orbits than those of the TNOs/Centaurs could be also useful perform astrometric measurements, in particular for the smallest objects, in

[4] https://www.cosmos.esa.int/web/gaia/release

order to better estimate the location of the path shadow and to alert the possible observers.

Astrometric measurements have many other applications such as: i) general orbit determination for a given object; ii) determination of the orbit of satellites; iii) discovery of satellites from the astrometric photo-center wobble of the prime target, etc.

As a by-product of our astrometric SBNAF program, all these astrometric data can be submitted to the Minor Planet Center (MPC) in order to improve the orbital elements of the involved objects which translate in an improvement of the ephemeris provided by MPC and other public services as JPL-Horizons.

2.3 List of related works

List of works related to astrometric measurements acquired in the SBNAF context at date 31-March-2017. A list of SBNAF-related measurements is included for each work (other publicly available data sets not related to SBNAF are often used within these publications).

- Discovery of a satellite of the large trans-Neptunian object (225088) 2007 OR10, by Kiss et al., ApJL, accepted Mar 3, 2017
    - *Astrometric HST measurements*
- Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations, by Kiss et al. 2016, MNRAS 457, 2908
    - *Long-term optical lightcurve observations from K2, Campaign 3*
    - *Astrometric K2 measurements*
- The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids, by Szabó et al. 2017, A&A, 599, A44
    - *Long-term optical lightcurve observations from K2, Campaign 6*
    - *Astrometric K2 measurements*
- Uninterrupted optical lightcurves of main-belt asteroids from the K2 Mission, by Szabó et al. 2016, A&A, 596, A40
    - *Long-term optical lightcurve observations from K2*
    - *Astrometric K2 measurements*
- Large Size and Slow Rotation of the Trans-Neptunian Object (225088) 2007 OR10 Discovered from Herschel and K2 Observations, by Pál et al. 2016, AJ 151, 117
    - *Long-term optical lightcurve observations from K2*
    - *Astrometric K2 measurements*
- See also the list of related works for the stellar occultation technique where astrometric measurements are, directly or indirectly, used (Section 3.3).

3 Stellar occultations

This is a simple technique to derive sizes and projected shapes of small bodies in a very direct way. First it is needed to predict when the body will pass in front of a star and then simply measuring the flux of the star before, during and after the occultation from a few locations within the predicted shadow. It provides areaequivalent diameters with kilometric accuracy. This technique can reveal the presence of atmospheres, discover satellites, rings or any other material orbiting around the object. Stellar occultation technique is well developed for planets, satellites and MBAs, but it is only an emerging field for TNOs and Centaurs. Predicting and observing stellar occultations by TNOs is extremely difficult and challenging because the angular diameters of TNOs are very small and neither the stellar catalogues nor the TNOs orbits have the accuracy required to make reliable predictions well in advance.

3.1 Brief description of the technique

Stellar occultations caused by small bodies typically last several tens of seconds. The basis of this kind of observation is simple: take CCD (or video) images of the occulted star with short integration times, but enough to get a signal to noise ratio of at least 10-20. In general, no filters should be used to maximize the signal to noise ratio, and it is also important to try to minimize the readout time of the CCD camera (to minimize the dead times) either by using binning or by taking a window or a ROI (Region of Interest) of the CCD. If the readout time is, for instance, 1s, use integration times of around 4s so that the percentage of time loss is only around 25%. A common mistake is to use too short exposure times; in these cases, the risk of missing the ingress or the egress of the occultation are very high and if the ingress or egress are missed no reliable chord lengths can be determined, which ruins the observations. So, in summary, the integration time and the readout should be balanced. It is also important to start observing at least around 10-15 minutes before the nominal occultation time and to finish 10-15 minutes after that in order to get a good baseline to characterize the noise and to allow obtaining drops in flux due to possible satellites, rings, debris around the object, etc. Try to keep at least one reference star in the field of view to monitor transparency fluctuations. Computers should be synchronized with the best time precision possible, using internet time servers or other methods (e.g. GPS time inserters). For a detailed description of this technique see Elliot (1979), Santos-Sanz et al. (2016) and references therein.

3.2 Applications

Data and results from stellar occultations can be used to properly scale shape models derived from lightcurve inversion techniques or to improve these shape models when a multi-chord stellar occultation is recorded. Stellar occultations data and results are also included in dedicated papers, in particular for stellar occultations produced by elusive TNOs/Centaurs, or those produced by other small bodies interesting for any other reason. Shortly, results derived from stellar occultations are published within research papers, directly or indirectly related to results obtained with this technique, or they are presented in international conferences. On the other hand, predictions of the stellar occultations by SBNAF targets are or will be published in the deliverables: D5.1 'Occultation candidates for 2016', D5.2 'Occultation candidates for 2017' and D5.3 'Occultation candidates for 2018'. Last, but not least, occultations results are at the end included in the PDS occultation files[5].

[5]https://sbn.psi.edu/pds/resource/occ.html

3.3 List of related works

List of works related to stellar occultation measurements obtained within the SBNAF project at date 31-March-2017. A list of SBNAF-related measurements is included for each work (other publicly available data sets not related to SBNAF are often used within these publications).

- D5.1 Occultation candidates for 2016
    - *Astrometric measurements from different ground-based observatories (OSN, CAHA, La Hita, ORM, ASH1, ASH2)*
- D5.2 Occultation candidates for 2017
    - *Astrometric measurements from different ground-based observatories (OSN, CAHA, La Hita, ORM, ASH1, ASH2)*
- D5.3 Occultation candidates for 2018 (tbd)
- Results from the 2014 November 15th multi-chord stellar occultation by the TNO (229762) 2007 UK126, by Benedetti-Rossi et al. 2016, AJ 152, 156
    - *Astrometric measurements from different ground-based observatories (OSN, CAHA, La Hita, ORM, ASH1, ASH2)*
    - *Stellar occultation measurements from several locations*
- Results from a triple chord stellar occultation and far-infrared photometry of the trans-Neptunian object (229762) 2007 UK126, by Schindler et al. 2016, A&A accepted (ADS & arXiv:1611.02798)
    - *Astrometric measurements from different ground-based observatories (OSN, CAHA, La Hita, ORM, ASH1, ASH2)*
    - *Stellar occultation measurements from several locations*
- James Webb Space Telescope Observations of Stellar Occultations by Solar System Bodies and Rings, Santos-Sanz et al. 2016, PASP 128, 8011S
    - *Summary of Stellar occultation measurements from several locations, some of them SBNAF-related*
- Several other publications related to this technique are in preparation.

4 Absolute photometry

Absolute photometry is the technique dedicated to obtain absolute magnitudes in any of the standard photometric systems (e.g. as the Johnson-Morgan or UBV photometric system which is the most useful one, Johnson & Morgan 1953). In the particular case of solar system objects the absolute magnitude is, by definition, the apparent magnitude of the object when it is located at 1 AU from the Sun and from the observer at any particular filter.

4.1 Brief description of the technique

To obtain absolute magnitudes (H-magnitudes) of solar system objects it is needed to observe the target at photometric sky conditions and also to observe during the same night photometric standards stars at different airmasses, in order to properly correct the object magnitudes by airmass extinction. This kind of observations must be repeated for different sun-target-observer phase angles in order to build the so-called phase curve (magnitude vs. phase angles) which allows to finally obtain the H-magnitude of the object. A more detailed description of the absolute photometry technique can be found in Li et al. (2015), and references therein.

4.2 Applications

Absolute magnitudes are very relevant for albedo estimations of our SBNAF targets. H-magnitude data are also a pivotal input for thermal and thermophysical modelling, they are needed to properly calibrate optical lightcurves and to interpret the stellar occultations results. All SBNAF works on these last subjects published or presented in conferences include absolute photometry measurements.

4.3 List of related works

List of works related to absolute photometry measurements in the SBNAF context at date 31-March-2017. A list of SBNAF-related measurements is included for each work (other publicly available data sets not related to SBNAF are often used within these publications).

- Large Halloween Asteroid at Lunar Distance, by Müller et al. 2016, A&A 598, A63
    - *3-band mid-infrared observations with ESO VLT/VISIR*
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN, La Hita)*
    - *Absolute magnitude in V and R-bands*
- 2008 OG19: a highly elongated Trans-Neptunian object, by Fernandez-Valenzuela et al. 2016, MNRAS 456, 2354
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN)*
    - *Absolute magnitude in R-band*
- Physical properties of centaur (54598) Bienor from photometry, by Fernandez-Valenzuela et al. 2016, MNRAS, accepted
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN, NOT)*
    - *Absolute magnitude in V and R-bands*
- Spectral and rotational properties of near-Earth asteroid (162173) Ryugu, target of the Hayabusa2 sample return mission, by Perna et al. 2017, A&A 599, L1
    - *Optical lightcurve observations with ESO VLT/VISIR*
    - *Absolute magnitude in V-band*
- Several other publications related to this technique are in preparation.

5 Thermal data

Thermal data are the measurement of the thermal emission of an object (in contraposition to the measurement of its reflected light). Thermal emission of closer small bodies (NEAs/MBAs) can be well detected at near/mid-infrared (~4-21 μm, with peak ~ 10-20 μm). For distant objects (e.g. Centaurs/TNOs) far-infrared wavelengths are more adequate to measure their thermal emission (~25-500 μm, with peak ~ 70-160 μm).

5.1 Brief description of the technique

Near/mid-infrared data can be acquired from ground-based observatories at M, N and Q bands (e.g. VLT/VISIR, Subaru/COMICS, IRTF, etc), also mm/submm data can be obtained from ground facilities (e.g. IRAM, ALMA, NOEMA, etc). The thermal fluxes (usually expressed in mJy) are extracted from the data acquired with any of the ground-based observatories. A detailed description of the technique can be found in Harris & Lagerros (2002), Delbo et al. (2015), and references therein.

5.2 Applications

Thermal fluxes are used to obtain the Spectral Energy Distributions (SEDs) of the objects at the thermal regime. These SEDs are fitted using thermal or thermophysical models from which sizes, albedos and thermal/surface properties can be obtained. H-magnitudes are needed as input parameters to run these models.

All thermal infrared fluxes of SBNAF targets from different ground-based facilities will end up in a public IR database (deliverables: D2.5 'Internal IR database' and D2.6 'Public IR database', both in preparation).

5.3 List of related works

List of works related to thermal measurements in the SBNAF context at date 31-March-2017. A list of SBNAF-related measurements is included for each work (other publicly available data sets not related to SBNAF are often used within these publications).

- D2.5 IR database (internal, in preparation)
- D2.6 IR database (public, in preparation)
- Large Halloween Asteroid at Lunar Distance, by Müller et al. 2016, A&A 598, A63
    - *3-band mid-infrared observations with ESO VLT/VISIR*
    - *Multi-epoch optical lightcurve observations from several ground-based observatories (CAHA, OSN, La Hita)*
    - *Absolute magnitudes in V and R-bands*
- Several other publications related to this technique are in preparation.

6 Outlook

In this deliverable we have briefly described the ground-based observational techniques used within the SBNAF project (time series observations, astrometric measurements, stellar occultations, absolute photometry and thermal measurements), stressing especially the observational data and applications derived from these techniques. We also have listed all the publications or documents related to the SBNAF ground-based observations obtained with some of these techniques at 31 March 2017. These lists will be updated in future deliverables. We are not including Adaptive Optics (AO) observations (e.g. using WHT/AOLI or ESO VLT/SPHERE, etc) or radar measurements in this document because our project is not directly involved in these observational techniques. Nonetheless, we will make use of AO and radar data and shape models that are publicly available or obtained in the context of punctual collaborations with other teams/projects. Last but not least, at the end of our project we plan to publish some of the SBNAF related ground-based measurements (e.g. MBAs lightcurves obtained to derive shape models) in dedicated data papers. Other ground-based data (e.g. shape models, astrometry measurements, MBAs lightcurves, H-magnitudes) will be publicly available via data bases like ISAM[6], DAMIT[7], PDS, CDS or MPC.

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[6] ISAM: Interactive Service for Asteroid Models http://isam.astro.amu.edu.pl/

[7] DAMIT: Database of Asteroid Models from Inversion Techniques http://astro.troja.mff.cuni.cz/projects/asteroids3D/web.php