Project Number: 687378 – SBNAF - RIA
Project Acronym: SBNAF
Project title: Small Bodies Near and Far

Periodic Technical Report
Part B

Period covered by the report: from 01/04/2017 to 31/03/2019 (year 2 & 3)
Periodic report: 2nd

Following up on 1st periodic report (01/04/2016 to 31/03/2017 = year 1) and already partly covered by the progress report (01/04/2017 to 31/03/2018 = year 2).

1. Explanation of the work carried out by the beneficiaries and Overview of the progress

The reported work in this section draws partially on the mid-term and second-year progress reports because of the overlap with the current reporting period. Some of the progress contents in those earlier reports are reproduced for completeness here, but otherwise duplication has been avoided.

The EU Horizon2020-funded bench-mark study SBNAF (2016-2019) addressed critical points in reconstructing physical and thermal properties of near-Earth (NEA), main-belt (MBA), and trans-Neptunian objects (TNO). The SBNAF target list comprised recent near-Earth and main-belt interplanetary mission targets, different samples of main-belt objects, representatives of the Centaur population, and several dwarf planets (and candidates) beyond Neptune. Our approach was to combine different methods and techniques to get full information on selected bodies: lightcurve inversion, stellar occultations, thermo-physical modelling, radiometric methods, radar ranging and adaptive optics imaging. The applications to objects with ground-truth information from interplanetary missions Hayabusa, Hayabusa2, OSIRIS-REx, NEAR-Shoemaker, Rosetta, and DAWN allowed us to develop new tools for the interpretation of space data and to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method. The combination of the visual and thermal data from the ground and from astrophysics space missions (like Herschel, Spitzer, Kepler-K2, Hubble, and AKARI) was key to improving the scientific understanding of these objects and serves also as input for the interpretation of much larger samples like (i) the thousands of NEAs/MBAs observed by AKARI and WISE, (ii) the TNO samples observed by Spitzer and Herschel, (iii) the sample of large MBAs where Gaia provides masses, or (iv) the well-characterized MBAs which serve as infrared calibration standards.

In the context of the SBNAF project, we derived size, spin and shape, thermal inertia, surface roughness, and in some cases clues about their internal structure and composition, for objects from the near-Earth environment out to the most distant objects in the Solar System. In the context of the Hayabusa2 mission, these results were crucial for the operations and scientific exploitation of the mission itself.

Another important part was to build accurate thermophysical asteroid models to establish new primary and secondary celestial calibrators for submm/mm projects like ALMA, SOFIA, APEX, and IRAM, as well as to provide a link to the high-quality calibration standards of Herschel and Planck.

Within the SBNAF project, we developed and improved tools and web-services, we combined data from very different sources in sophisticated models to obtain new scientific results, and we produced highly reliable calibration and science products for the planetary community. In parallel, we conducted new (and often coordinated) observations with Kepler-K2, Hubble, ALMA, VLT, and many smaller-size telescopes around the world. These observations mostly consisted of visible photometry to characterize lightcurves, to improve stellar occultation predictions, and the occultation events. We presented our scientific results in refereed publications (more than 60 overall) and a large collection of conference contributions, including dedicated conference sessions on SBNAF topics in the European Planetary Science Congress in 2017 and 2018. We also organized a well-attended workshop on “Thermal Models for Planetary Science III” in February 2019 in Budapest. All publications are in open access, the various tools, services and products are available on our public web page, in ESA, NASA and other archives, and will be further advertised in upcoming planetary science conferences.

In a broader context, our efforts have helped and will help the whole planetary science community, and hence society itself, to better understand the nature of small bodies, their threat to our planet, and their possible role in the delivery of water and other organic materials that were necessary for life to develop here and, possibly, in other parts of the Solar System. All relevant project information and legacy are available on the SBNAF public page at http://www.mpe.mpg.de/~tmueller/sbnaf[1], including direct links to our public deliverables, refereed publications, and tools and services and related documentation (sometimes featured in the relevant deliverables).

1.1 Objectives

The main objective of the SBNAF project was to enhance the scientific return from different astrophysics and planetary missions related to small bodies and dwarf planets in our Solar System. We used very different data sets from ground (professional and amateur observations), airborne, and space projects and combined these measurements with newly developed tools and techniques to make the best possible use of those ESA, NASA, and JAXA missions. At the same time, we developed sophisticated web tools, provided calibration products, and established new scientific data products. The SBNAF activities added scientific value through advanced analysis of the data, leading to a wide variety of scientific publications and higher-level data products for further exploitation by the Planetary Science community. We provided enhanced data products which were uploaded to ESA and NASA archives.

Our team included world-leading experts in different fields: lightcurve inversion techniques to reconstruct shapes and spin properties of small bodies, and handling of infrared data from the ground and from the space, including their reduction and calibration, are two of the main areas covered. In the SBNAF team there were highly experienced observers with world-leading expertise in stellar occultation measurements, as well as photometric and spectroscopic observations, and also experts on thermo-physical modelling. By combining the expertise in our team, the SBNAF project had specified the following **major objectives**:

- Develop new tools and optimized procedures for the determination of size, shape, spin and thermal properties for NEAs, MBAs, and TNOs, from combined visual and infrared observations, both from space and from the ground.
  - ➢ Final Status (Apr 2019): several deliverables were related to this objective, with core information given in "D3.4 Volume determination", "D3.5 Joint lightcurve and thermal models", an updated version of "D6.5 Ground-truth shape models", "D6.6 Thermally resolved shape models", and "D6.7 Quality assessment system for the models"; several publications on NEAs, MBAs, and TNOs address this point; several tools and the description of the techniques are available from our public web page (and will be maintained by the different institutes beyond the SBNAF project).
- Provide expert-reduced maps and fluxes of Herschel measurements in the infrared for feedback to the Herschel Science Archive (HSA) via dedicated studies on small near-Earth and large main-belt asteroids (including calibration observations), and the largest

[1] To guarantee the mid- to long-term availability of the SBNAF results, tools, services, products, etc. we decided to buy a new domain (www.sbnaf.eu) for 10 years, funded by Konkoly Observatory. There will be a transition phase with both pages running in parallel, but starting in 2020 the new domain will host the official SBNAF page.

Centaurs and trans-Neptunian objects.

- ➢ Final Status (Apr 2019): new, high-quality products for Herschel NEAs, MBA and TNO observations have been provided to the HSA, related deliverables are "D2.2 NEA HAS upload", D2.3 MBA HSA upload" (both submitted and approved in RP1) and "D2.4 TNO HSA upload"; several asteroid-related calibration products have been provided to the Herschel, ALMA, IRAM, SOFIA, and a few other far-IR/submm/mm calibration teams ("D4.3 Calibration asteroid model predictions", "D4.4 Secondary asteroid models", "D4.5 Final asteroid models");

- Advance the field of thermo-physical characterization of small bodies by combining disk-resolved asteroid observations from interplanetary missions (Hayabusa, Rosetta, Dawn, NEAR-Shoemaker) with disk-integrated thermal and optical observations from space and ground.
  - ➢ Final Status (Apr 2019): the work in this context was covered by several NEA (Ryugu, Bennu, Eros), MBA (Vesta, Lutetia, Ida), and TNO (Pluto) publications (either led by or with strong contributions from the SBNAF team), but there was no dedicated deliverable connected to this point. We discuss different aspects of this benchmarking process in "D1.3 Mid-term report" and in our reply to the milestone 2 discussion related to our first periodic report. Critical tests and benchmarking were carried out in the last year, including the important comparison between our extensive model predictions for Ryugu and the in-situ results coming from the Hayabusa2 mission (see also Science paper by Sugita et al. 2019), but also in the context of a volume uncertainty assessment for several NEA and MBA benchmark objects published in 2019.
- Link the established asteroid-related calibration from Herschel (with data coming also from Planck, AKARI, Spitzer and ISO) to ALMA and other sub-mm/mm observatories.
  - ➢ Final Status (Apr 2019): In the context of "D4.4 Secondary asteroid models" we tested model predictions against far-IR/submm/mm observations. Thermophysical model predictions for 5 primary asteroids and about 20 secondary asteroids provide the new calibration link between Herschel (at FIR wavelengths) and ALMA or other submm/mm observatories. However, the object's emissivity properties are crucial and had to be determined object by object, but due to the lack of data this was only possible for selected targets. This work is also documented in "D4.5 Final asteroid models" and has been communicated/exchanged with the various calibration teams worldwide. So far, only the submm/mm emissivity aspects for TNOs and Centaurs have been published. The planned publication on MBAs was delayed due to the lack of suitable high-quality measurements.
- Setup of a public database for infrared observations of small bodies (selected NEAs, MBAs, Trojans, Centaurs, TNOs) with thermal measurements from all infrared space missions and selected ground-based surveys.
  - ➢ Final Status (Apr 2019): The SBNAF database of solar system object thermal infrared observations ('database' for short) was created, tested, populated with data and made available to the public as described in the deliverables D2.5 (internal version) and D2.6 (public version). The internal version became operational in November, 2018, and after further testing and subsequent improvements it was made available to the scientific community on February 12, 2019. We made an official announcement of the public database on the TherMoPS-III workshop, February 20-22, 2019, Budapest (http://thermops2019.hu/). The original publication related to the public database is the Release Note on February 12, 2019. The last version of the public database (mainly additional Herschel Space Observatory data with respect to the original one) is described in the latest Release Note (March 29, 2019), which is the current official

description of the database. The TherMoPS-III presentation and the latest Release Note are part of the SBNAF Deliverable D2.6. There is a publication in preparation to be submitted to a peer reviewed scientific journal describing the database and its potential applications.

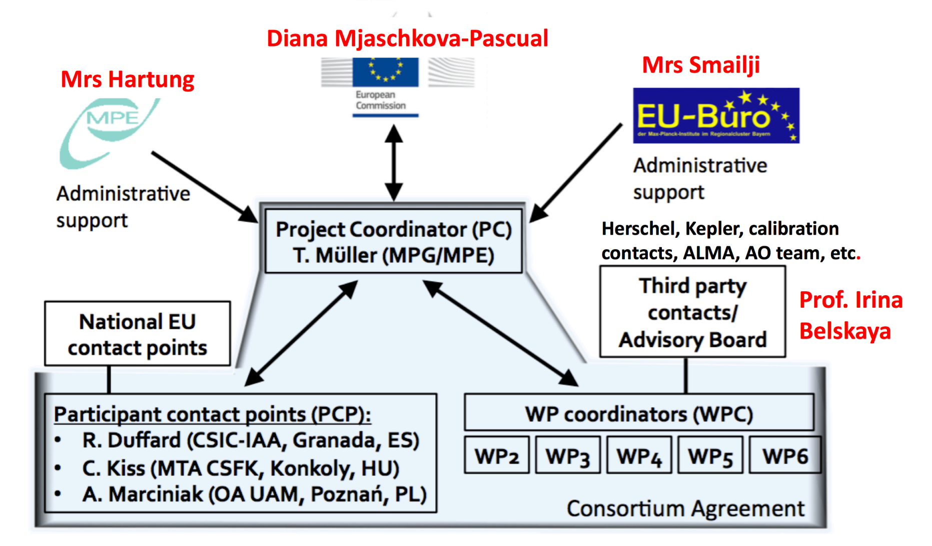
- Establish high-accuracy constraints – object densities, spin parameters, shapes, and thermal properties – of selected single and binary asteroids for testing formation and evolution models of the Solar System.
  - ➢ Final Status (Apr 2019): This topic dominated the scientific work for the entire SBNAF period. Tools and methods have been established to determine and quantify the reliability of volume information (D3.4), which is required e.g. to determine densities when the Gaia mass determinations are released (well after the SBNAF end). For the rotational properties there were two aspects: statistical studies on light curves in general (see e.g. the publication by Butkiewicz-Bąk et al. 2017), and the determination of high-quality spin properties for individual objects (see solutions presented in the ISAM service and the publication "Shaping asteroid models using genetic evolution (SAGE)", by Bartczak & Dudziński, 2018, and "Volume uncertainty assessment method of asteroid models from disk-integrated visual photometry", by Bartczak & Dudziński, 2019). The focus of the work was on the determination of shape (and volume), rotational properties and thermal properties (thermal inertia, surface roughness, emissivity). We assessed shape/spin solutions via thermal data (e.g., Marciniak et al. 2018/2019). Many of our publications feature radiometric studies as well as aspects from lightcurve inversion, occultation, or AO imaging (e.g., occultation publications on 2007 OR10, 2007 UK126, or Haumea, or VLT AO studies on large MBAs where we had significant contributions). The synergy between the expertise by all partners led to full thermophysical characterisations for our targets, with solid discussions on the quality of the established object properties. Examples can be found in all publications on individual NEAs, MBAs, or TNOs.
- Enhance the scientific outcome of small body observations of astrophysical infrared space missions (Herschel, Planck, and AKARI) by combining space and ground data.
  - ➢ Final Status (Apr 2019): Several of our SBNAF publications contain Herschel, AKARI, Spitzer, Kepler-K2, or Hubble data. One AKARI-specific catalogue paper was published (Alí-Lagoa et al. 2018), two Herschel-specific catalogue papers are in preparation (with the reduced high-quality data already publicly available in the HSA and the extracted fluxes in our IR database). In general, for all our targets and all our publications we systematically used the available thermal (space) data to add new information and to enhance the scientific outcome. We also did SBNAF-specific infrared studies (in combination with auxiliary data from ground or occultation measurements) to answer some of the key science questions related to NEAs, MBAs, and TNOs.
- Deliver asteroid model solutions for Hayabusa-2, Gaia, ALMA, and other ground-based submm/mm projects.
  - ➢ Final Status (Apr 2019): Our Hayabusa-2 related model solution for the mission target Ryugu was published (Müller et al. 2017; Perna et al. 2017; de Leon et al. 2018). The publication on "Asteroid Ryugu Before the Hayabusa2 Encounter" by Wada et al. (2018) summarizes the pre-mission knowledge on Ryugu. Meanwhile, first results from the Hayabusa2 in-situ measurements (in comparison with pre-mission information) have been published in Science (Watanabe et al. 2019; Sugita et al. 2019; Kitazato et al. 2019). In the context of Gaia, we pushed for high-quality shape, spin and volume solutions for a range of large MBAs in preparation for the Gaia asteroid

mass release in the mid-term future. This included new lightcurve and absolute photometric measurements from ground, the establishment of new lightcurve inversion techniques, the combinations with other observing techniques (AO imaging, occultations, radiometry) to improve the shape and spin solutions and to assign size information (and realistic error estimates) to these shapes. Radiometric studies related to ALMA and other submm/mm projects have been done, mainly in the calibration context (D4.4, D4.5) and for selected TNOs (Lellouch et al. 2017; Müller et al. 2019).

- Provide tools, techniques and crucial object properties in support of NEOShield-2, OSIRIS- REx, JWST, and ground-based observations of minor bodies.
  - ➢ Final Status (Apr 2019): Here we can list the ISAM service to visualize and provide to the community asteroid spin and 3-D shape solutions (currently 3122 models for 1618 asteroids), but also our results on thermophysical model studies of NEAs are relevant for NEOShield-2 and OSIRIS-REx. The preparatory work for JWST had started, but stopped again after the announcement of the launch delay. However, some team members are still part of the GTO proposals. We also had an (unsuccessful) attempt for an ERS proposal, and we prepared for the submission of several GO proposals on SBNAF targets.

1.2 Explanation of the work carried per WP

1.2.1 Work Package 1: Management & Outreach



Management structure for the SBNAF project. Names given in red were recent changes (EU officer, local EU and administrative contacts, external reviewer).

During the reporting period from April 2017 to March 2019 we encountered no major problems within WP1. The coordination of the SBNAF project was done by the PI (Thomas Müller), supported by Víctor Alí-Lagoa, in close collaboration with the group leaders of AMU (Anna Marciniak), IAA (Rene Duffard/Jose Luis Ortiz), and Konkoly observatory (Csaba Kiss). All critical points, questions related to procedures, contracts, financial aspects, etc. were solved with the help of the EU officer, and our national and local EU experts, and by regular interactions between the team members.

The progress in the six WPs was as expected and described in the Grant Agreement No 687378. All deliverables foreseen for the second period have been uploaded to the EU web portal. A few deliverables were late by a few days/weeks due to technical reasons or travelling/-

conference commitments. As part of WP1, we organize regular Webex team meetings of 1-2 hours length every two to three weeks (in total 31 webex meetings in the second period). The meeting minutes and the arising action items were collected, tracked, and followed up on our internal web page. In case of problems, we tried to mediate between the team members, the participant contact points, or the WP leaders.

The biggest workload in WP1 was related to the email/webex/telecon communication between the beneficiaries and the very frequent updates on the internal and public web pages which were the main sources of information for the team members, the EU officer, our external experts, and the public. Also, the first periodic report, the mid-term report (D1.3) and the progress report after year two were large workloads. Via our public web page and astronomy archives for publications we ensuree open access for all tools, public deliverables, documents, and publications. Key observations and generated data products are also available from other archives, like the *Herschel Science Archive* or the *Centre de Données astronomiques de Strasbourg* (CDS), or the Planetary Data System (PDS), see also D5.8. The Solar System and small-body topics are also of great interest to the public and as part of WP1 we fostered outreach activities and we offered qualified feedback to media requests.

During the second period, there were three major reports connected to WP1:

i. First periodic report (May 2017):

- Individual work declarations
- Person-month work distributions
- Part A (public part) with summary, description of work performed, progress beyond the state of the art and impact
- Report on explanations on the use of resources
- Part B: work carried out and overall progress in each WP, deliverables, impact, update of the plan for exploitation and dissemination of results, use of resources
- Deliverables, Milestones, Risks, Questionaire, Publications, Gender balance
- Financial statements

ii. D1.3 Mid-term report (Nov 2017):

- Mid-term project status with short status of all WPs and deliverables
- Summary of results, publications, conference contributions, tools & services
- Technical/organisational problems, delays, risks
- Outreach activities
- New elements based on observations with Kepler-K2, AO imaging, HST, ALMA; proposal preparations for ALMA, HST, JWST, VLT; successful new (and unplanned) observations of TNO/Centaur rings, and two very close NEAs.
- Including feedback from several external experts, based on email exchange and presentations during our team meetings in 2017
- Answers to the points raised by the external reviewer after our first periodic report.

iii. Progress report covering year 2 (Apr 2017 to Mar 2018):

- Explanation of the work carried out
- Overview of progress
- Objectives and current status
- Explanation of the work carried out per WP and open points
- Impact of the SBNAF work
- Follow-up of recommendations and comments from previous review

- Use of resources

Followed by the final project report (this document).

During the second reporting period we also had the following in-person team meetings:
- 3rd team meeting, AMU/Poznań, May 04-06, 2017
- 4th team meeting, Konkoly/Budapest, Oct 04-06, 2017
- 5th team meeting, IAA/Granada, Apr 25-27, 2018
- 6th team meeting, MPE/Garching, Nov 12-14, 2018
- The TherMoPS III workshop in Budapest, Feb 20-22, 2019
- The final SBNAF project/team meeting in AMU/Poznań, May 07, 2019

The meeting contributions are all collected on SBNAF-internal web pages, as well as the minutes, notes, action items, and conclusions.

Milestones MS01 „Kick-off", **MS04** „Mid-term review", and **MS15** „Final SBNAF meeting" are connected to WP1. With the final meeting on May 7, 2019, we reach all milestones.

As part of WP1 we also looked into all **risks** identified in the SBNAF Grant Agreement. Overall, the pre-project identified risks did either not materialize or the planned risk-mitigation measures worked very well. No severe problems were encountered during the entire SBNAF project phase.

1.2.2 Work package 2: Infrared observations

The goals of WP2 were twofold. First, some tasks in this WP (D2.1, D2.2, D2.3, and D2.4) focused on data obtained with the Herschel Space Observatory and the main goal of these tasks were to produce expert-reduced Herschel data of primary focus targets: (a) of large TNOs (photometric and lightcurve observations); (b) MBAs (science and calibration observations); (c) dedicated NEA observations. A second group of tasks were dedicated to the compilation of a database of infrared observations of solar system targets, collecting infrared data from previous missions (Spitzer, Planck, WISE, AKARI, IRAS, ISO, MSX) and published ground-based mid-IR, submm, millimetre observations.

In the second period (Apr 2017 – Mar 2019) we completed "D2.4 TNO HSA upload" and reached "MS2 Expert-reduced data to HSA". In addition, we have established our proposed database of thermal IR measurements of asteroids, first as an internal service for testing ("D2.5 IR database (internal)"), later on, as a public service for the astronomical community ("D2.6 IR database (public)").

D2.4 TNO HSA upload (30 Sep. 2017 – uploaded 28 Nov. 2017)

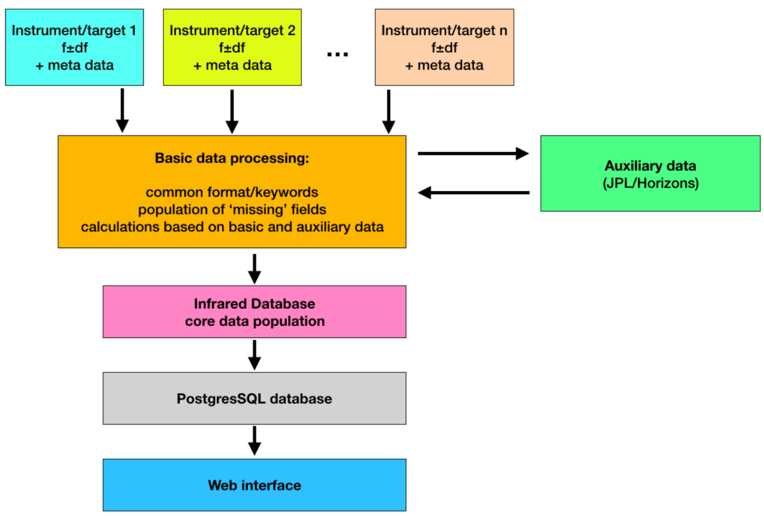
- The immediate goal of this delivery (D2.4) was to provide the science community with expert reduced data products of Herschel/PACS trans- Neptunian object and Centaur observations. The D2.4-related new products are uploaded to and accessible through the Herschel Science Archive (http:// www.cosmos.esa.int/web/herschel/science-archive).
- Details of this deliverable are also given in the progress report covering the second year of the SBNAF project (see item iii in Section 1.2.1).
- In the context of D2.4 we provided **3594 FITS products** with preprocessed TNO/Centaur observations to the Herschel Science Archive.

With the preparatory work in D2.1 and the products created in the context of D2.2, D2.3, and D2.4, we reached our **MS03 Expert-reduced data to HSA**:

- The items that we delivered in D2.2/D2.3/D2.4 are the most comprehensive and best reduced products of Herschel/PACS solar system target (minor body) observations.
- These products can (and will) be used to directly extract FIR flux densities.
- These flux denisties will be the fundation for multiple scientific publications and they are part of the infrared database (covered by D2.5 and D2.6 of the SBNAF project).
- The expert-reduced data are available via the Herschel Science Archive (HSA) and also in the NASA/IPAC Infrared Science Archive for the planetary community.

A significant part of the work in WP2 during the second period was related to the preparations for our database of IR observations of asteroids. The two deliverables are: **D2.5 IR database (internal)** (30 Sep 2018) and **D2.6 IR database (public)** (31 Mar 2019):

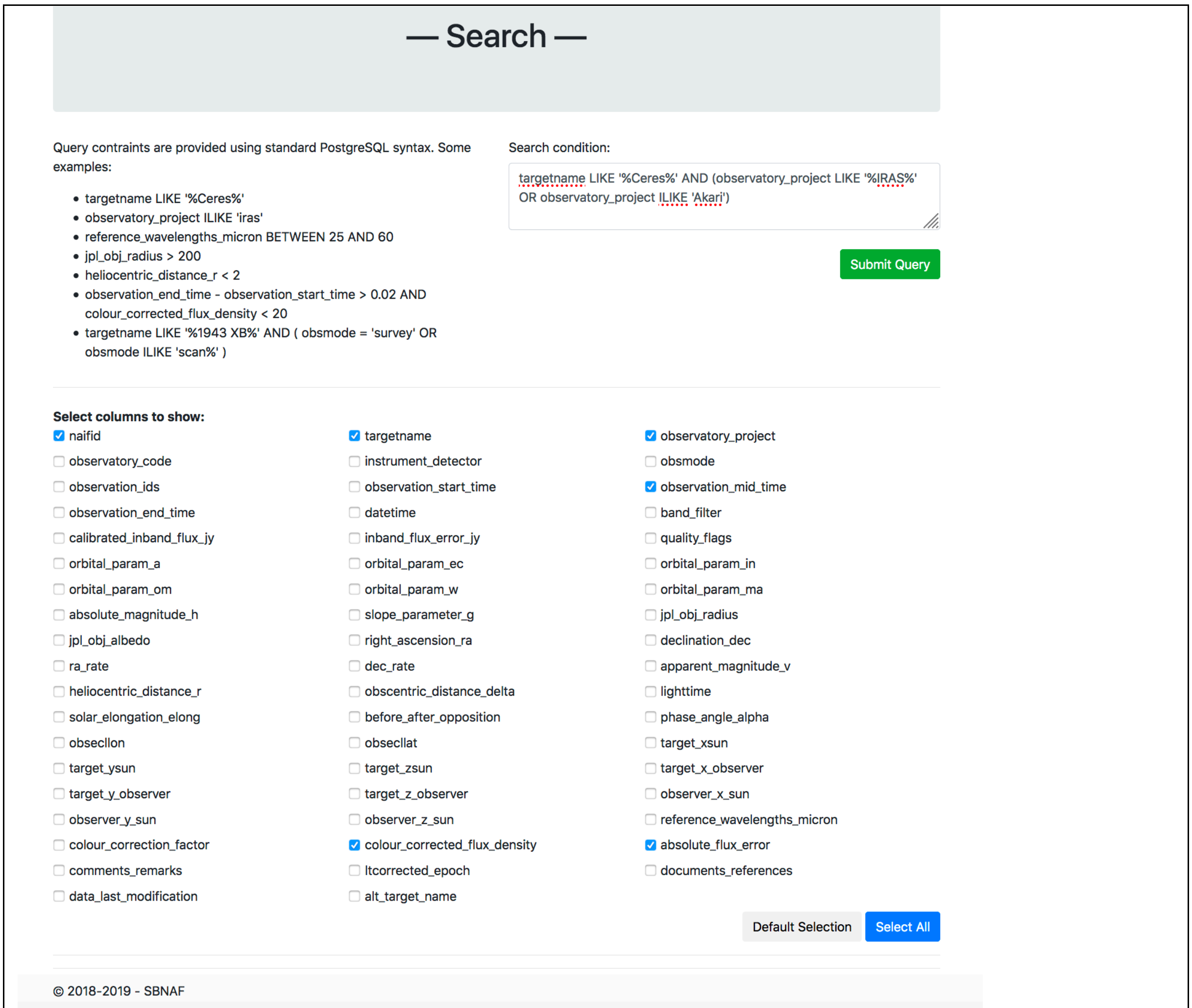
- This work was carried out under the leadership by Konkoly observatory
- The IR database was opened to the public in early 2019 during our workshop on "Thermal Models for Planetary Science III" (TherMoPS III; http://thermops2019.hu/).
- The official address of the database is https://ird.konkoly.hu
- At the end of the SBNAF funding period, the database included thermal observations of NEAs, MBAs, and TNOs/Centaurs
- The database includes more than 20,000 entries from the AKARI infrared survey, about 900 from the MSX satellite, about 25,000 from IRAS, about 120,000 from the WISE all-sky survey, and about 2000 individual measurements from the Herschel Space Observatory.
- The database has full online documentation and a proper release note.
- The database is compatible with the VESPA interface (Virtual European Solar And Planetary Access).
- The operations and maintenance of the database is guaranteed until the end of 2021 by funding support from the Hungarian Academy of Sciences and the National Research funding in Hungary.
- It is planned to continue the database service long term with options to add more data (e.g., from ground-based observations or from JWST), to add auxiliary information on individual or all targets, to run interactively specific scripts to calculate radiometric solutions, etc. (outside the SBNAF project).



Outline of the processing of data from the basic entries (catalouges and target-specific papers) to the web-interface of the SBNAF infrared database.

With the work in D2.5 and D2.6 we reached our **MS14 Infrared database of SBNAF targets**:

- We completed the database of infrared observations for our SBNAF targets (and many more in addition).
- The database was announced to the Planetary Science community in February 2019 during the workshop on "Thermal Models for Planetary Science III" (TherMoPS III; http://thermops2019.hu/), and will be advertised in future conferences and workshops.
- A release note for the database, including online information about the content, was issued and is available to the general user.
- A publication describing the content of the database is in preparation (originally foreseen as a paper for the TherMoPS III workshop proceedings).



Infrared database for thermal observations of asteroids and TNOs. Query form for the infrared observation of 1 Ceres (taken by IRAS or AKARI) and displaying the default output selection: 'naifid', 'targetname', 'observatory project', 'observation mid time', 'colour corrected flux density', and 'absolute flux error'.

Mission	JPL code	instrument	filters	observing mode	N_{obs}
AKARI	500@399	IRC-NIR	N4	IRC02	1
		IRC-MIR-S	S7, S9W, S11	survey, IRC02, IRC11	6955
		IRC-MIR-L	L15, L18W, L24	survey, IRC02, IRC51	13824
HSO	500@-486	PACS	blue,green,red	chop-nod, scan map	1852
MSX	500@399		MSX_A,MSX_C,MSX_D,MSX_E	survey	901
IRAS	500@399		IRAS12,IRAS25,IRAS60,IRAS100	survey	25064
WISE	500@-163		W3,W4	survey	121383

List of observatories/missions, observatory codes, instruments, filters, possible observing modes, and the number of measurements with a specific instrument, in the present version of the Infrared Database. Except for WISE, there are no available positions for the low-Earth orbit missions, so they are referred to as geocentric (JPL code '500@399')".

The infrared database (https://ird.konkoly.hu) is presently operated in Konkoly Observatory. After initial security issues, these problems were solved in May 2019 by buying the requireced security certificate. Future operations of both the public and internal versions of the infrared database will be provided by Konkoly Observatory staff. Operations until the end of 2021 will be supported by the Hungarian Academy of Sciences (EU- HUNKPT grants) and the National Research, Development and Innovation Office, Hungary (NKFIH, grant nr. K125015). Data from older publications are planned to be included or made public (e.g. unpublished Herschel Space Observatory measurements) and the database welcomes submission of own data (e.g. from newly accepted publications) in the future, in a pre-defined format. The SBNAF Infrared Database has the option to be included in the VESPA interface (Virtual European Solar and Planetary Access, http://www.europlanet-vespa.eu). A proposal was submitted to the 2017 call to include the SBNAF infrared database in the VESPA services. The VESPA service would guarantee more visibility for our IR database, but it still requires local (here: at Konkoly Observatory) operations and maintainance.

1.2.3 Work package 3: Lightcurve inversion techniques

The main task in the work package on lightcurve inversion techniques was to develop and refine asteroid spin and shape modelling techniques, and to join various types of data for model scaling and validation. Another task was to provide the models with their parameters to the community via the ISAM[2] service (Interactive service for asteroid models, see below).

During the project's second period, we implemented a major upgrade of the ISAM service with the addition of the 3D shape models in a format of "obj" files to all ~1600 target models, ready to be downloaded and applied in any of the widely used graphical programs. This is also applicable for further research, e.g. as an input for thermophysical modelling. Before that upgrade, shape models were only available as 2D projections and anaglyphic apparent "3D" views. The list of new shape models available include (i) those produced and vetted by our team or with strong contribution from our team, and (ii) those produced independently by other researchers:

i. The models described in deliverable D3.5, "Joint lightcurve and thermal models", have been uploaded to the ISAM service, with full functionalities, including the downloadable .obj files. These models have been published in three papers within the SBNAF project (Marsset et al. 2017, Müller et al. 2017, Marciniak et al. 2018).

[2] http://isam.astro.amu.edu.pl

ii. We also uploaded the several shapes resulting from the intensive development in the field of 3D modelling of large asteroids using adaptive optics data in combination with lightcurves and/or occultation data (publications by Viikinkoski et al. 2017, and Hanus et al. 2018). Also, the table in deliverable D3.3 has been updated accordingly to include the evaluation of the newly available ADAM shape models.
iii. The most recent ISAM upgrades are described in "D3.6 Joint multi-data inversion models": the downloadable shape models (with key header information) in OBJ format; information about asteroid occultations (used to verify shape solutions and to scale them); subpages on uncertainty of physical parameters, and thermophysical model information.

On Gaia-GOSA, we have more than 140 registered users and 538 nights of observations. Full light-curves have been observed for more than 50 objects, including complete rotations from two oppositions for several objects. Since 1 April 2017, 282 new nights of observations have been gathered. Most of the targets observed are SBNAF targets from the list of Gaia mass targets (described in D 6.4 and D 3.4) and calibrators (described in e.g. D 4.6 and D 3.3). Over 80% of the data are processed and the lightcurves are shown on the GaiaGosa webpage. The first paper including data from GaiaGOSA collection has been submitted and a second one is in preparation (to be submitted before final meeting in May). Moreover, we have started a new project within GaiaGOSA related to the Gaia mission which aims in determining precise asteroid volumes. GaiaGOSA users have meanwhile also contributed to occultation campaigns (see related deliverables in WP5). In cases where the GaiaGOSA data were used for publications, we also made them publicly available (via the CDS archive).

The Grant Agreement contained three deliverables for WP3 in the second reporting period:

D3.4 Asteroid volume determination

This deliverable provided a summary of techniques used for scaling various types of asteroid shape models, described the means to validated them, and also summarized the status of observing campaigns for the selected "Gaia perturbers" within the SBNAF project.

Usually, asteroid 3D shape models are obtained from lightcurve inversion methods and are scale-free. Additional observing techniques are needed to put these models to scale, in order to calculate their volume. This information, coupled with mass, will serve for precise density determinations, crucial for studying asteroid internal structure and composition. The described techniques include radiometry based on asteroid infrared flux; occultation timings, which result in shadow silhouettes of the occulting target; adaptive optics; radar echo; and in-situ exploration, the most precise way of asteroid shape determination. The requirements for a given type of data and associated technique's possibilities, reach, and limitations, have been described in subsequent sections of D3.4, providing a good reference source for the subject of determination of asteroid sizes and volumes.

The deliverable D3.4 also described various types of shape models in the calibration context, discussing advantages and disadvantages of each shape representation. Initially, a simple spherical or ellipsoidal shape model is used in thermophysical modeling, but due to the highly irregular shapes of many asteroids, it often cannot provide a good fit to thermal data. Next, the behaviour of convex, and more sophisticated non-convex shape models in the thermophysical context were described. These often displayed a better fit than a sphere, provided they are in phase with the observed thermal lightcurve and the shape representation is not too extreme.

The observing campaigns of chosen Gaia perturbers, described in the last section of the deliverable, are targeted not only to record the new lightcurves, but also to gather information on available occultation events (summarized in the last table in D3.4), and to search the archives for their infrared fluxes from a range of space missions (available data for each target summarized in the internal spreadsheet described in D6.4). Scaling using occultation chords and thermo-physical modelling has been applied on a few targets and published papers containing the results summarized in the deliverable. This paved a way for modelling and scaling the Gaia perturbers - documented in the Deliverable 6.8.

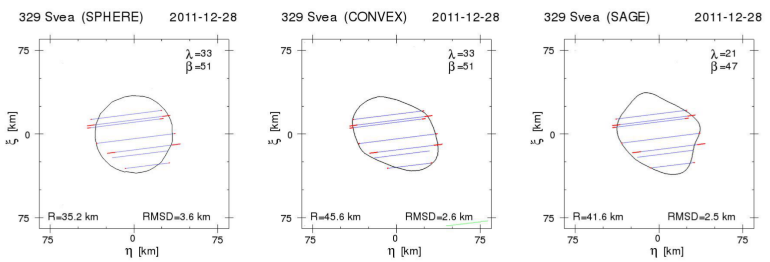


Figure 11: *Three different shape solutions of 329 Svea fitted to 2011 occultation. The R is the size of the model, i.e. the length of the longest vector in the model, based on the fit.*

Shape model	EVSD [km]	Volume [m^3]
	329 Svea – 2011	
Sphere	70 ± 7	$(1.83 \pm 0.56) \cdot 10^{14}$
Convex	72 ± 4	$(1.95 \pm 0.33) \cdot 10^{14}$
Nonconvex	70 ± 4	$(1.80 \pm 0.31) \cdot 10^{14}$

Table 4: *Diameter and volume determination of 329 Svea for three different shape models and two independent occultations.*

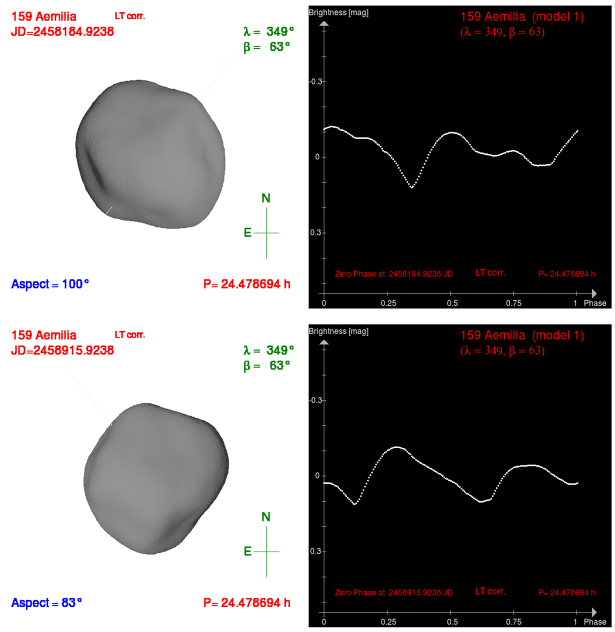
Figures extracted from deliverable D3.4, Asteroid volume determination.

D3.5 Joint lightcurve and thermal models

The main goal of this deliverable, which is not a report but connected to the ISAM service, was to make the solutions publicly available. Nonetheless, we summarised and discussed the various ways to join models based on optical data with the data obtained in the infrared range of the spectrum that we have investigated. This work is spread in several of our publications.

One of the ways was to perform immediate multi-data inversion in one optimisation process. Such an approach has been used in CITPM method (Convex Inversion Thermo Physical Modelling), reported by Durech et al. (2017). The advantage is the simultaneous optimisation of the thermo-physical model, which sometimes seemed necessary given that the nominal inversion shape was not always the best fitting one in the thermo-physical context. The CITPM has been demonstrated to work generally well on the selected sample of four targets in Durech et al. (2017). Also, it allowed Müller at al. (2017) to constrain the parameters of the Hayabusa2 mission target, asteroid Ryugu, better than when using the lightcurve data alone. However, in the case of (21) Lutetia, it provided a thermal inertia value that is significantly higher than that based on the in-situ shape. The critical point of this approach is the arbitrary weighting factor between the contributions from optical and thermal data.

The usual approach is to do the inversion on purely optical data and *a posteriori* study of the resulting spin and shape model by thermophysical modelling. This had also worked well on the majority of the studied targets, sometimes even allowing us to break the mirror-pole symmetry in the solutions for the spin axis and clearly pointing to one of two possible solutions. Thanks to such investigations, it was decided that the best approach to join optical and thermal data considering the time scale of SBNAF would be the two-stage fitting instead of optimisation of all parameters in one process.



Left: Example of sky projections of asteroid (159) at March 7th 2018, 10:10:13 (JD=2458184.923773) and two years later (top and bottom panels). Right: corresponding predicted light-curves.

D3.6 Joint multi-data inversion models

The last deliverable of WP3 described the ISAM service and its upgrades in during the final reporting period. Software and hardware details about the ISAM setup are given. ISAM's most relevant functionalities are: (i) to generate exact sky projections necessary for size determination from stellar occulation measurements; (ii) to create synthetic lightcurves; (iii) to animate an object's rotation while showing the simulated lightcurve in parallel; (iv) to create 3D images in various stereoscopic techniques; (v) to download the spin-shape solutions of interest in OBJ format. The ISAM service contained at the end of the SBNAF project 3122 models for 1618 different asteroids in total.

The recent upgrades are described in details, e.g. the new downloadable shape format including key header information, or relevant characteristics from stellar occultation observations for a specific asteroid. Based on the recent publication by Bartczak & Dudziński (2019), it was also possible to assign uncertainties to the physical parameters for a given object: on the volume, the rotation period, the initial rotation angle, and the orientation of the spin axis. The explanatory part gives guidelines to estimate uncertainties of the object's rotational phase into the future.

For more than 25 asteroids it was also possible to include thermal measurements and the results from thermophysical calculations: the number of (used/modelled) IR data, including thermal lightcurves if existing, the radiometric size and albedo solution, with statistical 1-sigma errors and chi2 fit values.

The ISAM statistics produced by Google Analytics shows the high (and steadily increasing) interest and impact of this service: There were about 1600 new users visiting the ISAM web pages.

Relevant **Milestones for WP3** are **MS02** "Benchmark study", **MS07** "Intermediate SAGE code", **MS09** Final SAGE code", and **MS11** "Volume determination for Gaia targets". The milestones were reached via deliverables, uploads to and upgrades of web services and tools, and a large number of publications. WP3 set a new path for obtaining high-quality volume determinations for MBAs, including proper error calculuations (see also WP6 for further discussion).

1.2.4 Work package 4: Asteroid-related calibration

One of the specific challenges in COMPET-05-2015 was listed as follows: "The challenge will however be to allow the European astrophysics community to make the best possible use of those missions by supporting space astronomy observation proposals, using archived data, and making comparisons **(including calibrations)** between different missions, instruments, and between space and ground-based data". WP4 addressed this challenge.

WP4 was closely related to "WP2 Infrared data" where we collected the available thermal measurements, to "WP3 Lightcurve inversion technique" where we tried to produce the best-possible shape and spin solutions for the objects in question, to "WP5 Ground-based observations" where we obtained missing information for the shape & spin determination (if needed) or occultation observations to scale the shape solutions, but also to "WP6 Synergies" where we tested our final solutions against ground-truth information or via other techniques, like AO imaging. The publication by Marsset et al. (2017) on the asteroid (6) Hebe illustrated the interplay between the different techniques. In the second reporting period, we produced secondary asteroid models based on reliable (coarse) shape and spin properties with very precise zero points in rotational phase to be able to phase the object's orientation at any given time. These asteroid models were scaled either by using occultation, AO, in-situ measurements or by applying radiometric techniques to the most reliable IR data points. We also found solid solutions for the thermal properties (thermal inertia, surface roughness, emissivity) for these large MBAs, which are very likely covered with low-conductivity, fine-grained regolith.

WP4 included many tasks that are handled step by step via a sequence of deliverables:

D4. 6 Selection of secondary asteroid calibrators (Apr 2017)

This deliverable was officially part of RP1[3] (approval in July 2017). It included a list of calibration needs and requirements of ongoing and future far-IR, submm, mm projects. It described our investigations on the potential use as secondary calibrators for many large main-belt asteroids. We had put our focus on the collection of available object information and thermal IR observations (+ detailed overview tables with all available thermal data: IRAS, MSX, AKARI, WISE, PACS/SPIRE, ALMA, Planck, ISO, Spitzer, others).

D4.6 is complemented by "D3.3 Shape and spin solutions for secondary calibrators" which had the focus on the required work related to lightcurves and visual observations in general. It was also complemented by "D5.2 High-precision photometry measurement table", which provided the necessary model input for absolute magnitudes and slope parameters.
D4.6 is available on public SBNAF page under "Results".

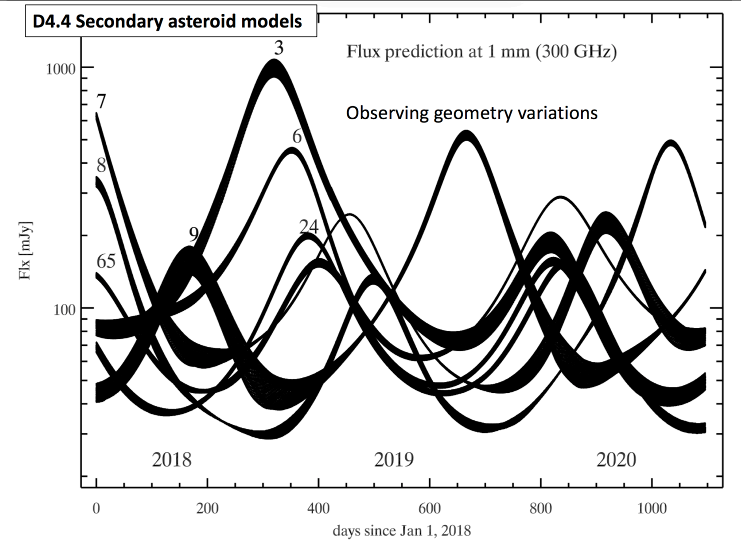
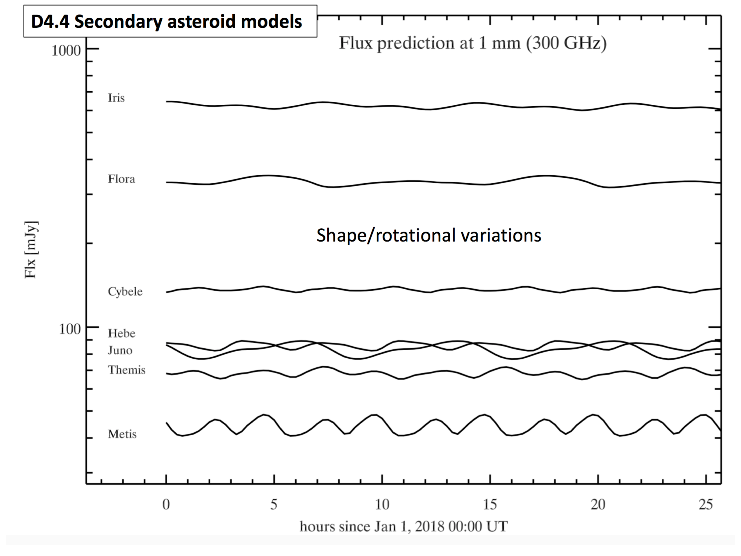
D4.4 Secondary asteroid models (Mar 2018)

D4.4 was following up on D4.6, but now using the established asteroid model solutions for absolute flux predictions at far-IR/submm/mm wavelengths for direct calibration applications. The various instrument/observatory calibration teams have access to these predictions and used the numbers to establish the absolute flux calibration for scientific observations. The contents of D4.4 can be summarized by the following points:

- Shape/spin solution: non-convex (KOALA/ADAM) or convex solutions from DAMIT, or SAGE solutions
- Radiometric solutions, for size, albedo, thermal inertia, surface roughness

[3] Reporting Period 1: Apr 2016 to Mar 2017.

- Determination/validation of submm/mm emissivity
  (tested against ALMA/APEX/SPIRE/...)
- TPM predictions for 10 frequencies (submm/mm range), for the time period 2018, 2019, 2020, with time resolution of 15 min (calibration model version 2)
- Full TPM solutions are available on request
- Documentation in a publication (in the mid-term future), including discussions of the derived properties and comparison with other solutions (from AO, occultations, in-situ measurements, etc.)

	*Asteroid model predictions for far-IR/submm/mm projects like ALMA, APEX, IRAM, SOFIA, and others. The figure shows the absolute fluxes at 1 mm (300 GHz) of several secondary calibrators over a 3-year period (2018-2020). The seasonal flux variations are mainly due to the changing distances between the object and the observer (=Earth). The line width is related to the short-term rotational flux variability.*
	*Asteroid model predictions for far-IR/submm/mm projects like ALMA, APEX, IRAM, SOFIA, and others. The figure shows the rotational flux variability for seven asteroids for Jan 1, 2018 at 1 mm wavelength (300 GHz). The objects cover a flux range between a few 10 mJy and almost 1 Jy. The short-term variations are caused by the object's shape and rotation properties. The absolute flux level, and the timing of the rotational variability was tested against lightcurves and thermal data.*

D4.5 Final asteroid models (Mar 2019)

Within D4.5 we established new and improved asteroid model solutions for absolute flux predictions. At the same time, we improved the quality of the model predictions by testing against existing thermal measurements. One difficulty was to get access to the calibration measurements (like from ALMA) which are usually not well documented and not publicly available. We also aimed for getting more visibility of our calibration contributions by documenting our work in a publication, but this publication is still in preparation (including a dedicated comparison of model predictions and observations in the calibration-critical submm/mm range). In "D4.5 Final asteroid models" we presented our final solutions for primary and secondary asteroids and made them available in the ISAM service. The thermophysical model predictions with high time resolution (typically one data point every 15 min) are available on our SBNAF web page for regular downloads by calibration teams around the world.

The **WP4 Milestones** are also related to WP3 and WP6: **MS07** „Intermediate SAGE code", **MS10** „Models for asteroid calibration", and **MS13** „Submm/mm study on MBAs". The corresponding work is documented in the above-mentioned deliverables, a few publications, and especially via the asteroid calibration products delivered to many calibration teams worldwide: As part of WP4 we have established contacts to various calibration experts (Herschel, Planck, ALMA, SOFIA, APEX, IRAM, ESO-VLT, other IR/submm/mm projects, etc.). We received frequent requests for specific calibration products: mainly asteroid or planet model predictions at specific wavelengths or for observing geometries. But we also provide technical/calibration advice based on past experience from ISO, Spitzer, AKARI, or Herschel. A new calibration project just started recently: a collaboration with the ESO-VLT MATISSE team (NIR-MIR interferometer combining all four VLT telescopes; L, M, N bands, spectral resolution 20 <R<250 in N-band). They requested asteroid model predictions for calibration purposes.

1.2.5 Work package 5: Ground-based observations

WP5 had the main objective to execute observations from ground-based telescopes with the goal to acquire auxiliary data on the targets needed for other work packages. On this particular point the main tasks were to coordinate and carry out observations and to produce results on physical properties of near-Earth Asteroids (NEAs), Main Belt asteroids (MBAs), Centaurs, and trans-Neptunian objects (TNOs). The observations included time-series and absolute photometry, astrometric measurements, stellar occultations and high angular resolution imaging. More details on the tasks of WP5 were given in other project documents (e.g. the First periodic report). Observations of optical lightcurves of the selected SBNAF objects were done basically using the following telescopes:

- 40cm telescope at La Sagra Observatory in Spain.
- 80cm telescope at La Hita Observatory in Spain.*
- 1.5m telescope at Sierra Nevada observatory in Spain.*
- The 1.23m telescope at Calar Alto Observatory in Spain.*
- The 45cm ASH1 at CASLEO, San Juan, Argentina.*
- The 40cm ASH2 at San Pedro de Atacama, Chile.*
- 1.5m telescope based at the Bosque Alegre Observatory, in Argentina.*
- The 90cm and 1.0m telescopes at Piszkesteto Mountain Station, in Hungary.
- The 40cm telescope at Borowiec Observatory, in Poland.
- The 80cm telescope at the Observatori Astronomic del Montsec in Spain.
- The 0.25 BEST and 0.15m VYSOS-6 telescope at Cerro Armazones, in Chile.
- The I64 observatory under the Gaia-Gosa collaboration in UK
- The I39 Cruz del Sur observatory under the Gaia-Gosa collaboration in Chile.
- The 40cm Albox Observatory telescope in Spain.
- The 20cm Anunaki observatory, in Spain.

In addition, we obtained high accuracy astrometry from CCD images to refine shadow-path predictions for stellar occultations using the telescopes marked with (*) in the previous list and:

- The 90cm at Sierra Nevada observatory in Spain.
- The 2.2m telescope at Calar Alto Observatory in Spain.
- The 2m Liverpool Telescope at Roque de los Muchachos Observatory in Spain.
- The 1.2m Stella Telescope at Teide Observatory in Spain.

After one or two observations, some occultation events predictions were discarded because the predicted shadow missed the Earth. Conversely, when a shadow path was identified to cross a telescope-dense region on Earth (Europe, South America, Japan, USA, Australia, New Zealand) the prediction was further refined and the observers (amateurs and professionals) were alerted. Professional telescope time was also requested whenever possible (VLT in Chile, Casleo in Argentina, IAC-Canary Island Observatories in Spain) and observations were carried out.

In the second and third year of the SBNAF project we observed 46 stellar occultations (and predicted hundreds of them): 14 by MBAs (12 positive) and more than 32 by Centaurs and TNOs (15 positive). We presented/reported them in international conferences and/or we published –or are in the process of publishing them– in scientific journals. We have also obtained around 4000 hours-worth of SBNAF target lightcurves that led to the refinement of the rotational period and amplitude of the targets. In many cases, the data were included in lightcurve inversion models (WP3 and WP6).

More than 40 peer-reviewed articles using data obtained within WP5 have been published (or accepted) during the second period. All of them were related with the different techniques used within WP5. The list of these papers was included in the impact section of this report and deliverables D5.7 „Observational publications 2” and D5.8 „Observational publications 3“.

The deliverables related with WP5 prepared during this second period are the following:

D5.5 Time-series photometry measurement table (31 Mar 2017)

D5.5 was part of RP1 (approval in July 2017). It contained an overview table with available time-series photometry measurements.

D5.6 Observational publications 1 (31 Mar 2017)

D5.6 was part of RP1 (approval in July 2017). It included a brief description of the different observational techniques used to obtain auxiliary data of the SBNAF targets and applications of all these observational data.

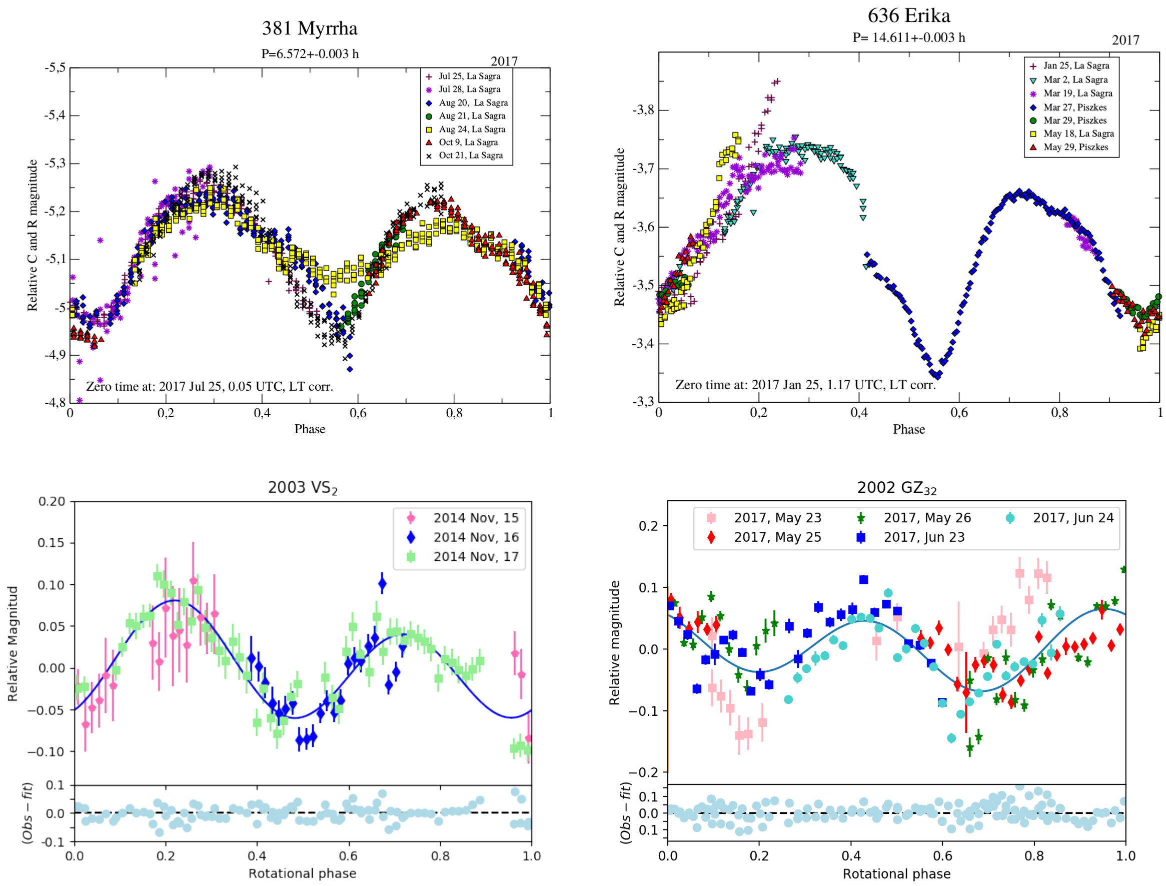


Fig.1.2.5.1- Top left, top right: two examples of rotational lightcurves of MBAs obtained within WP5. Bottom left: TNO 2002 VS$_2$. Bottom right: Centaur 2002 GZ$_{32}$.

A list of works (published or in preparation) related to each observational technique within the SBNAF project was provided. This list was updated for the deliverables: D5.7 „Observational publications 2“ and D5.8 „Observational publications 3“.

D5.3 Occultation candidates for 2018 (31 Dec 2017)

The potential occultation candidates for 2018 were presented. This deliverable followed deliverables D5.1 and D5.2, and was related to milestones MS5 "Occultation predictions with 10 mas accuracy", and MS12 "25 successful TNO occultation measurements". In this document, we first gave a short state of the art of the stellar occultation technique, then we discussed about the expected goal to reach ~10 mas accuracy in the prediction of stellar occultations by TNOs. After that, we gave a list of stellar occultations observed within the SBNAF project, and finally we provided our stellar occultation predictions for the year 2018.

D5.7 Observational publications 2 (31 Mar 2018) & D5.8 Observational publications 3 (31 Mar 2019)

These deliverables were updates of the list of works (published or in preparation) included in deliverable D5.6. These works are related to each observational technique within the SBNAF project, all of them include the SBNAF grant acknowledgement and (most of them) are publicly available via arXiv. Some of the works were repeated within different observational techniques because they included relevant results related with various techniques. The list was updated after year 2 (D5.7) and again in the deliverable: D5.8 „Observational publications 3“, covering the second reporting period.

D5.9 Observations delivery to MPC, CDS & PDS (31 Mar 2019)

In this deliverable we briefly described the observations and data obtained within SBNAF WP5 that are publicly available in the data archives of the Planetary & Astronomy Science Communities. Some of the data obtained within WP5 were also included in different database services, and/or in open-access papers.

The deliverable was structured by data available in MPC (Section 1), CDS (Section 2), PDS (Section 3), and in other databases/services (Section 4). In Section 4 we mention the stellar occultation predictions (in close collaboration with the ERC Lucky Star project), the web service in Rio de Janeiro/Brasil with the public collection of occultation results, the ISAM service in Poznań where the resulting 3-D shape models (and occultation information) are stored, the public SBNAF database for infrared observations of asteroids, and the Herschel Science Archive and IRSA archive where our Herschel special products are stored and made available to the public.

The open access to the SBNAF-related publications is given via ADS and also via our public SBNAF web page. At the end of the project on Mar 31, 2019, ADS found 68 publications with the SBNAF EU acknowledgment, almost all of them are available in open access. About 50% of these publications in ADS include links to „*external data products*“ pointing to CDS, SIMBAD, ESA, ESO, Herschel, ALMA, NED, MAST, etc.

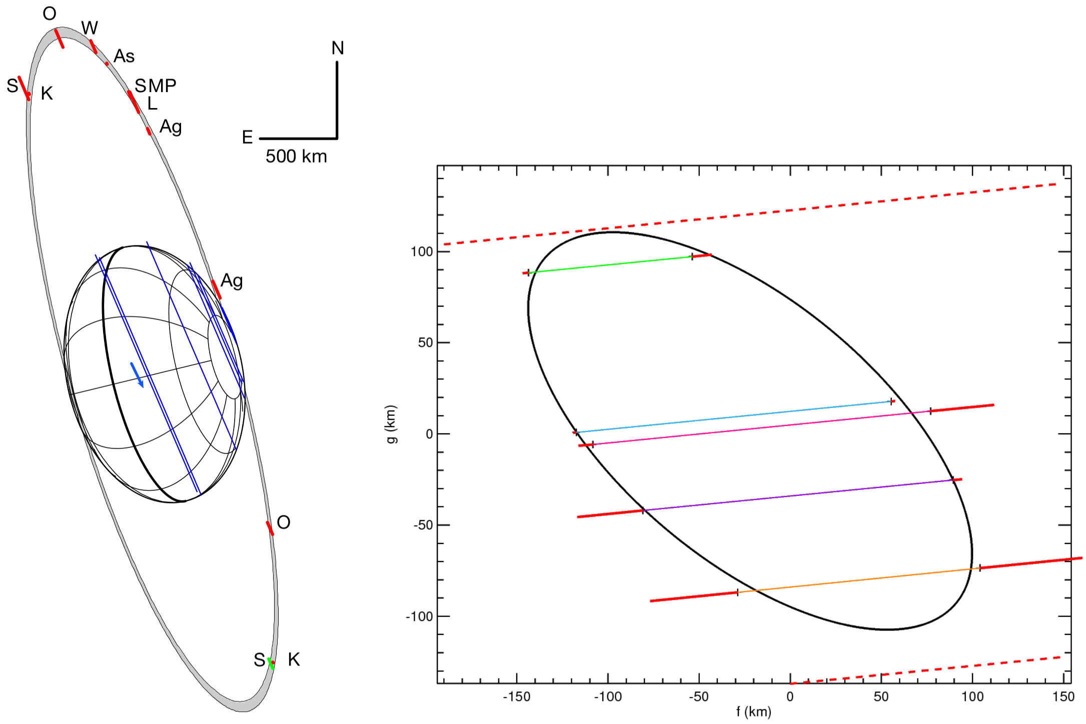


*Fig.1.2.5.2- **Left panel:** result on the stellar occultation by the dwarf planet Haumea with the detection for the first time of a ring around a trans-Neptunian object. These results were published in Ortiz et al. 2017 (Nature). **Right panel:** results on the stellar occultation by the centaur 2002 GZ_{32} (Santos-Sanz et al. in preparation).*

Milestones directly related to WP5:

- MS05: "Occultation predictions with 10 mas accuracy to be reached in month 24 (31 Mar 2018). Means of verification: Reaching TNO occultation prediction accuracy of better than 10 mas for the shadow path. Means of verification: Success measurement of TNO occultation after inclusion of the Gaia stellar catalogue in the prediction tools".

- MS05 has been reached by the end of the project. Haumea, Bienor, and Huya are recent examples of occultations with uncertainty predictions well below 10 mas (around 4-5 mas in some cases!). However, it is important to note that there is no method to guarantee this accuracy in the predictions, even for some of the larger TNOs and despite the availability of the Gaia DR2 data catalogue for the relative astrometry a few days prior to the occultation event. There are some problems that prevent high-quality predictions, like astrometry which is influenced ('modulated' or contaminated) by the gravitational effects of undiscovered satellite(s). Also, the occulted star can have undetected companion(s) which affect the astrometry (and therefore the prediction of the occultation event). There are very intense astrometry campaigns needed during the days/weeks before a potential occultation event happens, and here, the observing conditions (weather) and the available instruments/telescopes influence the final accuracy. Our general conclusion is that each case is different and must be treated very carefully and in an independent way, but for "nominal" TNO occultations it is meanwhile possible to reach the 10 mas accuracy for the shadow prediction. More details are given in "Stellar occultations by Trans-Neptunian Objects: from predictions to observations and prospects for the future", by J. L. Ortiz et al. 2019, chapter in "The Trans-Neptunian Solar System" (D. Prialnik, M.A. Barucci and L. Young, eds.), accepted in early 2019.

- MS12: "25 successful TNO occultation measurements to be reached in month 36 (31 Mar 2019) Means of verification: The total number of successful TNO occultation measurements reaches 25, including measurements of objects below 500 km size (all dwarf planets). Means of verification: Summary presentation of all TNO occultation events in a major conference. Summary publication on occultation measurements of all dwarf planets in the trans-Neptunian region, in combination with thermal data".
  - We have observed more than 60 stellar occultations during the SBNAF project obtaining 26 positive detections. This means that the ambitious Milestone 12 (MS12: *25 successful TNO occultation measurements to be reached in month 36*) has been reached on time. It is expected that astrometric data obtained from most of these occultations will be provided to MPC in the near future. More information about all these occultations is in our password-protected SBNAF targets web page: http://asteroidstnos.iaa.es/content/results#overlay-context=content/sbnaf. A review oral contribution of this work was given at the ThermoPS-III conference organised by the Konkoly team in Budapest (Feb. 2019).

1.2.6 Work package 6: Synergies from ground and space

The main goal of this work package (WP) was to make scientific exploitation of the different techniques and tools used and developed in the other work packages in combination. To that end, it was necessary to benchmark the different approaches against ground truth information and to compare the techniques that provide complementary information in order to identify their strengths and weaknesses and define strategies to combine them to overcome their limitations. In this sense, it was also crucial to appropriately quantify errors, which is especially complicated in the case of three-dimensional shape models.

We next summarize the work carried out in the framework of deliverables D6.6, D6.7, and D6.8 falling into the second reporting period. We also included the resubmitted version of deliverable D6.5 to address the main objection raised by the external referee. Finally, since most of our activities already involve the different tools and services (e.g. ISAM, preparation of the IR database), products (IR and optical data, occultations), and project members to collaborate and apply their expertise in different fields, our scientific output was framed in the synergetic frame of WP6 and has materialized in the many publications accepted or submitted for review during these second period (see also Sec. 1.3).

D6.5 Ground-truth shape models (Version 2) (Sep. 2017)

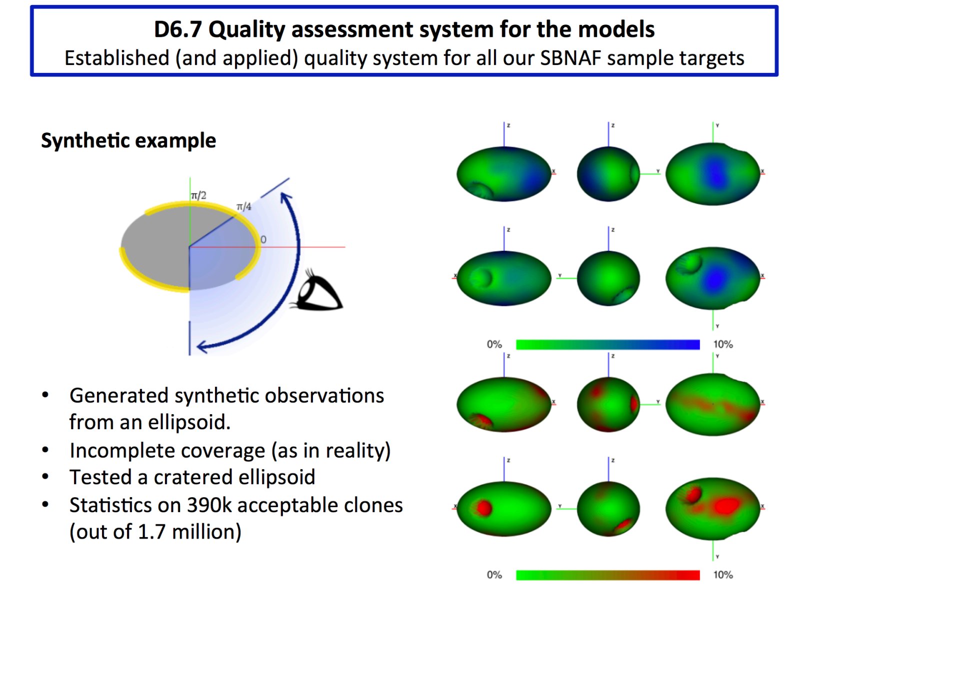
Our external referee requested the reopening of D6.5 on the grounds that it was insufficient to assess whether the SAGE model had been robustly validated. The reason for this was that, at the time of submission of Version 1 (March 2017), all our works were featured in articles that had been submitted to journals for peer-review or were in preparation, so we opted to omit details from the deliverable given it was a public report. In the meantime, those works had been published, so Version 2 contained some relevant details and references to the official publications. In response to the feedback we obtained from the referee after our 3rd Team meeting in Poznan (May 2017), we had expanded Version 2 by studying all publicly available ground-truth information of targets visited by spacecraft (including fly-bys) and assessing which ones offer good prospects for benchmarking and scientific exploitation. This was summarized in Table 3 in the deliverable.

D6.6 Thermally resolved shape models (Sep. 2017)

This deliverable summarized the thermo-physical modelling carried out on multiple shape models (convex, non-convex, and all corresponding spheres) of five targets featured in Marciniak et al. (2018). In addition, the deliverable expanded on the discussion provided in the article about the minimum thermal-data coverage required to ensure adequately constrained thermophysical parameters and, in the best cases, the rejection of multiple ambiguous solutions. Contrary to what is commonly assumed, we discussed that the thermal infrared data does not contain, in general, detailed information of the shape, especially the shorter wavelength data. Furthermore, solving shape ambiguity and producing well-constrained thermophysical properties not only requires a balanced coverage of pre- and post-opposition observations (i.e. sampling of the morning/evening temperatures) but also a good sampling of the northern and southern hemisphere cross-sections (described by the aspect angle). This work served as a guide to anticipate a successful scientific exploitation based on currently available data or otherwise to identify critical epochs and strategies (observing geometry, aspect angle, pre-/post-opposition, wavelength) to maximize new information content in planning observations.

D6.7 Quality assessment system for the models (Mar. 2018)

Shape models published in the literature do not come with any sort of quantified information about the uncertainty of the shape. In this deliverable we presented the fundamental aspects of a quality assessment system developed (Bartczak & Dudziński 2019, MNRAS 485, 2431B.) to take any shape model as input (convex, ADAM, SAGE, etc.) and to produce a measure of the uncertainty as a number. The shape uncertainty will be crucial for estimating volume and hence density uncertainty. In a nutshell, the approach is statistical and uses millions of randomly perturbed clones of the input shape and all optical light-curve data available for the target. Here (see figure below), an example using a synthetic shape (a cratered triaxial ellipsoid) and an optical light-curve catalogue with incomplete apparition coverage (as in reality) is given. At the end of the SBNAF project, the ISAM service contained already several 10 asteroids which underwent the D6.7 Quality assessment system (see also results given in D3.8 „Joint multi-data inversion models“).



Schematic summary of the quality assessment system for the models. Left: illustration of the partial coverage of the synthetic observations of an ellipsoid created to demonstrate the basis of the method (Bartczak & Dudziński, 2019). Right: cratered ellipsoid to which the method is applied and corresponding positive and negative deviations from the original shape.

Model uncertainty

Physical parameter of model	Value and uncertainty	
Volume (R_{max}=1)	$2.03081958^{+49\%}_{-33\%}$	
Period	$7.045876^{+0.000008}_{-0.000010}$	h
Rotation phase γ	62^{+12}_{-14}	deg
Epoch	2447890.369635	JD
ΔT	17730.683	day
Pole solution	(λ) 58.2^{+5}_{-10} (β) -9.6^{+22}_{-10}	deg

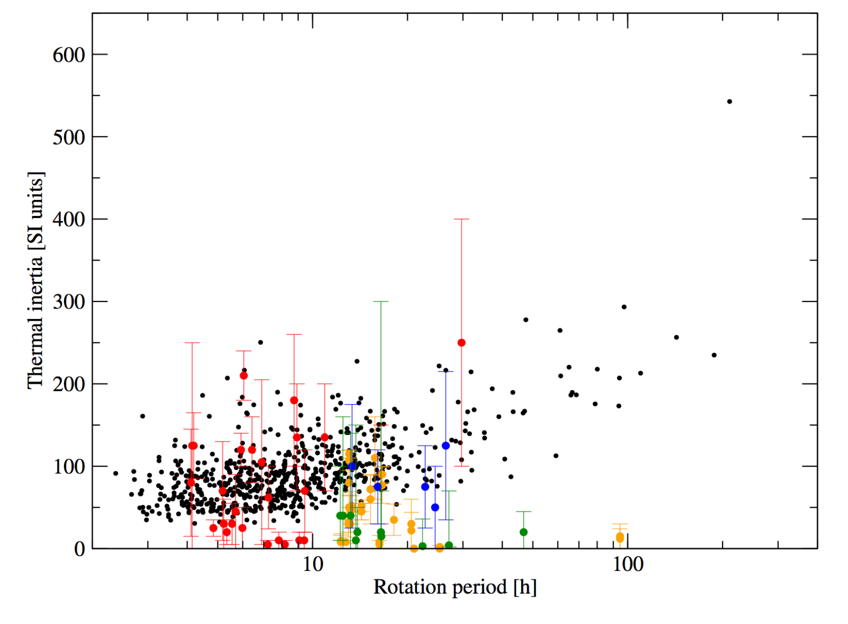
For several 10 asteroids the ISAM web service also provides a sub-page on the rotational and physical properties of a given asteroid model (example here: 13 Egeria, spin-shape-size solution model 5). Deliverable D3.8 describes the procedures behind these results.

D6.8 3D shape models for large MBAs (Jan. 2019)

Here, we presented shape model solutions scaled by stellar occultations, thermophysical modelling or AO results, as baseline for the volume determination of the Gaia mass sample. The deliverable built up on D6.4 „Gaia asteroid list“, and D3.4 „Asteroid volume determination“. Both deliverables were crucial to identify objects with missing/incomplete lightcurves and to push for new occultation measurements for these targets. Extensive observing campaigns on these SBNAF Gaia mass targets followed, taking advantage of the large network of ground-based observers all over the world (see also observatories listed in WP5). Here, we should mention the SuperWASP asteroid archive which added very valuable lightcurves to our project but were overlooked by a large part of the community so far.

D6.8 describes also the procedure for the spin-shape modelling and the quality assessment work. A new element for the large MBAs was the scaling of the derived models by stellar occultations (Sec. 4) and by radiometric techniques (Sec. 5) using a thermophysical model code for the available thermal measurements of a given asteroid. Section 6 summarized the results for 17 asteroids in total, and showing comparisons between SAGE, ADAM or simple convex shape models for several objects. The summary tables at the end list the existing occultation information for these objects, all tested models, input data, size solutions, together with comprehensive comments on each solution. These scaled 3D shape models of large MBAs will be used in combination with the mass estimates which will be provided by Gaia in the near future.

Several **Milestones** are connected to WP6 and reflect the synergy work within the SBNAF project: **MS06** Hayabusa2 target characterization, **MS07** Intermediate SAGE code, **MS08** Quality assessment system, **MS09** Final SAGE code, **MS11** Volume determination for Gaia targets. All these milestones are reached by multiple publications on the specific topics. More details about the „means of verification“ for each MS are given in the corresponding section on SBNAF milestones.



Plot of thermal inertias (Γ) versus rotation period taken from Marciniak et al. (accepted, Astronomy & Astrophysics). We tested a hypothesis by Harris & Drube (2016) that the thermal inertias of slow rotators should increase. They estimated 100s of thermal inertias (black dots) based on simple thermal models and the values of G available at the time (red dots, compiled by Delbo' et al. 2015). However, the new values (green and blue, from Marciniak et al. 2018 and 2019, orange from Hanuš et al. 2018) do not confirm such trend.

In the second reporting period we continued to exploit the possibilities and limitations of combining multiple techniques and data. We summarized our findings in recent deliverables, multiple publications, conference contributions, and upgrades to our tools and methods. The above figure on the thermal inertia of asteroids as a function of their rotation period is a good example of the collaborative efforts within the team and including a large network of observers worldwide (taken from Marciniak et al. 2019). But the most important result of our collaboration in WP6 is that the SBNAF team members gained valuable experience and a common understanding of the complementary nature of data and techniques to best characterize small bodies near and far. These fruitful collaborations will continue in the future, beyond the SBNAF project.

1.3 Impact

In our initial project description, we identified ten areas where we expected impacts by SBNAF-related work. Scientific output, tools and services expected for the reporting period have been delivered, such as studies in support for on-going planetary mission targets (Ryugu and Bennu), Herschel expert-reduced data products, calibration-related flux predictions for Herschel, ALMA, SOFIA, APEX, etc., production of new shape and spin solutions for MBAs, procedures to test, validate and scale shape solutions or more accurate stellar occultation predictions (phasing in Gaia results) and successful occultation observations. These actions have been collected in the deliverables summarized in this document and/or in a large list of publications in scientific journals, which is the major medium through which scientific impact is materialized. Based on our target sample we identified open points and a range of specific scientific questions that we wanted to address in the SBNAF project (Table 1.1 in the SBNAF proposal). Most of these questions were discussed, and largely answered, in the SBNAF-related publications.

Publications: In the second project phase (Apr 2017 to Mar 2019) we published (or contributed to) the following articles: 18 refereed articles in 2017, including the Nature article on "The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation" by Ortiz et al. 2017 (Nature 550, 219-223), 32 publications in 2018, including the Nature Astronomy article on "Ring dynamics around non-axisymmetric bodies with application to Chariklo and Haumea" by Sicardy et al. 2018 (Nature Astronomy 3, 146-153), and currently 14 published or accepted articles in 2019 (plus another 5 submitted papers). Overall, we counted 78 articles either led by SBNAF team members or with strong contributions from the SBNAF project. These publications acknowledge the funding from the European Union's Horizon 2020 Research and Innovation Programm (under Grand Agreement no 687378). The list of publications at the end of the SBNAF project are all listed in the EU SYGMA system with the corresponding DOI. The citations to these papers are steadily going up, currently well above 500 (excluding the Gaia publications). There are still several SBNAF-related publications in preparations or close to submission. All related publications can be easily identified in the following way via ADS (also at a later stage):
https://ui.adsabs.harvard.edu/search/q=%20full%3A%22SBNAF%22
Or
https://ui.adsabs.harvard.edu/search/q=%20full%3A%22687378%22
(in the second case there is some cleaning required since the ID „687378" also appears in a few other publications, not related to SBNAF).

Conferences: During the second reporting period (April 2017 to March 2019) we attended the following conferences where we presented SBNAF-related results:

- Ürkutatási Fórum, Apr 5-7, 2017, Sopron, Hungary (Hungarian Space Forum)
  - "Small Bodies: Near and Far" — kis égitestek karakterizálása földi, űr- és helyszíni adatok alapján
- Asteroids, Comets, Meteors 2017, Montevideo, Uruguay, April 10-14, 2017
  - Physical properties of TNOs and Centaurs from stellar occultations and thermal observations
  - What is Bienor hiding in its photometric behaviour?
  - Measuring sense of rotation of V-type asteroids outside the Vesta family
  - Shape uncertainty of asteroid models from inversion techniques
  - Ryugu: 15 months to showdown
  - Updated asteroid diameters and albedos from AKARI/IRC mid-infrared data

    - Photometry of asteroids in crowded star fields in SBNAF project
    - Results from stellar occultations by trans-Neptunian object (84922) 2003 VS2
    - 2008 OG19: A Varuna-like trans-Neptunian object?
    - Debiasing asteroid spins and shapes - observations, modeling, and validation
    - Asteroid shape reconstruction from radar echo images
    - First Results from "Small Bodies Near and Far (SBNAF)": A benchmark study for the characterization of asteroids and TNOs
- Polish National Astronomical Meeting, 11-14 September 2017, Zielona Góra
    - Debiasing asteroid spins and shapes - observations, modeling, and validation
    - Photometry of asteroids in crowded star fields in SBNAF project
    - Inner Main Belt V-type asteroids as tracers of early planetesimals
- 12th European Planetary Science Congress (EPSC), 17–22 September 2017, Riga, Latvia
    - Session SB12: Small Bodies Near and Far; Convener: T. Müller; Co-conveners: P. Santos-Sanz
    - The 2017 January 21st multi-chord stellar occultation by the dwarf planet Haumea. Preliminary results
    - Physical characterization of Kuiper belt objects from stellar occultations and thermal measurements
    - Herschel-PACS high-precision FIR fluxes of NEAs and MBAs
    - Small Bodies Near and Far (SBNAF): Characterization of asteroids and TNOs
    - Thermal emission of the Eris-Dysnomia system
    - K2 and Herschel/PACS light curve of the Centaur 2060 Chiron
    - Serendipitous observations of asteroids in Herschel PACS and SPIRE maps
    - Asteroid phase-curves from Gaia-calibrated data
- 49th Annual Division for Planetary Sciences Meeting, 15-20 October 2017, Provo, Utah
    - The stellar occultation by the dwarf planet Haumea
    - A dense ring around the dwarf planet Haumea
    - Absolute colors and phase coefficients of Trans-Neptunian objects: HV - HR colors
    - The thermal emission of Centaurs and Trans-Neptunian objects at submm wavelengths from ALMA observations
    - Spatially resolved thermal emission of the Eris-Dysnomia system
    - Search for signatures of extended emission around dwarf planets on Hubble Space Telescope archival images
- 4th AKARI international conference, October 17-20, 2017 at the University of Tokyo/Japan
    - Asteroids and the solar system: insights from the thermal infrared
    - AKARI and the Small Bodies: Near and Far (SBNAF) project
- Physics opportunities with a new universe's view: the SKA radio telescope, 6-7 Nov 2017, Instituto de Física Corpuscular CSIC/UV, Paterna, Valencia/Spain
    - The potential of SKA to detect the thermal emission of distant Solar System objects
- JWST Solar System Workshop, 13-15 December 2017, Noordwijk, The Netherlands
- TNO/KBO workshop "The Trans-Neptunian Solar System" , Mar 26-29, 2018, Coimbra, Portugal
    - The iciest dwarf planet?
    - "TNOs are Cool": Herschel Survey of the Trans-Neptunian Population
    - Interpretation of Haumea's thermal emission in the light of the occultation results
    - Compositional study of TNOs beyond 2.2 μm in preparation for the JWST
    - Thermal properties of bright Transneptunians and Centaurs from PACS and SPIRE observations at 70-500 micron with HERSCHEL
    - Transneptunian objects at thermal wavelengths: thermophysical and emissivity properties
    - Kepler-K2/Herschel Centaurs
    - Physical properties of the Haumea family observed at far-infrared wavelengths
    - Varuna: a multi-wavelength portrait of this intriguing object
- Europlanet - VESPA workshop, Apr 16-20, 2018, Prague, Czech Republic
- Near-Earth Asteroids: Properties, Detection, Impacts and Protecting Earth, Garching/Munich, Germany, May 14 - Jun 8, 2018

- SPICE Training class held by NASA's Navigation and Ancilliary Information Facility (NAIF) at ESAC, Villafranca de la Cañada, Madrid, Spain, June 19-22, 2018
- Asteroids and Comets - Inside Out Workshop (ACIO18), September 4th-6th 2018, Tampere, Finland
- EPSC 2018, Sep 16-21, 2018, TU Berlin, Berlin, Germany
    - Astrometry and photometry of TNOs and asteroids using Gaia DR2
    - Small Bodies Near and Far (SBNAF): Challenges in the Physical and Thermal Characterization of NEOs, MBAs and TNOs
    - An extensive photometric study of the dwarf planet Makemake
    - Thermal properties of slowly rotating asteroids
    - Asteroid spin properties derived from thermal data
    - The stellar occultation by the Transneptunian Object 2002TC302 on January 28th 2018. Preliminary results.
    - Mapping Trojan Asteroids in the thermal infrared with TROTIS
- DPS 2018, Oct 21-26, 2018, Knoxville, Tennessee, USA
    - K2 light curves of eight Centaurs
    - The mass and density of the dwarf planet 2007 OR10
    - Thermal properties of large main belt asteroids derived from Herschel PACS data
    - The Mass, Density, and Figure of the Kuiper Belt Dwarf Planet Makemake
    - Spin State of (5247) Krylov
    - Volume uncertainty assessment method of asteroid models from disk-integrated
    - Star occultations by asteroids
    - The hypnotic dance of Patroclus and Menoetius: Ground-based observations of their 2017-2018 mutual event season
    - Physical properties of trans-Neptunian objects and centaurs
    - Thermal Infrared Observations of C-type Asteroid 162173 Ryugu by Hayabsua2
- Gaia Science Alerts Workshop, Oct 8-10, 2018, Vipava, Slovenia
    - Asteroid studies supported by Gaia
- TherMoPS (Thermal Models for Planetary Science) III, Budapest, Hungary, Feb 20-22, 2019
    - Combined inversion of optical and thermal data of asteroids
    - The thermal inertia of (16) Psyche revisited
    - Filling the gap. Asteroids with slow rotation in thermal infrared
    - Thermophysical modelling of Centaurs & TNOs
    - Properties of resonant trans-Neptunian objects based on Herschel Space Observatory data
    - What can we learn of TNOs / Centaurs from the combination of thermal data and stellar occultations?
    - The first global thermal images of asteroid 162173 Ryugu by Hayabusa2
    - High-resolved thermographic observation of craters and boulders on Ryugu
    - Global thermal inertia and surface roughness of asteroid Ryugu by TIR on Hayabusa2
    - Database for thermal infrared observations of solar system small bodies
    - Far-infrared and submm flux densities from serendipitous observations of asteroids in Herschel PACS and SPIRE maps
    - The Moon as flux calibrator for TIR measurements of Ryugu during the Hayabusa2 approach phase in June 2018
    - Thermal properties of large asteroids from Herschel PACS data
    - GaiaGOSA and ISAM- services for asteroid studies
    - Small Bodies Near and Far: Synergies from ground and space
- ESO/VLT large programme meeting, Mar 20-22, 2019, OHP, France
    - Hygia and Interamnia studies within SBNAF project
    - Gaia GOSA observations of VLT targets
    - Shape uncertainties

The **impact of the SBNAF-related tools and services** are more difficult to quantify. The ISAM service with spin-shape solutions for more than 1600 asteroids and practical tools for professional and amateur astronomers is gaining more and more attention, reflected in the numbers for new and returning visitors produced by Google Analytics (see D3.6 for more details).

The Gaia-GOSA service has meanwhile more than 140 active users and the number of contributed observations is steadily increasing. This service was advertised and supported by the SBNAF project, at the same time we benefited from the uploaded lightcurves when we tried to find good spin-shape solutions for the SBNAF targets. The new links betweeen the Gaia-GOSA users, the SBNAF team, the VLT AO team, occultation experts, and the Gaia mission are key in making substantial progress in the characterization of large MBAs.

The public release of our IR database of asteroid/TNO thermal observations only happened in February 2019, but we could already see great interest in this service during our SBNAF workshop on "Thermal Models for Planetary Science". We presented this service to about 60 participants. Future operations of the infrared database are guaranteed until the end of 2021 by funding of the Hungarian Academy of Sciences and by National Research funding. The database is also prepared to be included in the VESPA interface (Virtual European Solar And Planetary Access).

The **impact of SBNAF-related products** (occultation predictions, new products for the Herschel archive, calibration products) can be seen by a long list of publications related to these products. The occultation predictions (mainly for TNOs and Centaurs) opened up a new avenue for (professional and amateur) observers and put European astronomers in a lead position in this field. The new Herschel products of NEAs (D2.2), MBAs (D2.3), and TNOs (D2.4) are unique at least for another decade and will be exploited in the near-to-mid-term future by the planetary science community. The asteroid calibration products are less visible, but picked up and used by various calibration teams. These asteroid model predictions are important to enable a high-quality flux calibration for many submm/mm observatories in the world.

Our work on combining different techniques (occultation with thermal measurements, or AO with occultation and lightcurve inversion, or thermal with lightcurve inversion) produced very nice results, documented in a long list of publications. We also tried to push the combination of different techniques (occultation and thermal) for trans-Neptunian objects which are extremely difficult to characterize otherwise. This expertise has meanwhile very good visibility which can be seen in new collaborations in and outside Europe. The SBNAF work on NEAs (like Ryugu) became also important in the context of interplanetary mission and for the interpretation of in-situ data.

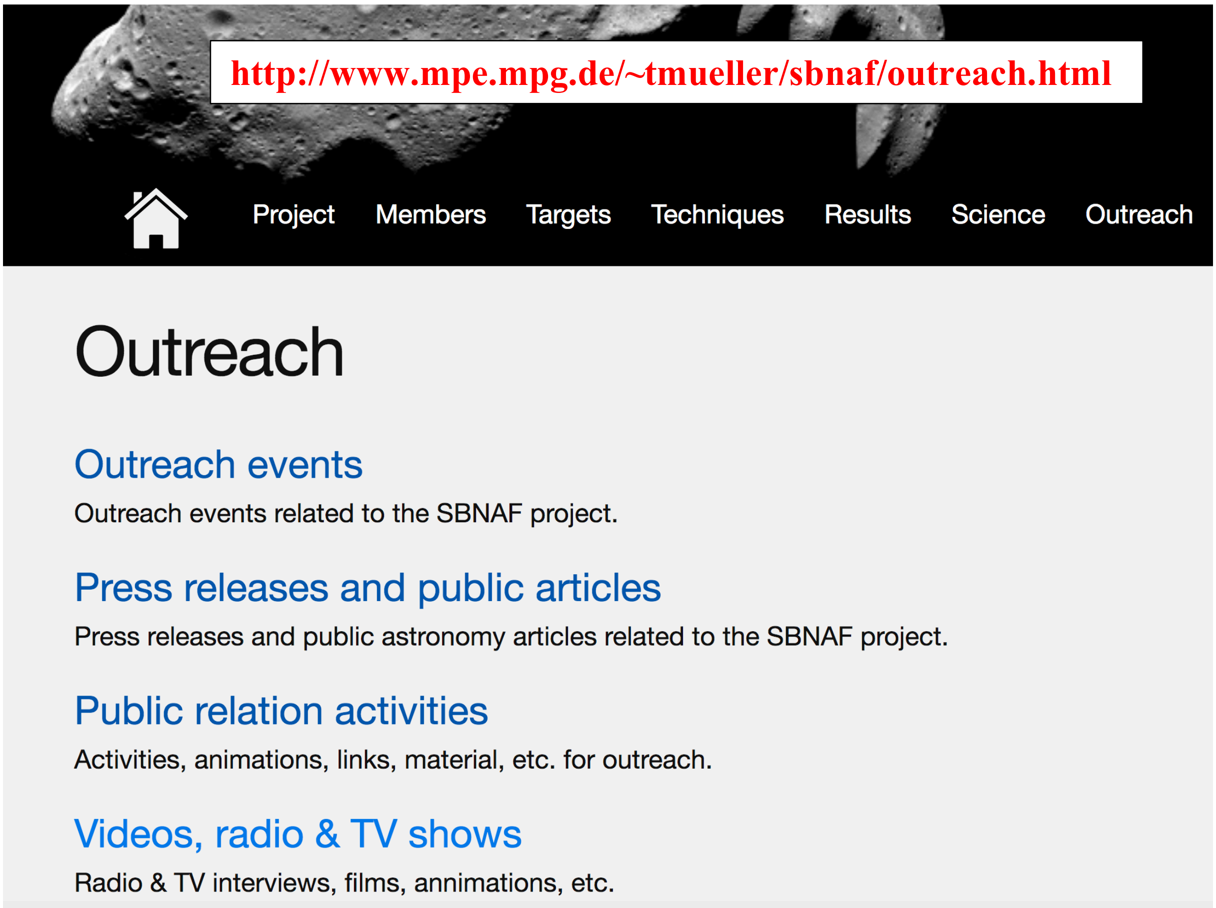
Most of the **SBNAF related observations** (lightcurves, photometric data, colours, infrared-/submm-/mm-observations, occultations, etc.) were made available via public databases for the Planetary Science community, like the Minor Planet Center (MPC), the Centre de Données astronomiques de Strasbourg (CDS), the Planetary Data Systems (PDS), and other archives like the Herschel Science Archive (HSA) or the NASA/IPAC Infrared Science Archive (IRSA). In addition, the data presented in SBNAF-related publications are fully available through the open-access strategy. One of the final SBNAF deliverables in WP5 (D5.9 Observations delivery to MPC, CDS & PDS) describes the various data repositories for our SBNAF data and how to find them. The best strategy is to use the new Astrophysics Data System (ADS) at https://ui.adsabs.harvard.edu/ which shows that about 50% of our publications include *external* *data products* linked to CDS and to other data archives like SIMBAD, ESA, ESO, Herschel, ALMA, NED, MAST, etc.

In the second reporting period (Apr 2017 to Mar 2019) the **new elements in the SBNAF project** were (i) the phasing in of Kepler-K2 lightcurve observations of MBAs, Trojans, Centaurs, and TNOs; (ii) the collaboration with AO imaging experts for the characterization of MBAs; (iii) new attempts to obtain submm/mm observations of our targets (via IRAM and ALMA); (iv) cross-comparison between remote and in-situ observations for NEAs. These aspects will have significant impact in the field of small-body (NEAs, MBAs) and TNO research in the future.

Workshop: In February 2019, we organized the TherMoPS (Thermal Models for Planetary Science) III workshop at the Academy of Sciences in Budapest, Hungary. The workshop was very well attended with about 65 participants from all over the world, including experts from NASA, ESA, DLR, and JAXA. During the 3-day meeting, we had oral and poster sessions on the following topics: Thermal models I+II; Asteroids; Centaurs, TNOs and icy bodies; Thermal in-situ measurements I+II; Laboratory, input data, calibration; Survey results I+II; The Moon; Satellites, Rings & Mercury; followed by discussions sessions on each topic. The SBNAF team organized the workshop and presented the project results, tools, services and several interesting science cases. One of the highlights of the workshop was the first Hayabusa2 touchdown on Ryugu which happened during the workshop. First images and results were shown directly after the event by three Japanese workshop participants from JAXA. All workshop abstracts and many talks and posters are available from the workshop page: http://thermops2019.hu/.

2. Update of the plan for exploitation and dissemination of result

No update of the original plan was needed. The SBNAF team was very active in producing outreach material (Youtube videos, posters, 3-D asteroid shape models, flyers, articles in public/amateur astronomy journals, etc.). The various topics on small bodies were presented in many public events, like the "Asteroid Day" (every year on June 30), the Marie Skłodowska-Curie action "European Researchers Night" (every year on the last Friday in September), public open-door institute days, public talks in the context of astronomical events like the Perseid Meteor shower or eclipses, or in public lectures/seminars either given at the institute premises, scientific fairs, schools, or in public places like town halls or shopping malls. Some of our technical and scientific work was also used for press releases and public articles, with the highest-impact topic being related to the discovery of a ring around Haumea (see Nature paper above).



The SBNAF outreach material and also the press releases (we counted 26 press releases in total, via the host institutes, ESA, NASA, JAXA, HST, JPL, the EU, and others) are presented in English and available worldwide from our public web page. The SBNAF public talks and articles were usually presented in one of the four SBNAF languages (Polish, Spanish, Hungarian or German) and reach the local and regional population.

QR code for our public web page

The SBNAF project was and still is very well visible from Google searches: We tested “SBNAF” searches from different places in Europe and typically 9 out of the 10 first Google hits were (are) related to our project.

3. Update of the data management plan

Not applicable. We did not participate in the pilot project on "Open Research Data in Horizon 2020" and therefore no "Data Management Plan" was required.

4. Follow-up of recommendations and comments from previous review(s)

4.1 Recommendations from the external review related to the first periodic report (covering Apr 2016 to Mar 2017)

Our first external referee (P. Pravec) requested the reopening of D6.5 on the grounds that it was insufficient to assess whether the SAGE model had been robustly validated. At the time of submission of D6.5 (March 2017), all our works were featured in articles that had been submitted to journals for peer-review or were in preparation and we opted to omit details from the deliverable, since it was a public report. Meanwhile, all those works have been published, so we included some relevant details and references in an updated (and public) version of D6.5. In addition, in response to the feedback and suggestions from the referee (P. Pravec) after our 3rd Team meeting in Poznan (May 2017), we have also re-examined all available ground-truth information existing for targets visited by spacecraft (including fly-bys except a couple of cases where the resolution of the images is too poor) and assessed which ones offer good prospects for benchmarking and scientific exploitation. This work is summarized in Table 3 in the updated deliverable D6.5.

Furthermore, our referee recommended additional benchmarking cases including thermal infrared analysis to more robustly establish the reliability of the SAGE approach and fulfill Milestone 2. Work in that line had already been taken soon after our review meeting and several SAGE models vetted against thermal IR data have been published (Marciniak et al. 2018) and are available in the ISAM service. Finally, because this recommendation is well in line with the major project objectives of developing a quality system for shape models and maximize thermo-physical characterization of our targets, we continued to work in this direction up the end of the project. The latest results of the benchmarking studies are given in Bartczak & Dudziński 2019: Volume uncertainty assessment method of asteroid models from disc-integrated visual photometry, MNRAS 485, 2431-2446. This method was used to assess the uncertainties of fictitious test models and real targets, i.e. (21) Lutetia, (89) Julia, (243) Ida, (433) Eros, and (162173) Ryugu.

4.2 Clarification: Lucky Star project collaboration and synergy

The EU H2020 'LuckyStar' project (ERC Programme under Grant Agreement no. 669416) was totally focused on stellar occultations by selected distant Solar System small bodies (i.e. Centaurs and TNOs). On the contrary, the SBNAF project was studying the physical properties of a group of selected Solar System small bodies ranging from near (NEOs) to far (Centaurs and TNOs), by means of a multi-technique approach. The different techniques used within the SBNAF project (e.g. photometry, astrometry, radiometry, stellar occultations, high angular resolution, radar...) were complementary and allowed us to physically characterize our selected targets. Stellar occultations were thus one particular technique among the list used within SBNAF. These were fundamental structural differences between the projects.

Regarding the overlap, the team in Granada (IAA-CSIC) produced its own refined stellar occultation predictions and also obtained and processed the very relevant and necessary input (e.g. very precise astrometry of selected targets). Then, these predictions and data were shared with other teams to help all participants decide whether and where to trigger observations for the predicted event or not. Other participants or collaborators of the Lucky Star project also sometimes did their own refinements with their own techniques using our data, but the workload of refinement was mostly on our shoulders.

Finally, observing occultation events successfully and with a high density of information requires numerous observers (professional and amateur) from different parts of the world to cooperate and act in coordination, so collaboration with the LuckyStar team (P.I. Bruno Sicardy) and also with the Rio de Janeiro team in Brazil, was not only desirable, but also inevitable if we wanted to maximize the scientific results of these activities. It is in this sense that the SBNAF and Lucky Star collaboration led to very important scientific synergies. This was visible in the author list of some of the occultation publications where members of both teams were included. There was no budget overlap because none of the SBNAF personnel was paid via the Lucky Star project.

4.3 Response to the REA Review Report related to the review meeting in Granda/Spain in April 2018

Recommendation 1:
To be found a suitable solution for storing and making available observational data so that it can be used by the Planetary Science community.

Answer 1:
During the last year of the SBNAF project we focused on making our observational data and project results available to the Planetary Science community. This is documented in deliverables „D5.9 Observations delivery to MPC, CDS & PDS“ and „D5.8 Observational publications 3“.

Recommendation 2:
Using GAIA DR2 in order to achieve Milestone 12 " 25 successful TNO occultation measurements to be reached in month 36."

Answer 2:
Directly after the release of the Gaia DR2 in April 2018, these improved stellar positions and proper motions were used to upgrade the occultation predictions. This upgrade allowed us to reach MS12: we have observed more than 60 stellar occultations during the SBNAF project obtaining 25 positive detections by March 2019. At the same time, this upgrade also allowed us to reach „MS5 Occultation predictions with 10 mas accuracy“.

4.4 Recommendations concerning past & future work (taken from Individual Project Review Report, Prof. Belskaya, following up on the progress meeting in Granada/Spain in April 2018)

Recommendations concerning the period covered by the report (year 2 only):
The deliverables provided for the 2nd year of the project have shown that the team obtained practically all results defined in DoA. The problem in reaching the Milestone 8 is not critical

since the quality assessment code (D6.7) has been developed and the paper is in preparation. I evaluate the 2nd year of the project as very successful and productive year.

Answer:
The description of the quality assessment code (D6.7) has been published in two papers:
02/2018: Shaping asteroid models using genetic evolution (SAGE), P. Bartczak & G. Dudziński, MNRAS 473, 5050B (2018); DOI: 10.1093/mnras/stx2535;
05/2019: Volume uncertainty assessment method of asteroid models from disc-integrated visual photometry, P. Bartczak & G. Dudziński, MNRAS 485, 2431-2446 (2019); DOI: 10.1093/mnras/stz300.

Recommendations concerning future work (year 3):

1. It is important to continue their work on shape model validation for several other asteroids with the ground truth information, to point out what minimum set of data are needed to use non-convex shape modelling technique, specify to what extent the accuracy of shape modelling is needed to calculate precise volume of the body.
2. For the selected SBNAF objects for which polarimetric data are available it would be useful to check whether polarimetry can provide additional constraints on their surface properties, e.g. to compare polarimetric and radiometric albedos of selected asteroids. Noticeable differences between polarimetric and radiometric albedos can indicate possible problems in thermal modelling or particular surface properties of the considered object.
3. High-quality observational data obtained within the project are of a great value for future small bodies study. It is important to find a way to store lightcurve data, especially for TNOs for which lightcurve inversion technique can be applied after tens of years of lightcurve observations due to their slow apparent motion.

Answers:

1. Please refer to our answer above with reference to the two publications by Bartczak & Dudziński (2018/2019).
2. We looked into the comparison between radiometric and polarimetric albedos, and there is not enough overlap between SBNAF targets and polarimetry targets (that we could gather) to make a sound statistical comparison. Nevertheless, geometric albedos derived from thermal models on AKARI and WISE data (Alí-Lagoa et al. 2018, Mainzer et al. 2016, respectively) match well within the expected error bars (~20%) with polarimetry-derived albedos or the averages for the corresponding taxonomic classes reported by, e.g. Belskaya et al. (2017), Cellino et al. (2015ab). There is, however, a notable exception: (2) Pallas, which is known to be an anomalous object. The diameter of Pallas as derived from TPM is well in line with the stellar occultation one (Dunham et al. 2016, PDSS 243 D) and AO images (Carry et al. 2010, Icarus 205, 460C), so the discrepancy in the albedo and the anomaly must be related to its visible photometric properties.
3. We agree and we do put strong emphasis on making our observational data and project results available to the planetary community, see „D5.9 Observations delivery to MPC, CDS & PDS“ and „D5.8 Observational publications 3“.

5. Deviations from Annex 1 and Annex 2

5.1 Tasks

There was no need for changes for the tasks described in the six different work packages.

5.2 Use of resources

The funding distribution between the four beneficiaries did not require any changes. At the end of the second year, all 4 beneficiaries together had spent 64.8% of the total budget according to our financial expert at MPE, perfectly in line with the budget plan, and there was no significant change in year 3. In the table below, we give the PM per WP for year 1 (Apr 1, 2016 to Mar 31, 2017), for year 2 (Apr 1, 2017 to Mar 31, 2018), for year 3 (Apr 1, 2018 to Mar 31, 2019), and the numbers listed in the Grant Agreement (GA).

Beneficiary	Year	WP1	WP2	WP3	WP4	WP5	WP6	Total
MPE	1	1.9	4.3	0.0	3.9	0.0	6.9	17.0
	2	2.0	3.5	3.0	4.0	1.0	10.5	24.0
	3	4.5	3.0	1.5	2.5	1.0	11.7	20.7
	$\sum$	8.4	10.8	4.5	10.4	2.0	29.1	65.2
	GA	6.0	10.8	6.0	11.4	2.4	29.4	66.0
CSIC	1	1.0	4.0	0.0	0.0	6.0	4.0	15.0
	2	0.3	1.0	1.0	0.0	12.0	11.0	25.3
	3	0.4	0.0	1.0	0.0	7.7	11.0	20.1
	$\sum$	1.7	5.0	2.0	0.0	25.7	26.0	60.4
	GA	1.0	3.6	3.6	0.0	25.2	24.2	57.6
MTA CSFK	1	0.3	38.1	0.0	0.6	4.0	4.0	47.0
	2	0.3	16.1	0.0	0.3	4.0	4.0	24.7
	3	0.4	23.9	0.0	0.3	4.0	4.0	32.6
	$\sum$	1.0	78.1	0.0	1.2	12.0	12.0	104.3
	GA	1.0	75.2	0.0	1.8	12.0	12.0	102.0
UAM	1	0.0	0.0	16.5	0.6	13.2	17.7	48.0
	2	0.0	0.0	13.5	0.6	13.2	20.3	47.6
	3	1.0	0.0	15.5	0.0	13.8	17.7	48.0
	$\sum$	1.0	0.0	45.5	1.2	40.2	55.7	143.6
	GA	1.0	0.0	45.5	1.2	40.2	56.1	144.0

Notes:

- MPE: The difference between the PMs given in the GA and the total conducted hours is mainly related to a small MPE contribution to another EU project (ESBO-DS, GA no. 777516), and recent work to prepare EU proposals for future projects. The hiring of a second person at MPE was delayed by one month. 3.5 PM from Apr/May 2019 were added to WP1 in year 3 to account for the work on the final meeting, final report, updates of EU web pages, and the completion of the last deliverables.
- CSIC: There is a net difference (smaller than 5%) between the total PMs executed and the ones estimated by the GA. The main difference is due to the dedication of Rene Duffard. In the GA, a 100% dedication was assumed for the last 2 years, but due to commitments for another European project, his PM contribution was lower in the end. This is also the

reason for hiring Nicolas Morales, dedicated full time to WP5. Our real contribution was higher in WP6 and WP2 and lower in WP3. We dedicated more resources to the Synergies (WP6) than to the Inversion techniques (WP3) as was origianlly planned.

- MTA CSFK: The listed MMs agree nicely with the planned MMs in the GA. Three additional MMs were spent in WP2, mainly because of the complexity to set up and operate a public database, capabable of handling several hundred thousand infrared observations.
- UAM: The small deviation in MMs is due to small gap (11 days) between employment contracts of TSR who left near the end of second year, and EPG who filled this position.

Computer cluster at AMU/Poznań (30 k€):
AMU partner of the SBNAF project planned and purchased the components for the computer cluster for extensive CPU-consuming calculations of asteroid spin and shape models using SAGE genetic algorithm. For finding unique solution with this algorithm, thousands of possible shapes need to be checked, and for the shape uncertainty assessment, millions of clones need to be created. The purchase of the cluster was delayed a few months due to lenghty administrative procedures, and a need to adapt the room and install air conditioning. These additional costs, as well as the cost of the server computer were covered by the Rector of AMU. The cluster became fully operational in the middle of the second year of the project in summer 2017.

5.2.1 Unforeseen subcontracting

Not applicable. No subcontracting was done in the second SBNAF period.

5.2.2 Unforeseen use of in kind contribution from third party against payment or free of charges

Not applicable. No paid in-kind contributions from third parties was needed in the second SBNAF period.

HISTORY OF CHANGES		
VERSION	PUBLICATION DATE	CHANGE
1.0	12.04.2019	Initial version
1.1	23.04.2019	Version provided to EU
1.2	29.05.2019	Final version uploaded to the EU system