SBNAF, Modified D1.3 Mid-term Report

Including now:

1) Mid-term report as of September 2017
2) 2nd periodic report (May 2018), part A
3) 2nd periodic report (May 2018), part B

Project Number: 687378 – SBNAF - RIA
Project Acronym: SBNAF
Project title: Small Bodies Near and Far
Period covered by the report: from 01/04/2016 to 30/09/2017 (mid-term report) and 01/04/2017 to 31/03/2018 (2nd periodic report).

Progress Report

1. **D1.3 SBNAF public mid-term report (Apr 2016 to Sep 2017)**
   (Introduction, WPs & Deliverables: Status and Open Points, Milestones, Scientific results, Technical results, Outreach activities, Discussion and outlook).

2. **2nd Periodic Report (May 2018), Part A: Public Summary**
   (Summary of the context and overall objectives of the project, Work performed (Apr 2017 to Mar 2018), Progress beyond the state of the art and expected potential impact).

3. **2nd Periodic Report (May 2018), Part B: EU Internal**
   (Explanation of the work carried out and overview of progress: Objectives, Explanation of the work carried out per WP, Impact; Update of the plan for exploitation and dissemination of results, Update of the management plan; Follow-up of recommendations and comments from previous review: Recommendations from the first-year external review, Clarification: Lucky Star project collaboration and overlap; Deviations from Annex 1 and Annex 2: Tasks, Use of resources per beneficiary).

European
Commission

Deliverable

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

Topic: COMPET-05-2015 - Scientific exploitation of astrophysics, comets, and planetary data
Project Title: Small Bodies Near and Far (SBNAF)
Proposal No: 687378 - SBNAF - RIA
Duration: Apr 1, 2016 - Mar 31, 2019

WP	WP1 Management & Outreach
Del.No	**D1.3**
Title	**Mid-term report**
Lead Beneficiary	MPG
Nature	Report
Dissemination Level	Public
Est. Del. Date	30 September 2017
Version	1.0
Date	07 November 2017
Lead Author	T. Müller, MPE, tmueller@mpe.mpg.de

WP1 Management & Outreach
Objectives: To coordinate and manage the SBNAF team and the WPs in line with the objectives, milestones, and deliverables described in the proposal and in conformity with the consortium agreement (CA).

SBNAF Mid-Term Report

1. Introduction

The SBNAF public mid-term report is not part of the official requested reporting scheme of the H2020 projects, but here defined as a deliverable about 18 months after the project has started. The goal of this report is to give a short status of all WPs and deliverables, to present the results, publications, conference contributions, tools, project-specific web-pages (internal & external), but also to give an overview of the team members, expertise, contributions to the SBNAF project. The mid-term report also discusses technical & organisational problems, delays, changes with respect to the Grant Agreement statements. It also gives outreach activities and our connections to the public. There is no official financial statement connected to this report.

All relevant project information is available on the SBNAF-internal, password-protected web page: http://www.mpe.mpg.de/~tmueller/SBNAF/sbnaf.html. The public page at http://www.mpe.mpg.de/~tmueller/sbnaf advertises the project to the public and the planetary community:

2. WPs & Deliverables: Status and open points

a) WP1 Management and Coordination (Lead beneficiary: MPG)

The workload in this WP1 is significantly higher than expected, with high workload at the beginning of the project and in the context of the biannual team meetings. Most of the work is related to the communication within the team, clarification of administrative and financial aspects, maintenance of web pages (internal and public), documentation of conducted work, action items, collection of work, outreach, conference, and auxiliary material, organization and conduction of in-person, Skype, and Webex team meetings, handling of deliverables, reports, etc.
We organize regular online meetings to exchange information and discuss upcoming deliverables and ongoing science projects, as well as planning of observing proposals and observations, organization of data reduction, conference attendance, etc. These meetings take place every 2-3 weeks and the meeting minutes are made available on the SBNAF internal page. We also collect and follow up on action items on a separate page which serves also as a repository for topics, documents, emails, discussion points, etc.
The deliverables D1.1 and D1.2 were completed on time, D1.3 was delayed by about six weeks due to the close connection to our team meeting at Konkoly Observatory in October 2017.

- D1.1 Internal web page (30 Apr 2016)
- D1.2 Public web page (31 May 2016)
- D1.3 Mid-term report (planned for 15 Nov 2017)

<u>Open points & problems:</u>

- No major obstacles are expected for the second half of the project, assuming that there are no significant changes in the available manpower and contact points.
- We expect that towards the end of the project we will lose manpower since many team members are only on short-term contracts and have to find new jobs.
- Due to local procedures and AMU administration issues, the purchase and full operation of a computer cluster has been delayed.

b) WP2 Infrared observations (Lead beneficiary: MTA CSFK)

The objectives of WP2 are to produce expert-reduced Herschel data of primary focus targets: (a) large TNOs (photometric and lightcurve observations); (b) MBAs (science and calibration observations); (c) dedicated NEA observations. To collect auxiliary infrared data from previous missions (Spitzer, Planck, WISE, AKARI, IRAS, ISO, MSX) and published ground-based mid-IR, submillimetre, millimetre observations and to prepare data for integration in a unique database. To create a database of infrared observations of all SBNAF targets (TNOs, MBAs, NEAs) with the option for extension to a larger sample.
In the first 1.5 years of the project the focus was on the production of “User provided data products (UPDP)” for an upload to the Herschel Science Archive (HSA). In the second 1.5 years the emphasis is on the creation of a public database for thermal observations of asteroids.

- D2.1 Herschel tools (30 Sep 2016): A final set of tools and methods for Herschel/PACS moving target data reduction was created and made available to the Herschel Science Center (HSC) and the Planetary Science community. In parallel, we created overview lists of the various Herschel/PACS data sets for NEAs, MBAs, Centaurs, TNOs, and satellites, together with the parameters which are relevant for the data reduction (photometer observing mode, instrument and satellite settings).

- D2.2 NEA HSA upload (31 Dec 2016): All Herschel/PACS NEA observations were manually reprocessed and the photometry was extracted for various publications. The new data products were delivered to the HSC and they are meanwhile available via the HSA and also in the NASA/IPAC Infrared Science Archive. Details are described in D2.2 and in a special release note for the HSA.
- D2.3 MBA HSA upload (31 Mar 2017): The standard data reduction worked fine for most of the MBA observations. Only in very few cases we had to reprocess the data with our SSO-specific tools. The new UPDPs were delivered to the HSC and they are meanwhile available via the HSA and soon also in the NASA/IPAC Infrared Science Archive for the planetary community. Details are described in D2.3 and in a special release note for the HSA.
- D2.4 TNO HSA upload (15 Nov 2017): All Herschel/PACS TNO and Centaur observations were manually reprocessed and UPDPs were created, often from the combination of several observations to eliminate background contamination. The new UPDPs were delivered to the HSC and they will be made available via the HSA and soon also in the NASA/IPAC Infrared Science Archive. Details are described in D2.4 and in a special release notes for the HSA.
- D2.5 IR database (internal) (planned for 30 Sep 2018): We are currently setting up a prototype for a database to store thermal measurements of our SBNAF objects. We have created a first set of requirements for such a database.
- D2.6 IR database (public) (planned for 31 Mar 2019): Our goal is to have this database ready and open to the public by early 2019. This would allow to do careful testing by external experts in preparation for the workshop on "Thermal Models for Planetary Science (TherMoPS) III" which will take place in Budapest, Hungary, 20-22 Feb 2019 (organized by the SBNAF team). The IR database will also be extremely useful in the context of the JWST mission (current launch is foreseen for mid 2019).

Open points & problems:

- For our IR database, we have to understand the calibration and the quality aspects for the thermal measurements of asteroids very well in order to assign realistic error bars to each flux entry in the database. For some of the data sets (like the WISE red/blue calibrator discrepancy) we are still struggling with the correct handling of the measurements. This work also requires cross-calibration between different missions and instruments to better understand their absolute calibration schemes.
- We have started to think about a long-term availability of the WP2 results beyond the 3-year SBNAF duration: the Herschel products are available via the HSA and the NASA-/IPAC Infrared Science Archive, but for our IR database the future is not clear yet. One option would be to join the EU-funded Virtual European Solar And Planetary Access (VESPA[1]) project. VESPA aims at building a Virtual Observatory for Planetary Science, connecting all sorts of data in the field, and providing modern tools to retrieve, cross-correlate, and display data and results of scientific analyses. A first contact was established (during the EPSC conference in Sep. 2017) and VESPA requirements and guidelines were exchanged.

c) WP3 Lightcurve inversion technique (Lead beneficiary: UAM)

The goal of WP3 is to join various types of data for full physical models of benchmark asteroids and to develop web services with a database in order to provide the models to the community.

- D3.1 GOSA service upload (30 Sep 2016): The Gaia-Ground-based Observational Service for Asteroids (Gaia-GOSA, www.gaiagosa.eu) is a website contributing to the European Space Agency *Gaia* mission. It facilitates the planning of observations, the

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[1] http://europlanet-vespa.eu/

gathering of lightcurves, and serves as a repository for all kind of asteroid observations. As part of D3.1 new information has been included about stellar occultation predictions for selected asteroids. GOSA observers are now also able to plan observations of these events and to coordinate between observers. Observations gathered will be exploited within SBNAF project. On the basis of these observations it will be possible to determine asteroids' size, test or improve shape model and it will also lead to new discoveries (e.g. satellites, rings or any other material orbiting the main body).

- D3.2 Prediction of shape orientations (31 Mar 2017): The predictions of shape orientations are important in the context of forecasting occultation events. Via the ISAM (Interactive Service for Asteroid Models) service upgrade it is now possible to load any of the currently about 900 shape models and to make predictions about the object’s orientation at any given time. This will greatly facilitate the planning of occultation measurements and will help to verify shape/spin solutions or even to improve shape solutions. It will also allow to scale shape models from lightcurve inversion techniques which have no size assigned. This ISAM service upgrade is also important in the context of radiometric solutions and AO imaging results: details and examples are given in D3.2.
- D3.3 Shape & Spin solutions for secondary calibrators (31 Mar 2017): The main goal was to provide updated spin and shape models for around 30 large main-belt asteroids as secondary calibrators for WP4. This is a very important collection of information and data sources for these objects which will be used in the context of WP4 and WP6. The discussion for each object shows the need for more lightcurve observations in several cases. This work of collecting information for our sample will continue throughout the SBNAF project duration.
- D3.4 Volume determination (03 Nov 2017): One of the key elements is to establish reliable shape and volume determinations for large asteroids where Gaia will provide mass estimates from orbit perturbations. The critical part here is clearly the scaling of shape/spin solutions which can be done via radiometric techniques, occultation measurements, or other techniques like AO imaging, radar echo, or in-situ measurements. We describe these techniques, and introduce triaxial, convex, and non-convex shape models. We also collect critical observations for each object and demonstrate the validation of the scaling via stellar occultations and radiometric techniques. All these aspects are discussed with the goal to obtain the most realistic volumes (and errors) for large main-belt asteroids.
- D3.5 Joint lightcurve and thermal models (planned for 31 Mar 2018): The simultaneous usage of lightcurves and thermal data in the inversion process seems to be very complex, but we are working on solutions and recipes on how to test shape/spin solutions against thermal measurements.
- D3.6 Joint multi-data inversion models (planned for 31 Mar 2019): ongoing work for selected individual targets via dedicated publications (see section on recent publications).

<u>Open points & problems:</u>

- Good-quality shape models require multi-apparition high-quality lightcurves. For some targets, it is difficult to obtain enough data to find reliable shape-spin solutions. Sometimes the data have poor quality or our planned observing campaigns failed due to rejected proposals or bad weather, in other cases we will need observations during future apparitions (outside the SBNAF duration). There are also cases where the rotation period of a given object is very long (and/or the lightcurve amplitude is very small) which makes the inversion technique more difficult or even impossible.
- We know that many objects do have non-convex shapes and the reconstruction of the shape features are much more demanding and requiring more multi-apparition high-quality lightcurves than typically needed for convex inversion techniques. Also, the testing of non-convex shapes is not trivial, but can be done via AO imaging, occultations and radiometric tests. However, a final quality assignment for the non-convex solutions will be very difficult.

- We are also learning from the experience by other groups on simultaneous multi-data inversion attempts. Such exercises depend very much on how much weight is given to a specific data set and it is hard to find a balance between data from such different sources like optical lightcurves, occultation chords or AO images. Currently, we plan to work on lightcurve-based shape models, combined with scaling/validating of the solutions by using thermal data, occultation information and/or AO images.
- The calculation of non-convex shape solutions is very CPU consuming. Currently, we are limited in computer power due to budget restrictions for the refurbishment of the computer room at AMU/Poznań observatory which prevents us from the installation of the new cluster.

d) WP4 Asteroid-related calibration (Lead beneficiary: MPG)

The goal of WP4 is to improve asteroid model predictions for a transport of the space-based (Herschel, Planck, Akari) calibration to ground-based and airborne infrared, submm, and millimetre projects with a high demand for asteroids as calibrators. The prerequisites for higher-quality asteroid models for calibration applications are: (i) availability of a validated thermophysical model code to handle epoch-specific illumination and observing geometries; (ii) reliable shape/spin solutions for the large main-belt asteroids; (iii) high-quality size and albedo information; (iv) verified thermal properties; (v) characterization of the errors for specific objects and model predictions.
WP4 is closely related to the work in WP2 and WP5 (conducting and collecting of observations in the visible and infrared range), but also to WP3 (finding reliable shape and spin-vector solutions) and WP6 (combining all information in final shape-spin-size-etc. solutions for our calibration targets and characterizing the quality of the work). Another important aspect of WP4 is the identification and collection of calibration requirements of different observatories and instruments. This requires a close collaboration with the calibration teams and exchange of information and calibration products. We make all our asteroid calibration models available on our public web page at:
http://www.mpe.mpg.de/~tmueller/sbnaf/results/.

The SBNAF project supports worldwide calibration activities for ground-/airborne-/space-projects at mid-IR/far-IR/submm/mm wavelengths by providing highly reliable model predictions of selected well-known asteroids. These activities are documented in a series of deliverables which are produced as part of WP4 of the SBNAF project.

- D4.1 Observation summary table (30 Apr 2016): Provides a collection of existing and missing information & observational data (thermal IR and observations for shape and spin reconstruction) for the potential asteroid calibrators; criteria for the calibrator definition; model versions and quality category descriptions, as well as open points.
- D4.2 Submm/mm model predictions (30 Jun 2016): Provision of model v0 predictions (10-30% absolute accuracy) for 20 asteroids for period 2016-2020 mainly for calibration planning purposes. These models were delivered to the calibration teams of ALMA, APEX, IRAM, SOFIA, etc. and are available on our public web page. The deliverable includes the current best model input values like size, albedo, H-G solutions, various auxiliary information (apparent motion, phase angles, helio- and geocentric distances, background confusion and expected mm fluxes in the time period 2016-2020). We also listed the calibration contact points in the different observatories/projects and the relevant publications.
- D4.3 Calibration asteroid model predictions (30 Sep 2016): The deliverable describes the work which went into the setup for the current asteroid calibrator models (v0, v1, v2). For Ceres, Pallas, Vesta, and Lutetia we provided high-quality model (v2) solutions with high time resolution (15 min or 1 hour) at 10 reference frequencies for the period 2014-2020. In addition, we provided 1433 FITS files with thermophysical model predictions (model v1 or v2) for all 28 Herschel-PACS/SPIRE/HIFI calibration asteroids at observation mid-

time (in the "@herschel" reference frame). These predictions are meanwhile available from the Herschel Science Archive (HSA[2]) and on our public SBNAF page for the worldwide planetary community (together with a dedicated release note).

- D4.6 Selection of secondary asteroid calibrators (31 Mar 2017): In D4.6 we collected the calibration needs and requirements of ongoing and future far-IR/submm/mm projects. We also looked in more details at the available information/observations and discuss which of the large main-belt asteroids can be used as calibration standards. At the end, we established a recipe for the final selection of secondary asteroid calibrators.
- D4.4 Secondary asteroid models (planned for 31 Mar 2018): we already started to work on a final model setup for each individual (secondary) asteroid. The setup also includes a collection of thermal data, occultation data, AO images, etc. to find the best possible thermophysical solution for each asteroid (including shape/spin solution, size, albedo, thermal properties, quality description). This work goes in parallel with publications of results on subsets of this sample.
- D4.5 Final asteroid models (planned for 31 Mar 2019): At the end of the project we plan to make all final model solutions (with all model input parameters) available to the planetary community. Our findings will be published (mainly connected to physical and thermal object properties) in refereed journals with open access via the arXiv server. The scaled model solutions will be available via the ISAM service, dedicated far-IR/submm/mm predictions will be presented on the public SBNAF page and provided to the various calibration teams worldwide.

<u>Open points & problems:</u>

- The requirements for celestial calibration standards are often very challenging (on brightness, on absolute flux accuracy, on availability, on variability, etc.). Our final set of potential asteroid calibrators will fulfill many of the requirements, but not all.
- It is also not easy to assign reliable error bars to the asteroid model predictions, especially at submillimeter and millimeter wavelengths (or longer wavelengths) where we have only very few options to test and verify our models.
- A last point is related to requesting measurements in the context of establishing new calibrators: most of the observatories do not accept "calibration proposals" and additional observations are difficult to obtain.

e) WP5 Ground-based observations (Lead beneficiary: CSIC)

WP5 has the main goal to execute observations from ground- based telescopes with the objective to acquire more data on the targets. One type of observation is the occultation of a star by an asteroid, Centaur or TNO. On this particular point, the main tasks are to coordinate observations and produce results on physical parameters of the asteroids, Centaurs and TNOs.

- D5.1 Occultation candidates for 2016 (30 Apr 2016): In D5.1 we describe the candidates of asteroids and trans- Neptunian objects (TNOs) that could produce a stellar occultation during the year 2016 in regions where we have established networks of experienced observers (mainly Europe and South America). For the main belt asteroids, the uncertainty is smaller and the shadow path can be trusted, while for TNOs the orbits are less known with the consequence that the shadow path is only estimated and more telescopic observations (astrometry of stars and TNOs) are needed until the event is confirmed. The D5.1 predictions were produced using the free software Occult[3], together with our own refined techniques. The results on the TNOs list are unique as the IAA/Granada group is (in collaboration with the Paris-observatory group and the Rio de Janeiro group) the only team, which produces such predictions for TNOs.

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[2] Herschel Science Archive (HSA) http://archives.esac.esa.int/hsa/whsa/

[3] http://www.lunar-occultations.com/iota/occult4.htm

- D5.4 High-precision photometry measurement table (30 Sep 2016): Highly reliable photometry (absolute, calibrated magnitudes) is essential for our work in WP6 where we combine data from different sources and wavelengths. Here we describe the H-G, the H-G12, and the H-G1-G2 system in the context of our targets. We explain the various aspects related to NEAs, MBAs, and TNOs. At the end, we present an overview table with the high-precision photometry results for our SBNAF targets.
- D5.2 Occultation candidates for 2017 (31 Dec 2016): Similar to D5.1, but now for the year 2017.
- D5.5 Time-series photometry measurement table (31 Mar 2017): We describe the available lightcurve data (= time-series photometry) for our project. We conduct regular observing campaigns at many intermediate-size telescopes in Spain, Hungary, Poland, Chile, Argentina, and through the Gaia-GOSA network of observers. We also use the Kepler-K2 mission to obtain high-quality, long-duration lightcurves over several days (each time we find SBNAF targets in the corresponding FOV). In addition, we started to use WISE/NEOWISE W1 data which contain in many cases sparsely sampled lightcurves (only cases where the W1 at 3.4 micron contains mainly reflected light).
- D5.6 Observational publications 1 (31 Mar 2017): A brief description of the different observational techniques used to obtain auxiliary data of the SBNAF targets and applications of all these observational data. The techniques are: 1. Time-series observations; 2. Astrometric measurements; 3. Stellar occultations; 4. Absolute photometry; 5. Thermal data. A list of works (published or in preparation) related to each observational technique within the SBNAF project is provided. This list will be updated for the subsequent deliverables: "D5.7 Observational publications 2" and "D5.8 Observational publications 3".
- D5.3 Occultation candidates for 2018 (31 Dec 2017): Similar to D5.1 and D5.2, but now for the year 2018.
- D5.7 Observational publications 2 (31 Mar 2018): see D5.6, including the recently measured occultation events for the TNO Haumea (Nature publication) and the Centaur 2002 GZ_{32} (publication in prepration).
- D5.9 Observations delivery to MPC, CDS & PDS (28 Feb 2019): ongoing
- D5.8 Observational publications 3 (31 Mar 2019): see D5.6 and D5.7

<u>Open points & problems:</u>

- Good-quality occultation shadow-path predictions (mainly for Centaurs/TNOs) require astrometric observing campaigns in the months/weeks/days before the event. And even a successful prediction does not automatically lead to successful measurements if the shadow path is in regions with bad weather or without experienced observers or over the oceans. The success rate is therefore not very high, but improved over the last years. One important element for improved predictions was the first release of GAIA data[4]. The second release (in April 2018) might again improve the situation.
- Radiometric techniques require high-precision absolute photometry (H-G values) for the determination of the object's albedo. For some targets, it is difficult to obtain enough data to find reliable H-G solutions. Sometimes the data have poor quality or our planned observing campaigns failed due to rejected proposals or bad weather, in other cases we will need observations during future apparitions (outside the SBNAF duration). This issue affects often NEAs (e.g., our Halloween-target project, see Müller et al. 2017, A&A 598, A63), but also recently discovered Centaurs and TNOs.
- Publication of observational data is typically done when significant progress in a scientific project is reached. Some of the observational data are therefore not immediately available for the Planetary Science community.

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[4] https://www.cosmos.esa.int/web/gaia/dr1

f) WP6 Synergies from ground and space (Lead beneficiary: UAM)

WP6 combines observational data from space and ground, from remote, disk- integrated data and disk-resolved data from interplanetary missions to obtain (validated) high-quality model solutions for a wide range of applications: improvement of the scientific understanding, answering key questions for the reconstruction of minor body properties, calibration aspects, support for Gaia density determination, Hayabusa-2 target characterization and operational support, tools and methods for applications to large object samples.

- D6.1 Occultation vs. thermal tools (31 Jan 2017): This deliverable enumerates and discusses in a unified document —which is lacking in the specialised literature— several cases relevant for our SBNAF targets in which modelling of thermal infrared/sub-millimetre data can complement stellar occultation observations in order to maximise our knowledge about those targets. There are numerous different information and data-type availability for different types of targets (NEAs, MBAs, TNOs), so this deliverable aims to provide optimal guidelines to follow in each particular case as new data are collected. In addition, it helps to demonstrate how fundamental new occultation data are for SBNAF and justifies all the efforts devoted to obtaining them in addition to visible photometry. The table in Section 3 summarises the complementary aspects of occultation versus thermal tools.
- D6.2 Shape & spin solution for primary calibrators (09 Dec 2016): This deliverable is the result of a literature survey in search for the most up-to-date and accurate three-dimensional shapes and rotational properties of our four primary calibrators (1) Ceres, (2) Pallas, (4) Vesta, and (21) Lutetia. Because they are based on ground truth information, the collection of shapes presented in the next section constitutes a significant step forward in the use of "in-situ" object properties (shape, spin-axis orientation, rotation period, size, and absolute spatial orientation at a given time) for several of the “core” objectives of the SBNAF project (these products are particularly crucial for WP4 and WP6). Table 1 contains a summary of all the information extracted and the bibliographic references where they originate.
- D6.3 In-situ object properties (31 Dec 2016): In this deliverable, we compiled in-situ physical properties of selected targets from the literature, namely visited asteroids (1) Ceres, (4) Vesta, (433) Eros and (25143) Itokawa, and flyby targets (21) Lutetia, and (951) Gaspra. We have included quantities that are not strictly in-situ properties but inferred from models, such as thermal inertias, because they are important for the SBNAF project as they are uniquely based on spatially resolved data. The deliverable includes relevant comments about each target focusing on the masses, densities, and photometric and thermal properties (whenever available). This in-situ information provides crucial ground truth to test our models, which typically deal with disc-integrated data, to assess whether these models need improvements, and to quantify how critical these are. Table 1 collects all the information and references for each target.
- D6.4 Gaia asteroid list (31 Jan 2017): The so-called “Gaia perturbers” are large asteroids for which Gaia will be able to derive the mass very precisely. This will in turn allow their density to be calculated accurately if reliable shape models are obtained. This deliverable provides a list of selected targets among the “Gaia perturbers” that have sufficiently good data coverage to grant the production of a good-quality shape model. The selection criteria and quality codes assigned to each case are explained as well. Given their relevance to the on-going photometric campaign coordinated within the SBNAF project, cases for which follow-up observations would ensure a better shape determination were identified.

- D6.5 "Ground truth" shape models (31 Mar 2017): In the first version of this deliverable we enumerated SBNAF works that were submitted for publication in which non-convex shapes of asteroids with available ground-truth information were derived. By "ground truth" we consider spacecraft-, stellar occultation- and adaptive optics-based shape models and/or constraints on shape. The works submitted for publication included e.g. (433) Eros and (9) Metis (ground truth: space mission shape and rich set of occultation chords, respectively), (6) Hebe (ground truth: adaptive optics and occultations).
- D6.5 "Ground truth" shape models (Version 2) (updated on 29 Sep 2017): In the revised version, the status of all works featured in the first version changed from submitted to accepted or published in peer-reviewed journals, which allows the inclusion of details of the contents of these articles in this public deliverable. We highlight here the article by Bartczak & Dudziński, which was accepted for publication in Monthly Notices of the Royal Astronomical Society in September 2017, as of particular relevance to the SBNAF Milestone 2. It studied the "genetic evolution" algorithm SAGE to derive non-convex shapes and validated the shape models obtained for (433) Eros and (9) Metis with the rich ground truth information available for these targets. This work also included extensive simulations to reconstruct artificial shape models.
- D6.6 Thermally resolved shape models (30 Sep 2017): This deliverable illustrates the use of thermo-physical models (TPM) to rule out mirror shape solutions derived from lightcurve inversion techniques that fit the visible data statistically equally well. A large part of the work carried out was collected in the article by Marciniak et al. (accepted for publication in Astronomy & Astrophysics in Sept. 2017; attached in Appendix A). In the deliverable, we examine more closely the TIR data coverage of the targets featured in the paper and we expand the discussion in an attempt to understand the strengths and limitations of the approach more systematically. The aim is to identify what cases are best for benchmarking, calibration (work package WP4), and/or scientific exploitation in terms of visible, TIR, mm and sub-mm data, and quantify how the TPM and TIR information can be phased in the development of a system to assess the quality of shape models (deliverable D6.7).
- D6.7 Quality assessment system for the models (31 Mar 2018): ongoing
- D6.8 3D shape models for large MBAs (30 Sep 2018): planned.

<u>Open points & problems:</u>

- When combining data from very different sources and techniques it is not trivial to assign the correct weight to each data point and data type.
- There is also no general unique procedure for combining data from ground and space. It often depends on the final scientific goal of a given project. For WP4 we try to make the best possible thermal model predictions for calibration purposes (the reliability of the model input parameters like size, thermal inertia, etc. is only of secondary importance). For the list of Gaia mass targets, the main goal is to determine the objects' sizes. Here, it is essential to derive the best-possible volumes for the targets and the scaling of the shape model is crucial. But what is the best method to scale shape models? Occultations? Radiometric techniques? AO imaging? Or a combination of all?
- There are more areas where a good model solution is not automatically a physical representation of a given object: A high-quality shape-spin solution might fit all available lightcurves within the error bars, but might have problems to match occultation information, the AO images or the available thermal data. For some targets, there are indications of colour and/or albedo variations (and maybe also variations of the scattering properties) on the surface. The inversion techniques and radiometric techniques are then less reliable.

3. Milestones

Here, we list the first four milestones which have due dates in the first 1.5 years of the project duration (as given in the Grand Agreement).

Milestone number	Milestone title	WP number	Lead beneficiary	Due Date (in months)	Means of verification
MS1	Kick-off	WP1, WP2, WP3, WP4, WP5	1 - MPG	1	In-person kick-off meeting with all participants. Means of verification: Consortium agreements, communication links, project structure, schedules, SBNAF web page
MS2	Benchmark study	WP3, WP6	4 - UAM	12	Finalization of a study on convex and non-convex shape models (including thermal measurements) for objects with ground-truth information. Means of verification: Presentation in a major conference. Publication of results in scientific journal.
MS3	Expert-reduced data to HSA	WP2	3 - MTA CSFK	18	Finalisation of expert- reduced data upload to the Herschel Science Archive. Means of verification: Availability of data in the HSA to the planetary community.
MS4	Mid-term review	WP1, WP2, WP3, WP4, WP5, WP6	1 - MPG	18	SBNAF scientific mid- term review. Means of verification: Review of the project involving external experts.

MS1 was reached by holding the SBNAF kick-off meeting at IAA/Granada, Spain, from April 13 – 15, 2016 (see picture below). All presentations, notes, and the minutes are available on the project-internal page at:
http://www.mpe.mpg.de/~tmueller/SBNAF/GRANADA2016/granada2016.html

MS2 is related to a "benchmark study" on convex and non-convex shape models (including thermal measurements) for objects with ground-truth information. We discuss this point extensively in the version2 of D6.5 where we present shape models from both convex and non-convex inversion vs. ground truth. In a first paper by Bartczak & Dudziński, MNRAS, accepted in Sep 2017, the "ground truth" comparison between lightcurve-inversion spin/shapes solutions and in-situ findings is discussed for (433) Eros and (9) Metis. In a second paper by Marciniak et al., A&A, accepted in Sep 2017 we used thermal measurements (i) to assign size, albedo and thermal inertia to

several long-period asteroids; (ii) to test convex and non-convex shape solutions; (iii) to collect experience about the pros and cons of using thermal data in the context of deriving the key physical and thermal properties for a given object. A third publication by Marsset et al. 2017, A&A 604, A64, we combine information from AO imaging, occultations, lightcurve inversion techniques, and thermal radiometry to inter-compare the results from the different techniques and to obtain the best possible solution for this large main-belt asteroid. In addition to the three papers, we also presented these projects in various international conferences. With these publications and presentations, we have reached MS2. However, we consider the entire SBNAF project as a kind of "benchmark study" to test and validate different techniques and models in the context of finding the best-possible physical and thermal properties for small bodies. Thus, work relevant for this milestone will continue until the end of the project.

MS3 is reached via D2.1, D2.2, D2.3, and D2.4. All Herschel/PACS NEA, MBAs, TNO and Centaur observations were manually reprocessed and UPDPs were created and delivered to the HSC. They are meanwhile (or will be) available via the HSA and soon also in the NASA/IPAC Infrared Science Archive for the planetary community. Details are described in the listed 4 deliverables and in special release notes for the HSA.

MS4 is reached via the finalization of this mid-term report (D1.3). Our "mid-term" team meeting was held at Konkoly Observatory in Budapest, Hungary, from Oct. 4-6, 2017. We included several external experts (i) to learn about recent developments in different fields of measuring small body properties; (ii) to provide feedback to our SBNAF work. Their presentations and feedback, as well as the discussion points are collected in the meeting minutes and notes. In addition, we are in regular contacts with other groups in the world to discuss the best strategies in lightcurve inversion techniques, radiometric modelling, advances in occultation measurements and prediction strategies. We also follow closely the results from AO imaging campaigns, and study new observing options via ground-, airborne-, and space observatories, and at new wavelength regimes (like radio frequencies). In the calibration context (WP4) we are working in close collaboration with the various stakeholders to adopt our work to new calibration requirements. We also obtain very useful feedback via the refereeing process for our scientific work (more than 30 peer-reviewed publications so far). The SBNAF project work and strategy improved significantly via the feedback from our external project referee during the Poznań team meeting (May 4-6, 2017) and his expert report, as well as the EU assessment report in the context of our first periodic report (Apr 2016 – Mar 2017).

4. Scientific results

The SBNAF scientific results are published in open access. The project itself and most of the science topics are also presented in many conferences and workshops. Here, we give a summary for the first 1.5 years of the SBNAF project.

a) Publications

The SBNAF project and the results of our work (and SBNAF contributions to other projects) are published in open access journals or on arXiv (Astrophysics). We list all publications with the SBNAF-specific acknowledgement, a few of these papers have only minor SBNAF contributions. During the first 18 months of the SBNAF project, we produced on average about one peer-reviewed publication per month with a major SBNAF contribution. Currently, we counted more than 30 publications which contain the SBNAF acknowledgement: "The research leading to these results has received funding

from the European Union's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 687378."

- **Submitted:**
  - Herschel-PACS photometry of faint stars for sensitivity performance assessment and establishment of faint FIR prime photometric standards, Klaas et al., submitted in August to A&A
  - The AKARI IRC Asteroid Flux Catalogue: updated diameters and albedos, Ali-Lagoa et al., submitted in August 2017 to A&A
  - Surface ice and Tholins on the extreme Centaur 2012 DR30, Szabo, Kiss, Pinilla-Alonso et al., submitted June 2017
  - Main-belt asteroids in the K2 Uranus field, Molnár et al., submitted in June 2017 to ApJS
  - Thermophysical modelling of main-belt asteroids from WISE thermal data, Hanuš et al., submitted in August 2017 to Icarus
  - Thermal Infrared and Optical Photometry of Asteroidal Comet C/2002 CE10, by Sekiguchi et al., re-submitted to Icarus
  - In-space utilisation of asteroids (ASIME 2016 White Paper), Graps et al. 2016
- **Accepted:**
  - PRIMASS visits the Hilda and Cybele groups, De Prá, et al., accepted by Icarus in Nov. 2017
  - Small Bodies Near and Far (SBNAF): a benchmark study on physical and thermal properties of small bodies in the Solar System, Müller et al. 2017, accepted by Advances in Space Research in October 2017
  - Shaping Asteroid models with Genetic Evolution (SAGE), P. Bartczak & G. Dudziński, accepted by MNRAS in September 2017
  - The thermal emission of Centaurs and Trans-Neptunian objects at millimeter wavelengths from ALMA observations, Lellouch et al., accepted by A&A in September 2017
  - "TNOs are Cool": A survey of the trans-Neptunian region. XIII. Characterization of multiple trans-Neptunian objects observed with Herschel Space Observatory, by Kovalenko et al., accepted by A&A in September 2017
  - Photometric survey, modelling, and scaling of long-period and low-amplitude asteroids, Marciniak et al., accepted by A&A in September 2017
  - The structure of Chariklo's rings from stellar occultations, D. Berard et al., accepted by A&A in August 2017
  - Size and shape of Chariklo and its rings reflectivity from multi-epoch stellar occultations, R. Leiva et al., accepted by A&A in August 2017
- **Published:**
  - 01/2018: Spin states of asteroids in the Eos collisional family, J. Hanuš, M. Delbo', V. Alí-Lagoa, B. Bolin, R. Jedicke, J. Ďurech, H. Cibulková, P. Pravec, P. Kušnirá, R. Behrend, F. Marchis, P. Antonini, L. Arnold, M. Audejean, M. Bachschmidt, L. Bernasconi, L. Brunetto, S. Casulli, R. Dymock, N. Esseiva, M. Esteban, O. Gerteis, H. de Groot, H. Gully, H. Hamanowa, H. Hamanowa, P. Krafft, M. Lehký, F. Manzini, J. Michelet, E. Morelle, J. Oey, F. Pilcher, F. Reignier, R. Roy, P.A. Salom, B.D. Warner, Icarus 299, 84H (2018)
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b) Conferences and workshop contributions

Our SBNAF project and the results of our work are presented in many national and international conferences and workshops. Here is a list of SBNAF contributions (from large international conferences) which have available abstracts in ADS[5] (the presenting authors, the links and pdf documents are available on our SBNAF web pages):

- The 4th Workshop on Binaries in the Solar System, Prague, Czech Republic, 2016 June 21-23
  - Binaries in the Trans-Neptunian population (EFV)

[5] http://adsabs.harvard.edu/abstract_service.html

    - Update on SAGE algorithm: uncertainty maps for asteroid shape and pole solutions (GD)
- 41st Scientific Assembly of the Committee on Space Research, COSPAR 2016, Istanbul, Turkey, 30 Jul - 7 Aug 2016
    - Abstract: Small bodies: Near and Far (SBNAF) (TM)
- DPS-EPSC Joint Meeting 2016, Pasadena, CA, United States, 16-21 October 2016
    - Small Bodies: Near and Far (SBNAF) (RD)
    - Physical characteristics of Centaurs and trans-Neptunian objects from combined K2 and Herschel observations (CK)
    - Asteroid spin and shape modelling using two lightcurve inversion methods (AM)
    - Gaia-GOSA: An interactive service for coordination of asteroid observation campaigns (TSR)
    - Properties of resonant trans-Neptunian objects based on Herschel Space Observatory data (ATF)
    - Uncertainty maps for asteroid shape and pole solutions (PB)
    - Shaping Asteroid with Genetic Evolution (SAGE) using lightcurve and radar data (GD)
    - K2 and Herschel/PACS photometry of irregular satellites (AP)
    - The moon of the large Kuiper-belt object 2007 OR10 (GM)
    - Photometry of Main Belt and Trojan asteroids with K2 (GS)
    - Thermal inertia as an indicator of rockiness variegation on near-Earth asteroid surfaces (VAL)
- Asteroids, Comets, Meteors 2017, Montevideo, Uruguay, April 10-14, 2017
    - Physical properties of TNOs and Centaurs from stellar occultations and thermal observations (PSS invited talk)
    - What is Bienor hiding in its photometric behaviour? (EFV)
    - Measuring sense of rotation of V-type asteroids outside the Vesta family (DO)
    - Shape uncertainty of asteroid models from inversion techniques (PB)
    - Ryugu: 15 months to showdown (TM)
    - Updated asteroid diameters and albedos from AKARI/IRC mid-infrared data (VAL)
    - Photometry of asteroids in crowded star fields in SBNAF project (MBB)
    - Results from stellar occultations by trans-Neptunian object (84922) 2003 VS2 (PSS)
    - 2008 OG19: A Varuna-like trans-Neptunian object? (EFV)
    - Debiasing asteroid spins and shapes - observations, modeling, and validation (AM)
    - Asteroid shape reconstruction from radar echo images (GD)
    - First Results from "Small Bodies Near and Far (SBNAF)": A benchmark study for the characterization of asteroids and TNOs (TM)
- 12th European Planetary Science Congress (EPSC), 17–22 September 2017, Riga, Latvia
    - Session SB12: Small Bodies Near and Far; Convener: T. Müller; Co-convener: P. Santos-Sanz
    - The 2017 January 21st multi-chord stellar occultation by the dwarf planet Haumea. Preliminary results (JLO/PSS)
    - Physical characterization of Kuiper belt objects from stellar occultations and thermal measurements (PSS keynote talk)
    - Herschel-PACS high-precision FIR fluxes of NEAs and MBAs (TM)
    - Small Bodies Near and Far (SBNAF): Characterization of asteroids and TNOs (TM)
    - Thermal emission of the Eris-Dysnomia system (CK)

  - K2 and Herschel/PACS light curve of the Centaur 2060 Chiron (GM)
  - Serendipitous observations of asteroids in Herschel PACS and SPIRE maps (RS)
  - Asteroid phase-curves from Gaia-calibrated data (DO)
- 49th Annual Division for Planetary Sciences Meeting, 15-20 October 2017, Provo, Utah
  - The stellar occultation by the dwarf planet Haumea (PSS)
  - Dynamics of rings around elongated bodies (PSS, JLO, RD)
  - Absolute colors and phase coefficients of Trans-Neptunian objects: HV - HR colors (JLO, RD, EFV, PSS, NM)
  - The thermal emission of Centaurs and Trans-Neptunian objects at submm wavelengths from ALMA observations (TM, PSS)
  - Spatially resolved thermal emission of the Eris-Dysnomia system (CK)
  - Search for signatures of extended emission around dwarf planets on Hubble Space Telescope archival images (GM)

In addition, we attended many more workshops, national and international conferences with SBNAF-related contributions. We organized or co-organized workshops on SBNAF topics as SOC/LOC members (e.g., a specific SBNAF session in the EPSC2017 conference in Riga/Latvia, see above).

<u>Outlook:</u>
For the second half of the SBNAF project, we plan to attend various workshops, national and international conferences related to small bodies (for an updated list of workshops and conferences: see our internal and public web pages). In addition, we will organize the workshop "TherMoPS (Thermal Models for Planetary Science) III" in Budapest, Hungary, Feb 20-22, 2019, following up on TherMoPS I (Beaulieu sur Mer, France, Sep 15-17, 2008) and TherMoPS II (Puerto de la Cruz, Tenerife, Spain, Jun 3-5, 2015). We expect that about 50-100 experts in the field of small bodies will participate in this workshop, including members of the Rosetta, the New Horizons, the Hayabusa-2, the OSIRIS-Rex teams, as well as experts in observations and modelling of small bodies.

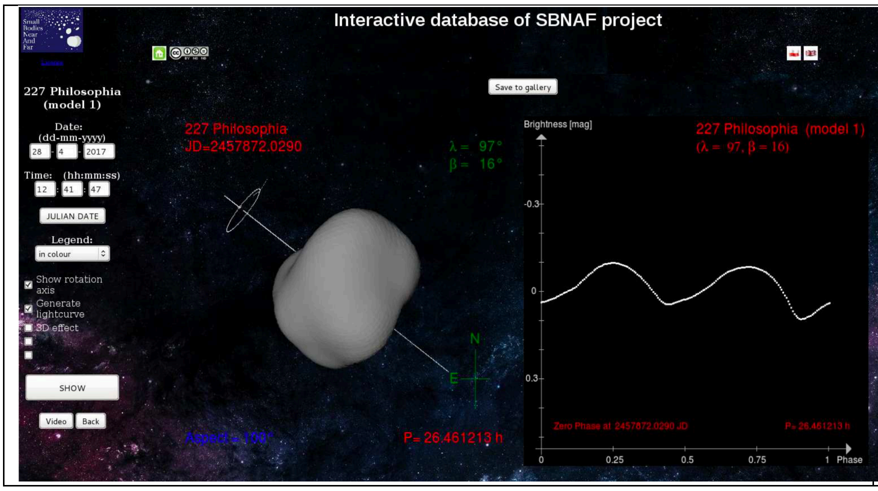
5. Technical results

There are different categories of technical results (see: http://www.mpe.mpg.de/~tmueller/sbnaf/results.html):

a) Tools & Services:

The Interactive Service for Asteroid Models (ISAM[6]) contains shape models for more than 900 asteroids. It allows to (i) to display an asteroid orientation as seen from Earth at any date; (ii) to generate lightcurves; (iii) to animate the rotation; (iv) to produce 3D views; and (v) to conduct shape and lighting analysis. D3.2 on "Prediction of shape orientations" is closely related and explains more details.

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



Example view of the "orientation" mode of the ISAM service. One of our SAGE models is displayed together with the corresponding lightcurve for the given viewing geometry.

The Gaia-Groundbased Observational Service for Asteroids (Gaia-GOSA[7]) is an interactive tool which supports observers in planning photometric observations of asteroids. The asteroid prediction tool is based on the Gaia orbit and scanning law provided by the European Space Agency and the ephemerides of Solar System bodies provided by the Minor Planet Center. These inputs have been coupled by a software tool developed and run by the Gaia Data Processing and Analysis Consortium (DPAC). D3.1 on "GOSA service upload" is closely related and explains more details.

As part of the SBNAF project, we prepare a database for thermal IR observations of small bodies (NEAs, MBAs, Trojans, Centaurs, TNOs). The database will include measurements from ground (mid-IR, submm, mm) and space (IRAS, MSX, AKARI, ISO, Spitzer, WISE, Herschel, Planck). The database is planned to be available to the planetary community in early 2019, well before the TherMoPS III workshop in Budapest. D2.5 and D2.6 are closely related (due dates in Sep 2018 and Mar 2019).

b) Products for the planetary community:

These products include: occultation predictions (D5.1, D5.2, D5.3), User Provided Data Products for the Herschel Science Archive (D2.1, D2.2, D2.3, D2.4), and the asteroid-related calibration products (all deliverables in WP4, also D6.2). More details can be found at http://www.mpe.mpg.de/~tmueller/sbnaf/results/bProducts.html.

c) Results, recommendations, recipes from the synergy work:

The results in this category are more difficult to describe since they are typically part of scientific publications. However, we want to point out a few synergy results which are connected to public deliverables during the first 18 months of the SBNAF project:

- D5.6 Observational publications
- D6.1 Occultation vs. thermal tools
- D6.2 Shape & spin solutions for primary calibrators
- D6.3 In-situ object properties
- D6.4 Gaia asteroid list
- D6.5 "Ground-truth" shape models
- D6.6 Thermally resolved shape models.

[7] http://www.gaiagosa.eu/

The content of these deliverables is summarized above. Within the deliverables we also point to the corresponding (past, ongoing, planned) publications.

6. Outreach activities

The major outreach activities are listed on our public page at http://www.mpe.mpg.de/~tmueller/sbnaf/outreach.html, separated into three categories: (i) outreach events; (ii) press releases and public articles; (iii) public relation activities, including also links, animations, and outreach material. We give some examples.

a) Outreach events

Here, we list selected events, but many more outreach activities are ongoing throughout the year where SBNAF team members are in contact with the public (schools, interested laymen, people of very different age and background):

- Multiple public talks, institute seminars, outreach activities, interviews, etc. on the **"Haumea-Ring-Satellite system"**, following up on the Nature publication "Ortiz et al. 2017, Nature 550, 219-223: The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation" in all SBNAF partner institutes
- Worldwide Asteroid Day, public event in Munich/Germany on June 30, 2016, with a SBNAF-related presentation programme and N24 TV coverage (was broadcasted in Sep/Oct 2016)
- Public presentations during the Perseid meteor shower with strong emphasis on SBNAF activities: on Aug 11, 2016 at Calar Alto Observatory (CAHA), Spain (two groups of about 50 visitors each), and on Aug 12, 2016 at Sierra Nevada Observatory (OSN), Spain (with about 250 visitors)
- Marie Skłodowska-Curie action: European Researchers Night (NIGHT), public Europe-wide event on Sep 30, 2016 with SBNAF presentations in different places:
    - In Granada/Spain: La Noche Europea de los Investigadores
    - In Poznan/Poland: Small Bodies: Near and Far
- Stellar occultation by Haumea on Jan 21, 2017, coordination of observing activities all over Europe with about 40 observatories (professional & amateur) participating, making it one of the largest TNO occultation campaign ever; about 10 observatories have detected the event successfully
- Cita con las estrellas, El Corte Ingles, Malaga: "El cinturón trans-Neptuniano: Esos pequeños/grandes mundos más allá de Neptuno" (The transneptunian belt: those small/large worlds beyond Neptune), given on Mar 2, 2017
- Public lectures/seminars with sky shows at Poznań observatory
    - Public lecture on "Dwa światy: planetoidy Ceres i Vesta" (Ceres and Vesta asteroid studies), Dec 9, 2016
    - Presentation "Rekonstrukcja kształtów planetoid z obserwacji radarowych", as part of the seminar "Modern Trends in Physics Research", AMU Faculty of Physics, Jan 27, 2017
    - Presentation "Badanie rotacji i kształów planetoid", Astronomical Observatory of Warsaw University, Feb 28, 2017
    - Presentation "Fotometria, modelowanie i skalowanie planetoid o długich okresach i niskich amplitudach", Toruń Centre for Astronomy, Nicolaus Copernicus University, May 15, 2017
- Paisajes del Sistema Solar, Parque de las Ciencias de Granada, Feria del Libro de Granada, Apr 22, 2017
- Worldwide Asteroid Day, public event on June 30, 2017:

  - Public "round table" event with several SBNAF asteroid experts at IAA/Granada on June 28, 2017
  - Public talk on asteroid risk/defence at the Volkssternwarte München by NEOSHIELD-2 experts, supported by SBNAF members, on June 30, 2017
  - Public talk at ESO on "The Fascinating World of Asteroids", following up on the Worldwide Asteroid Day, July 13, 2017
  - Worldwide Asteroid Day related internship at MPE (4 young students, supervised by SBNAF members) in July 2017
- Marie Skłodowska-Curie action: European Researchers Night (NIGHT), public Europe-wide event on Sep 30, 2017:
  - SBNAF presentation in Granada/Spain
  - Preparation of multiple 3-D printed asteroid models, designed for outreach activities including blind people
- Public "Open House" day at the research campus Garching, Germany (Oct. 2017) with about 1,800 visitors at MPE:
  - public talk "Exotische Welten: Asteroiden, Kometen und Planeten"
  - kids program (with about 300 children), including activities like "Touch an asteroid", display of several posters on small bodies, impact risk, overview of the solar system, planet X, etc., including also 3-D printed asteroids

b) Press releases and public articles

All press releases and articles are available on our SBNAF web pages.

2017:

- Haumea of the Outer Solar System (NASA's Astronomy Picture of the Day APOD from Oct 17, 2017)
- Astronomers discover ring around dwarf planet Haumea (HORIZON, The EU research & Innovation Magazine, 11 Oct 2017)
- Haumea, the most peculiar of Pluto companions, has a ring around it (Instituto de Astrofisíca de Andalucía, IAA-CSIC; 11 Oct 2017; English/Spanish)
- Ring around a dwarf planet detected (MPE/MPG press release; Oct 12, 2017; English/German)
- Haumea - the first dwarf planet with rings (Institute Astronomical Observatory, Faculty of Physics Adam Mickiewicz University in Poznań; Oct 12, 2017; English/Polish)
- World-wide press coverage of the Haumea Nature paper in many languages: The Guardian, New Scientist, Space.com, Science Magazin, Scientific American, Daily Mail, National Geographic, ABC, Planetary.org, The Verge, Science alert, Universe Today, Phys.org, Metro/UK, Arab News, Spaceref.com, Ghana Nation, GIZMODO, YouTube, Europa Press, Agenia SINC, El País, El Mundo, ABC/Spain, La Vanguardia, El Confidencial, Milenio, Canal Sur (min 11:22), iVoox, Nauka w Polsce, facebook.com, DAN TRI, Vietnam, Twitter (Carlos Moedas, European Commissioner for Research, Science & Innovation), Academic Film Studio of AMU, Poland, etc.
- Not the mother of meteorites (ESO Press Release; June 19, 2017)
- Hubble Spots Moon Around Third Largest Dwarf Planet (NASA, Hubble press release May 18, 2017)
- New asteroids named to honour astronomers from Poznań: group picture & press release & Poznańscy astronomowie mają swoje planetoidy! & Kolejne planetoidy oznaczone nazwiskami astronomów z UAM

- Meteoroides, Meteoros Y Meteoritos, Cómo se diferencian? (Revista de divulgación científica: Ciencia para todos los Públicos, Mar 2017)

2016:

- TNO 2016 BP81 discovery in Kepler-K2 data (MPS 749584 from Dec 11, 2016)
- NEA 2015 BO519 discovery in Kepler-K2 data (MPS 747529 from Dec 5, 2016)
- Kepler has caught hundreds of asteroids (Phys.org, Oct-24, 2016)
- Big Kuiper Object 2007 OR10 Has a Moon (Sky&Telescope Oct. 21, 2016)
- 2007 OR10 has a moon! (DPS/EPSC conference news, Oct. 19, 2016)
- Plutón, Plutón ..., Quién te ha visto y quién te ve (Información Actualidad Astronómica, revista.iaa.es, Oct. 2016)
- Radarkarte eines Asteroiden (Sterne & Weltraum, SuW 08/2016, Expert Answer)
- 2007 OR10: Largest Unnamed World in the Solar System (NASA JPL News May 11, 2016): combined Kepler & Herschel & ground-based data

c) Public relation activities

In this category, we provide a collection of images, YouTube movies, TV documentaries, tools, links to useful pages, etc., all related to SBNAF topics, most of them produced by the SBNAF team. The products of general interest are available from our public web page at http://www.mpe.mpg.de/~tmueller/sbnaf/outreach.html.
In addition, there are a number of outreach products to be used by team members for all kind of outreach activities (only available from our internal web page[8]).

7. Discussion and outlook

Our benchmark project includes several objects with ground-truth information from interplanetary missions. This kind of ground-truth information is unique in astronomy and leads to wide applications for objects without ground-truth information relevant to various projects in the planetary community outside SBNAF. It helps us to investigate limitations of current modelling techniques, to refine them beyond the state of the art, and to provide strategies for optimized observing campaigns at visual and thermal wavelengths.

Our tools and scientific results will contribute to the Basic Science demanded by the growing focus of Industry on mining asteroids and in-situ resource utilisation. The SBNAF results are immediately available to the astronomical community and to many amateur astronomers. Thanks to the occultation predictions and Gaia-GOSA services, amateur observers are providing substantial support for our project and spurring interest on our small-body studies among the general public. Along with other public outreach activities, this helps to broaden society's appreciation of our field, which is often reduced to the "impact hazard" question, and of astronomy and science in general. For example, our work is also scientifically relevant to profound problems such as the formation and evolution of our Solar System or the delivery of water and complex organic molecules to Earth.

From our point of view, the SBNAF project turned out to be very successful and productive. In the first 18 months, we completed 26 deliverables (out of the 38 for the

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[8] http://www.mpe.mpg.de/~tmueller/SBNAF/PUBLIC_OUTREACH/public_outreach.html

entire 3-year period) and reached 4 milestones (out of 15). The project is running very closely to the foreseen schedule in the SBNAF Grant Agreement. The close collaboration of four teams with very different expertise is key to assess small-body science from very different angles and to produce new tools, products and very interesting results and discoveries (see also the range of related press releases).
In addition to our plans laid out in the proposal, we would like to mention a few new ideas, opportunities, and developments:

- We submitted a SBNAF-related observing proposal responding to the JWST DDT-ERS call for early release science. The proposal was not successful. However, the JWST option will be an important avenue for the mid-term future of small-body science and we will push for several SBNAF-related smaller projects in the upcoming JWST GO call. We also have participations in three JWST GTO proposals related to SBNAF targets that will be executed in cycle 1 (currently foreseen in late 2019 and early 2020).
- Following up on the discovery of a ring around the dwarf planet Haumea, we are trying to characterize the multiple-body/ring system with ALMA in the submillimetre/millimetre range, and also with JWST in the thermal Infrared and with VLT at visual wavelengths.
- We took advantage of the Kepler-K2 observing options by submitting small-body related proposals for the cycles 8 (in 2016) to 18 (2018): see also related multiple publications.
- We also have accepted observing programmes on HST, SOFIA, VLT, and many other intermediate to large telescopes around the world.
- We started to look into possible science topics for the SKA[9], although this is will happen well after the end of the SBNAF project.

<u>Outlook:</u>
We are currently trying to find funding opportunities to continue our very successful collaboration beyond the end of the SBNAF project in March 2019.

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[9] https://skatelescope.org/

SBNAF, 2nd periodic report, part A

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

Progress Report
Part A: Public Summary

Period covered by the report: from 01/04/2017 to 31/03/2018
Following up on 1st periodic report (01/04/2017 to 31/03/2017) and the SBNAF mid-term report (D1.3)

I. Summary of the context and overall objectives of the project

The EU Horizon2020-funded benchmark study SBNAF (2016-2019) addresses critical points in reconstructing physical and thermal properties of near-Earth, main-belt, and trans-Neptunian objects. The combination of the visual and thermal data from the ground and from astrophysics space missions (like Herschel, Spitzer, Kepler-K2, Hubble, and AKARI) is key to improving the scientific understanding of these objects. The development of new tools is crucial for the interpretation of much larger data sets from WISE, Gaia, JWST, or NEOShield-2, but also for the operations and scientific exploitation of the Hayabusa-2 mission. Our approach is 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. We derive size, spin and shape, thermal inertia, surface roughness, and in some cases even internal structure and composition. The applications to objects with ground-truth information from interplanetary missions Hayabusa, NEAR-Shoemaker, Rosetta, DAWN, and soon also Hayabusa2 and OSIRIS-REx, allows us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method. Another important aim is to build accurate thermo-physical 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.

In this second period between April 2017 to March 2018 we improved the newly developed tools and web-services, we combined data from very different sources in sophisticated ways to obtain new scientific results, and we produced highly reliable calibration and science products for the planetary community. In parallel, we conducted (often coordinated) new observations with Kepler-K2, Hubble, ALMA, VLT, and many smaller-size telescopes around the world. We presented our scientific results in refereed publications (22 in the second year, including one publication in Nature) and a large collection of world-wide conference contributions, including a dedicated conference session on SBNAF topics in the European Planetary Science Congress in September 2017 in Riga/Latvia. 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 are advertised in many planetary science conferences. Our work gets more and more visibility through a wide range of outreach activities and press releases and several new scientific collaborations with external teams.

All relevant project information is available on the SBNAF-internal, password-protected web page: http://www.mpe.mpg.de/~tmueller/SBNAF/sbnaf.html. The public page at http://www.mpe.mpg.de/~tmueller/sbnaf advertises the project to the public and the planetary community, provides direct links to our public deliverables, refereed publications, and tools and services and related documentation:

http://www.mpe.mpg.de/~tmueller/sbnaf

II. Work performed (Apr 2017 to Mar 2018)

The second year of our SBNAF project (Apr 2017 to Aug 2018) was part of the Synergy Phase as described in the Grant Agreement Section 1.3.2 under point "(b) Synergy phase (M07 to M30)". The main **(*i*) results, (*ii*) science, and (*iii*) outreach** achieved during our second year are manifold. This summary follows the structure of the SBNAF public website, where this information is collected in full detail.

***i.* Results**

Following the public website under "Results", we distinguish three categories (http://www.mpe.mpg.de/~tmueller/sbnaf/results.html):

a. Summary of Tools & Services

(1) The public ISAM service, hosted at AMU/Poznań, is a model visualisation tool to conduct shape, illumination- and viewing-related analysis. During the second year, we have upgraded ISAM to include new spin-shape solutions from Viikinkoski et al. (2017) and Hanuš et al. (2016, 2017), and our new models described in deliverable D3.5 with full functionalities, including the downloadable .obj files. The latter have been published in three SBNAF papers (Müller et al. 2017, Marciniak et al. 2018, Marsset et

al. 2017). We have also (internally) updated the core information in D3.3, which now also includes the evaluation of the newly available ADAM shape models.

(2) The Gaia-GOSA service, also managed at AMU/Poznań, is an interactive tool to support observers in planning photometric observations. It is based on the Gaia orbit and scanning law provided by the European Space Agency. 120 registered users have provided 392 (uploaded) observing nights, 139 since April 2017. Full lightcurves have been obtained for 40 objects, mostly SBNAF targets from the "Gaia perturbers" (D6.4, D3.4) and "calibrators" lists (D4.6, D3.3). 50% of the data have been processed and will be uploaded to the CDS archive after successful spin/shape modelling.

(3) The asteroid IR database, managed at Konkoly Observatory, is connected to upcoming deliverables D2.5 and D2.6 (Sep. 2018, Mar. 2019). During this second year, we have already collected several thousand thermal infrared asteroid observations and carefully analysed them to comply with general database standards and our requirements. We added a wide range of auxiliary parameters from the JPL/Horizons system and developed and verified procedures to colour-correct the infrared measurements. We started developing a web interface that is currently in the test phase. It will be made available to the planetary community in the context of a dedicated workshop "Thermal Models of Planetary Science III", for which we have started with preparative actions (http://thermops2019.hu).

b. Summary of Products

(4) High-quality predictions for occultation events for the year 2018 (D5.3, submitted in Dec 2017) will allow amateur and professional astronomers to observe these scientifically important events. Predicting 25 successful TNO occultation events and reaching 10 mas accuracy is also a key element for our benchmarking goals in WP6. The occultation predictions were calculated at IAA/Granada with an institute-internal code. The star positions are currently based on the Gaia Data Release 1 catalogue (Apr 2017). The orbit calculations for the moving targets (here mainly TNOs and Centaurs) include results from large astrometric observing campaigns conducted in Spain and affiliated/collaborating observatories.

(5) The SBNAF project produces high-quality data products for asteroid and trans-Neptunian object (TNO) observations of the Herschel Space Observatory. These products are based on sophisticated, Solar-System specific data reduction and calibration schemes. The second-year deliverables, "D2.3 MBA HSA upload" and "D2.4 TNO HSA upload", together with release notes, were delivered to the Herschel Science Center. The lead for the generation of these products is at Konkoly Observatory and the verification is a SBNAF team effort.

(6) Asteroid-related calibration products connected to second-year deliverables D4.4 and D4.6 (WP4) are available from our public website. With lead at MPE/Garching, SBNAF continues to support worldwide calibration activities for ground-, airborne-, and space-projects at mid-IR, far-IR, submm/mm wavelengths by providing highly reliable model predictions (5-10% level accuracy) of selected asteroids over a long future time span. The main result from the second year is the establishment of a group of about ten high-quality secondary asteroid calibrators.

c. Summary of Synergies

The scientific and benchmarking work we have carried out in this phase is based on multiple techniques and datasets and thus it is framed under the label "Synergies".

(7) The deliverables in "WP6 Synergies" corresponding to this second year include an update for "D6.5 Ground truth shape models", "D6.6 Thermally resolved shape models", and "D6.7 Quality assessment system for the models". WP6 deliverables are accomplished under a shared lead between AMU/Poznań and MPE/Garching, and are available from our public website under *Results* → *Synergies*. These deliverables summarise our results and frame our work, which is spread throughout numerous scientific papers (see Section *ii*. below), in the global context of the project.

***ii*. Science**

Our science is disseminated to the scientific community through peer-reviewed articles and conference communications. All publications, accessible from our public website (http://www.mpe.mpg.de/~tmueller/sbnaf/science.html), have the required acknowledgement to the EU's Horizon 2020 Research and Innovation Programme, under Grant Agreement no 687378.

(8) Conferences and workshops: With 12 SBNAF-related contributions, the ACM2017 conference in Montevideo, Uruguay was the most important event in the second year. In the EPSC2017 conference in Riga/Latvia, we organised a dedicated session on "Small Bodies Near and Far" with 7 oral contributions and 4 posters. We were also very active in the DPS 2017 conference in Provo, USA (6 contribs.), the 4th International AKARI conference in Tokyo/Japan (2 contribs.), the TNO/KBO conference in Coimbra/Portugal (9 contribs.) and several other national and international conferences. In total, we counted about 30 publicly available SBNAF-related abstracts for posters and talks, and more than 10 additional workshop and/or conference contributions.

(9) At the end of the second SBNAF year we are proud to count 22 published refereed publications (04/2017 to 03/2018) and another 15 additional submissions containing most of our scientific output either produced as a team or with significant SBNAF individual/team contributions. The highlight of this period is the Nature paper by Ortiz et al. on "The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation", opening up a new avenue for planetary research.

***iii*. Outreach**

(10) During the second year we have continued to produce a wide range of outreach and educational material for the public. The most important science results are also connected to press releases, the highlight being connected to the Nature paper with worldwide press coverage, countless public articles, talks, interviews and other outreach activities (see http://www.mpe.mpg.de/~tmueller/sbnaf/outreach.html).

III. Progress beyond the state of the art and expected potential impact

Our benchmark objects have often ground-truth information from interplanetary missions. This helps us to refine existing model techniques beyond the current state-of-the-art, to provide strategies for optimized observing campaigns at visual and thermal wavelengths, and to investigate the possibilities and limitations of current modelling techniques. This kind of ground-truth information is unique in astronomy and leads to wide applications for objects without ground-truth information, and for various projects in the planetary community outside SBNAF. The SBNAF results are immediately available to the astronomical community, but also to many amateur astronomers who provide substantial support for our project. In addition, the results of our small-body studies are of great interest for the public.

The socio-economic impact in the short term is difficult to trace and quantify, but SBNAF's tools and scientific results will surely contribute to the Basic Science demanded by the growing focus of Industry on the prospects of mining asteroids and what has been termed “in situ resource utilisation" (ISRU). In the shorter term, the occultation predictions and Gaia-GOSA services are allowing amateur observers to actively further our knowledge of Small Bodies. These, along with other public outreach activities, broadens society’s appreciation of our field in particular, which is often reduced to the “impact hazard” question, and of astronomy and science in general. Many aspects of our scientific work are also very relevant in the context of understanding the formation and evolution of our Solar System, the delivery of water and complex organic molecules to Earth, and in spreading the fascination for small-body science in general.

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

Progress Report
Part B: EU-internal

Period covered by the report: from 01/04/2017 to 31/03/2018
Following up on 1st periodic report (01/04/2017 to 31/03/2017) and the SBNAF mid-term report (D1.3)

Structure of the report

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

The SBNAF bench-mark study (2016-2019) addresses critical points in reconstructing physical and thermal properties of near-Earth, main-belt, and trans-Neptunian objects. The combination of the visual and thermal data from the ground and from astrophysics space missions (like Herschel, Spitzer, Kepler-K2, Hubble, and AKARI) is key to improving the scientific understanding of these objects. The development of new tools is crucial for the interpretation of much larger data sets from WISE, Gaia, JWST, or NEOShield-2, but also for the operations and scientific exploitation of the Hayabusa-2 mission. Our approach is 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, NEAR-Shoemaker, Rosetta, and DAWN allows us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method.

In the context of the SBNAF project we derive size, spin and shape, thermal inertia, surface roughness, and in some cases even internal structure and composition, for objects from the near-Earth environment out to the most distant objects in the Solar System. Another important aim is to build accurate thermo-physical asteroid models to establish new primary and secondary celestial calibrators for ALMA, SOFIA, APEX, and IRAM, as well as to provide a link to the high-quality calibration standards of Herschel and Planck. The target list comprises recent near-Earth and main-belt interplanetary mission targets, two samples of main-belt objects (Gaia "mass/perturber sample" & "asteroid calibrator" sample), representatives of the Trojan and Centaur populations, and all known dwarf planets (and candidates) beyond Neptune.

In the second year between April 2017 to March 2018 we updated the recently developed new tools and web-services. We produced many highly reliable calibration and science products for the planetary community. At the same time, we present our scientific results in refereed publications (about 22 in the second year) and a large collection of conference contributions. All publications are in open access, the various tools, services and products are available on our public web page. Our team combines world-leading expertise in different scientific areas in a new European partnership with a high synergy potential in the field of small body and dwarf planet characterization, related to astrophysics, Earth, and planetary science.

1.1 Objectives

The main objective of the SBNAF project is to enhance the scientific return from different astrophysics and planetary missions related to small bodies and dwarf planets in our Solar System. We use very different data sets from ground (professional and amateur observations), airborne, and space projects and combine 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 develop sophisticated web tools, provide calibration products, and establish new scientific data products. The SBNAF activities add 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 community. We provide enhanced data products for upload to ESA and NASA archives.

Our team includes world-leading experts in different fields: lightcurve inversion techniques to reconstruct shapes and spin properties of small bodies; 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 are 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 newly formed team, the SBNAF project has 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.
  - Status Apr 2018: several deliverables are 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 techniques are available from our public web page;
- 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 Centaurs and trans-Neptunian objects.
  - Status Apr 2018: new, high-quality products for Herschel MBA and TNO observations have been provided to the HSA, related deliverables are "D2.3 MBA HSA upload" (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 ("D4.4 Secondary asteroid models");

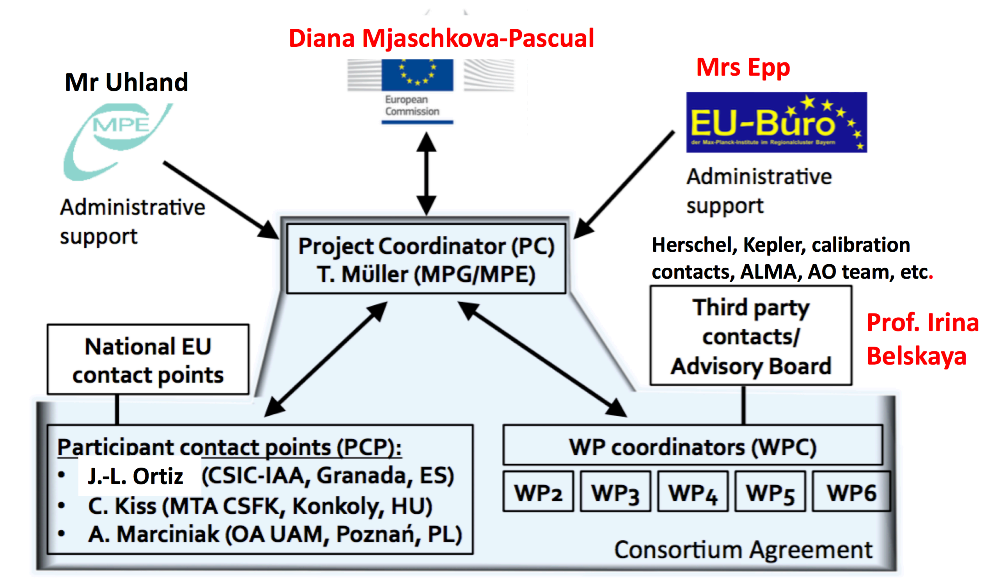
- Advance the field of thermo-physical characterization of small bodies by combining disk-resolved asteroid observations from interplanetary missions (Hayabusa, Rosetta, Dawn, NEAR-Shoemaker) with disk-integrated thermal and optical observations from space and ground.
  - Status Apr 2018: work in this context is ongoing, partly covered in NEA and MBA publications, 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 are programmed to be carried out in the upcoming year, including the important comparison between our extensive model predictions for Ryugu and the in-situ results coming from the Hayabusa2 mission.
- 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.
  - Status Apr 2018: In the context of “D4.4 Secondary asteroid models” we tested model predictions against far-IR/submm/mm observations. Our thermophysical models predictions for the 4 primary asteroids and about 10 secondary asteroids 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 have to be determined object by object, but due to the lack of data this is only possible for selected targets. This work will continue (related to “D4.5 Final asteroid models”) and a publication is planned.
- 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.
  - Status Apr 2018: The SBNAF IR database has been setup and filled with many thousand observational data points. All measurements were analysed step by step to fulfil our requirements and to comply with our and general database standards. We added a wide range of auxiliary parameters from the JPL/Horizons system for each observation entry in the database. We also developed and verified procedures to colour-correct all infrared measurements. The database includes the corresponding instrument-/filter-specific information and a proper documentation and references. We are now working on testing a user interface that allows the members of the consortium to access the data base remotely.
- 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.
  - Status Apr 2018: This topic will be on-going 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. For the rotational properties there are 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). The focus of the work is on the determination of shape (and volume), rotational properties and thermal properties (thermal inertia, surface roughness, emissivity). We assess shape/spin solutions via thermal data. Many of our publications feature radiometric studies as well as aspects from lightcurve inversion, occultation, or AO imaging. The synergy between the expertise by all partners leads 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.
  - Status Apr 2018: 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. In general, for all our targets and all our publications we systematically add the available thermal (space) data to add new information and to enhance the scientific outcome. We also do 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.
  - Status Apr 2018: Our Hayabusa-2 related model solution for the mission target Ryugu was recently published (Müller et al. 2017). Another publication on "Asteroid Ryugu Before the Hayabusa2 Encounter" by Wada et al. (2018) was submitted. More Ryugu studies will follow with the availability of new observational data. In the context of Gaia, we push 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 includes 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) and for selected TNOs (Lellouch et al. 2017).
- Provide tools, techniques and crucial object properties in support of NEOShield-2, OSIRIS- REx, JWST, and ground-based observations of minor bodies.
  - Status Apr 2018: Here we can list the ISAM service to visualize and provide to the community asteroid spin and 3-D shape solutions, but also our results on thermophysical model studies of NEAs are relevant for NEOShield-2 and OSIRIS-REx. The preparatory work for JWST (some team members are part of the GTO proposals, we had an (unsuccessful) attempt for an ERS proposals, and we plan to submit several GO proposals on SBNAF targets) has started and will be followed up during the next year.

1.2 Explanation of the work carried out per WP

1.2.1 Work Package 1: Management & Outreach



Management structure for the SBNAF project. Names given in red are recent changes (EU officer, local EU contact, external reviewer).

During the reporting period from April 2017 to March 2018 we encountered no major problems within WP1. The coordination of the SBNAF project is 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 is as expected and described in the Grant Agreement No 687378. All 10 deliverables foreseen for the second year have been uploaded to the EU web portal. A few deliverables were late by a few days 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 18 webex meetings in the second year). The meeting minutes and the arising action items (more than 130 in the second year) are collected, tracked, and followed up on our internal web page. In case of problems, we try to mediate between the team members, the participant contact points, or the WP leaders. Currently, there are no identified risks related to the WPs, deliverables or milestones.

The biggest workload in WP1 is related to the email/webex/telecon communication between the beneficiaries and the very frequent updates on the internal and public web pages which are the main sources of information for the team members, the EU officer, our external expert, and the public. Also, the periodic reports and the mid-term report (D1.3) were large workloads in the second year. Via our public web page and astronomy archives for publications we ensure 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). The Solar System and small-body topics are also of great interest to the public and as part of WP1 we foster outreach activities and we offer qualified feedback to media requests.

During the second year, there were two major reports connected to WP1:

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

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.

Outlook: WP1 is progressing as expected. The next team meetings will take place in November 2018 (Garching) and spring 2019 (April or May 2019 in Poznań). No official WP1 deliverable is foreseen for the third project year, but the final report will require significant manpower in the two months after the official end of the project.

1.2.2 Work package 2: Infrared observations

The goal of WP2 is twofold. First, some tasks in this WP (D2.1, D2.2, D2.3, and D2.4) focus on data obtained with the Herschel Space Observatory and the main goal of these tasks is 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 are 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 current 12-months period (Apr 2017 – Mar 2018) we completed “D2.4 TNO HSA upload” and reached “MS2 Expert-reduced data to HSA”. In addition, we have advanced work on upcoming deliverables connected to the infrared database:

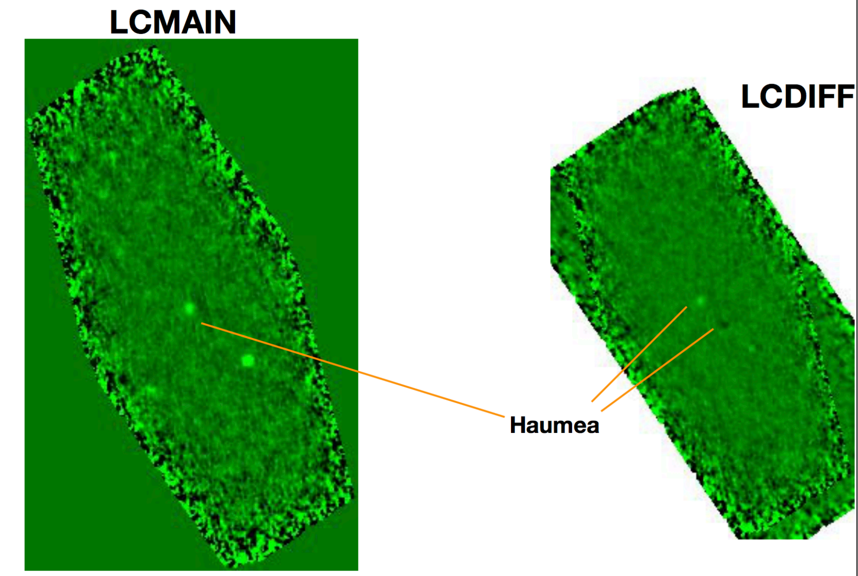
D2.4 TNO HSA upload (30 Sep. 2017 – uploaded 28 Nov. 2017)

- 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).
- Observations were performed under a few dedicated observing programs, the largest one being the 'TNOs are Cool! A Survey of the trans-Neptunian Region' Open Time Key Program (PI: Th. Müller). Some of the targets of this program were included in the AOT Validation and Science Demonstration Phases (AOTVAL thmuelle2 and SDP thmuelle3, PI: Th. Müller)
- Additional programs of PACS photometric observations of TNO and Centaurs include: Open Time Program 'Probing the extremes of the outer Solar System: short-term variability of the largest, the densest and the most distant TNOs from PACS photometry' (OT1 evileniu1, PI: E. Vilenius); DDT proposals 'The thermal lightcurve of Centaur (2060) 95P/Chiron' (DDT mustdo3; PI: E. Lellouch); 2012 DR_{30}: A wanderer from the far edges of the Solar System' (DDT ckiss2, PI: Cs. Kiss), and 'The "supercomet" candidate 2013 AZ_{60}' (DDT ckiss3, PI: Cs. Kiss).
- There are two main type of TNO/Centaur observations:
  1. Multiple-epoch observations of the same target. Here, the main goal of the observations was to obtain single, accurate flux densities of the targets in the three PACS bands (70, 100 and 160 μm). The observations were designed in a way that they could provide optimal background elimination as confusion noise due to sky background is a major limitation for far-infrared observations of faint targets. One single OBSID lasted typically for <30min. To achieve a sufficient signal-to-noise ratio observations of the same target in the same band were combined.
  2. Thermal emission light curve observations. In these cases, the target was observed typically for several hours, in contrast to the typically much shorter multi-epoch observations, repeating the same scanning pattern around the target up to ∼100 times. Here, the main goal was to resolve the thermal emission temporarily. Herschel/PACS TNO and Centaur light curve observations were typically executed for one pair of filters (either 70/160 or 100/160) for a specific target, depending on the target's expected spectral energy distribution.

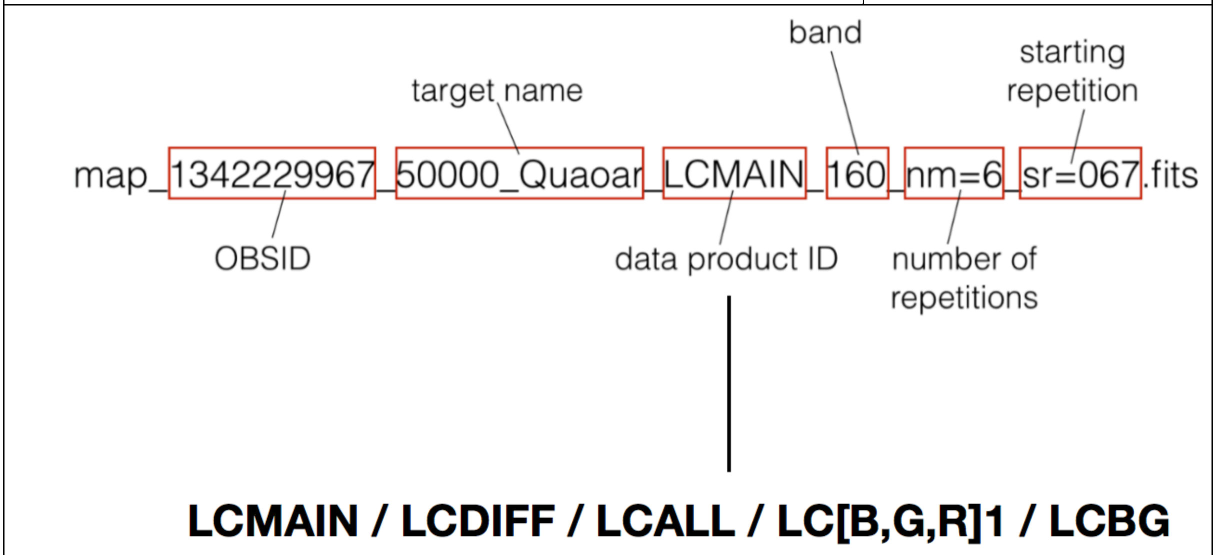
- We provided the new TNO/Centaur images to the Herschel Science Centre (HSC) for an upload to the HSA as User-Provided Data Products (UPDP). The delivery of products (FITS images) for the HSA came also with a product-specific release note. These UPDP are made publicly available from the HSA for all registered users.
- The UPDP delivery associated with this deliverable combined observations of the targets observed at multiple epochs. These kinds of data products are not produced by the Standard Product Generation pipeline of the Herschel Science Archive (HSA). We supply UPDPs only for those targets that strictly comply with the 'TNOs are Cool!' standard observing strategy and combined data product requirements. This is fulfilled for 132 Centaurs and trans-Neptunian objects, and in addition for one giant planet irregular moon,

Sycorax, that was also part of the Open Time Key Program. Due to these requirements, this delivery is restricted to scan-map observations, data obtained in chop-nod mode are not presented. We apply a reduction pipeline optimized for faint, slow-moving targets, and use specific methods to correct for possible pointing and positional uncertainties.

- In the context of D2.4 we provided **3594 FITS products** with preprocessed TNO/Centaur observations to the Herschel Science Archive.



Example of products produced in D2.4 for the upload to the Herschel Science Archive. Explanations are given in D2.4 and the connected release note. Below we show the naming conventions for the newly generated products.



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 **MS2 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 base of scientific publications are will be part of the infrared database (to be delivered as D2.5 and D2.6 of the SBNAF project).

Outlook:
A significant part of the work in WP2 during the second year was already related to the preparations for our database of IR observations of asteroids. These two upcoming deliverables are:

- D2.5 IR database (internal) (30 Sep 2018)
- D2.6 IR database (public) (31 Mar 2019)

This work will be carried out under the leadership by Konkoly observatory. We plan to open our IR database to the public already in early 2019 before our workshop on "Thermal Models for Planetary Science III (TherMoPS III; http://thermops2019.hu/) takes place.

1.2.3 Work package 3: Lightcurve inversion techniques

The main task in the work package on lightcurve inversion techniques is to develop and refine asteroid spin and shape modelling techniques, and to join various types of data for model scaling and validation. Another task is to provide the models with their parameters to the community via the ISAM[1] service (Interactive service for asteroid models, see below).

During the project's second year, 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 ~900 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).
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.

On Gaia-GOSA, we have 120 registered users and 392 nights of observations. Full light-curves have been observed for 40 objects, and complete rotations from two oppositions have been observed for 4 asteroids. Since 1 April 2017, 139 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 50% of the data are processed and the lightcurves are shown on the GaiaGosa webpage and will be made publicly available (via the CDS archive) as soon as the data are used for spin and shape modelling.

Regarding deliverables, the Grant Agreement contains two for WP3 during the current reporting period:

D3.4 Asteroid volume determination
This deliverable provides a summary of techniques used for scaling various types of asteroid

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

shape models, describes the means to validated them, and also summarizes the current status of a campaign to observe 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 D 3.4, providing a good reference source for the subject of determination of asteroid sizes and volumes.

The deliverable D3.4 also describes 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 is described. These often display 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 campaign of chosen Gaia perturbers, described in the last section of the deliverable, is 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 - a task predicted for completion in the Deliverable 6.8, planned for Month 30 (Sep. 2018).

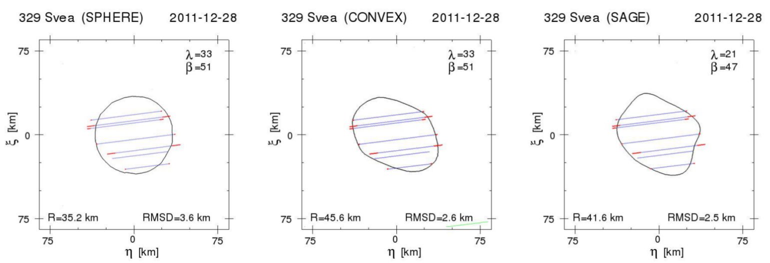


Figure 11: *Three different shape solutions of 329 Svea fitted to 2011 occultation. The R is the size of the model, i.e. the length of the longest vector in the model, based on the fit.*

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.*

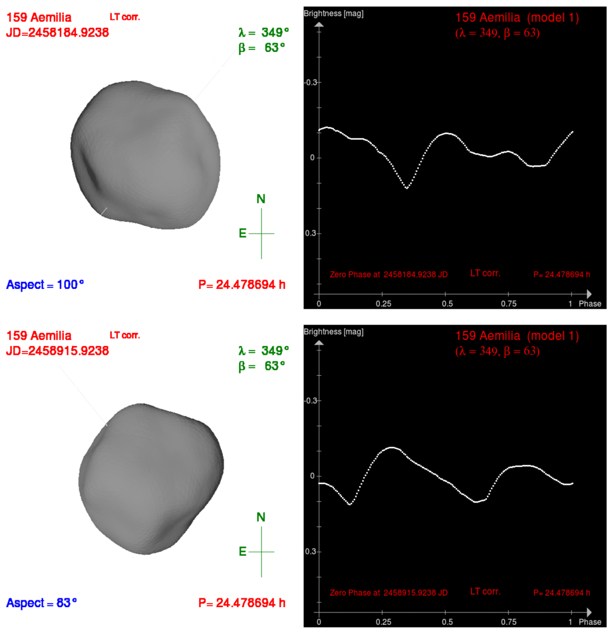
Figures extracted from deliverable D3.4, Asteroid volume determination.

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 summarise and discuss 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 is 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 seems necessary given that the nominal inversion shape is 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.

Another approach is to do the inversion on purely optical data and an *a posteriori* study of the resulting spin and shape model by thermophysical modelling. As usual, this has 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 approach to join optical and thermal data in the remainder of the SBNAF project will be the separate fitting instead of optimisation of all parameters 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.

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 addresses this challenge.

WP4 is closely related to "WP2 Infrared data" where we collect the available thermal measurements, to "WP3 Lightcurve inversion technique" where we try to produce the best-possible shape and spin solutions for the objects in question, to "WP5 Ground-based observations" where we try to obtain missing information for the shape & spin determination (if needed) or occultation observations to scale the shape solutions, but also to "WP6 Synergies" where we test 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 illustrates the interplay between the different techniques. In the second year, 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 includes many tasks that are handled step by step via a sequence of deliverables:

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

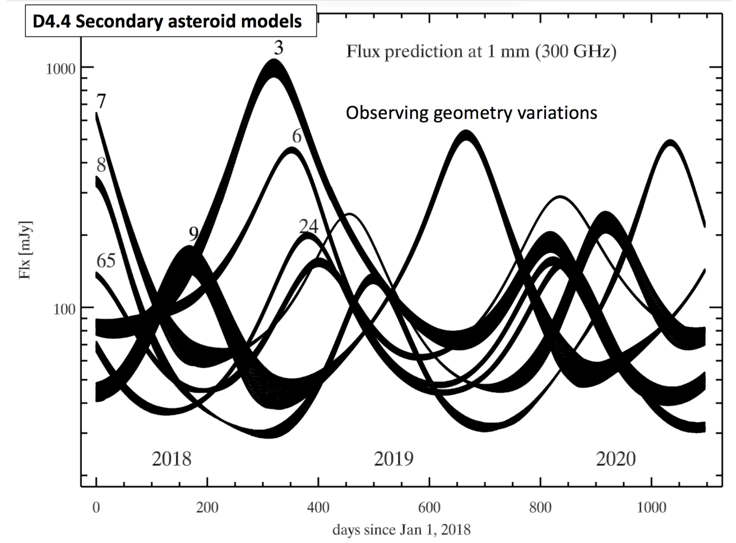
This deliverable was officially part of RP1 (approval in July 2017). It includes a list of calibration needs and requirements of ongoing and future far-IR, submm, mm projects. It describes our investigations on the potential use as secondary calibrators for many large main-belt asteroids. We have put our focus on the collection of available object information and thermal IR observations (+ detailed overview table 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 is 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".

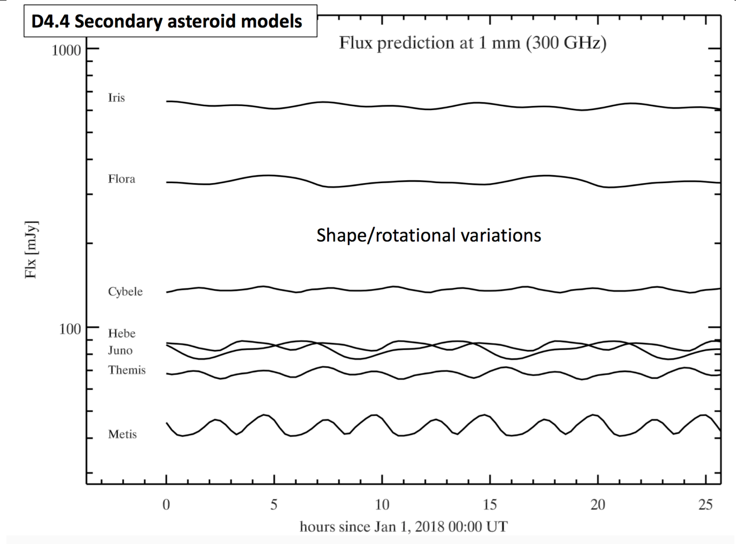
D4.4 Secondary asteroid models (Mar 2018)

D4.4 is 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
- 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.

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 receive frequent requests for specific calibration products: mainly asteroid or planet model predictions at specific wavelengths, 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: 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.

Outlook: We will continue to improve asteroid models for calibration purposes by adding new targets to our list of potential calibrators. At the same time, we try to improve the quality of the model predictions by testing against existing thermal measurements. One difficulty is to get access to the calibration measurements (like from ALMA) which are usually not well documented and not publicly available. We also aim for getting more visibility of our calibration contributions by documenting our work in a publication. In "D4.5 Final asteroid models" (Mar 2019) we will present our final solutions for primary and secondary asteroids and make them available in the ISAM service.

1.2.5 Work package 5: Ground-based observations

WP5 has 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 are 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 include time-series and absolute photometry, astrometric measurements, stellar occultations and high angular resolution imaging. More details on the tasks of WP5 are given in other project documents (e.g. the First periodic report). Observations of optical lightcurves of the selected SBNAF objects are 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 60cm 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 obtain 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 are discarded because the predicted shadow misses the Earth. Conversely, when a shadow path is identified to cross a telescope-dense region on Earth (Europe, South America, Japan, USA, Australia, New Zealand) the prediction is further refined and the observers (amateurs and professionals) are 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 year of the SBNAF project we observed 33 stellar occultations: 13 by MBAs (11 positive) and 20 by Centaurs and TNOs (9 positive). We presented/reported them in international conferences or we published –or are in the process of publishing them– in scientific journals. We have also obtained around 2000 hours-worth of SBNAF target lightcurves that lead to the refinement of the rotational period and amplitude of the targets. In some cases, the data were included in lightcurve inversion models (WP3 and WP6).

Around 31 peer-reviewed articles using data obtained within WP5 have been published (or accepted) during the second year period. All of them are related with the different techniques used within WP5. The list of these papers is included in the impact section of this report and deliverable D.5.7 “Observational publications 2”.

The deliverables related with WP5 prepared during this second year 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 contains 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 includes a brief description of the different observational techniques used to obtain auxiliary data of the SBNAF targets and applications of all these observational data.

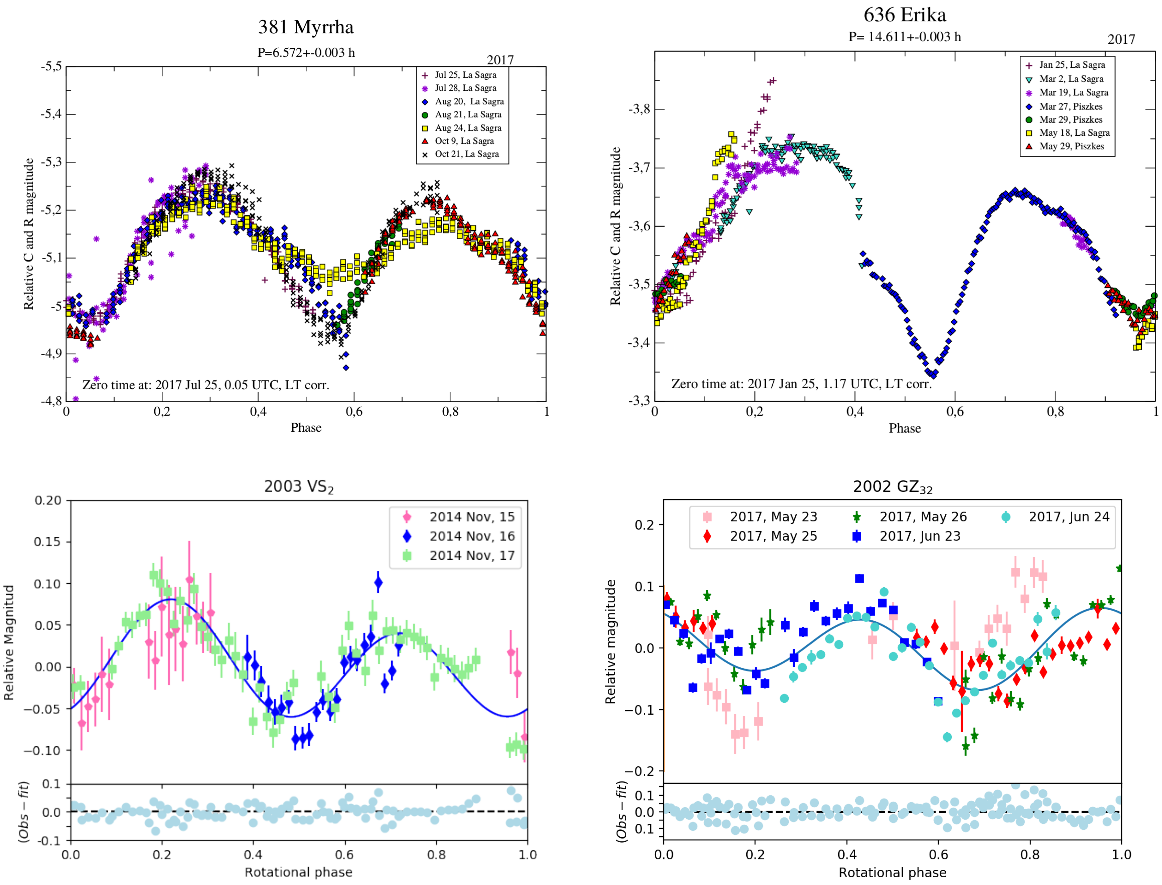


Fig.1.2.5.1- Top left, top right: two examples of rotational lightcurves of MBAs obtained within WP5. Bottom left: TNO 2002 VS_2. Bottom right: Centaur 2002 GZ_{32}.

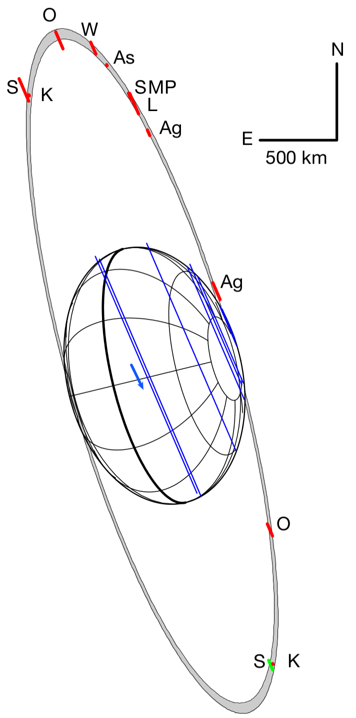
A list of works (published or in preparation) related to each observational technique within the SBNAF project is provided. This list will be updated for the subsequent deliverables: D5.7-‘Observational publications 2’ and D5.8-‘Observational publications 3’.

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

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

D5.7 Observational publications 2 (31 Mar 2018)

This deliverable is an update 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 are repeated within different observational techniques because they include relevant results related with various techniques. The current list will be updated in the subsequent deliverable: D5.8-'Observational publications 3'.



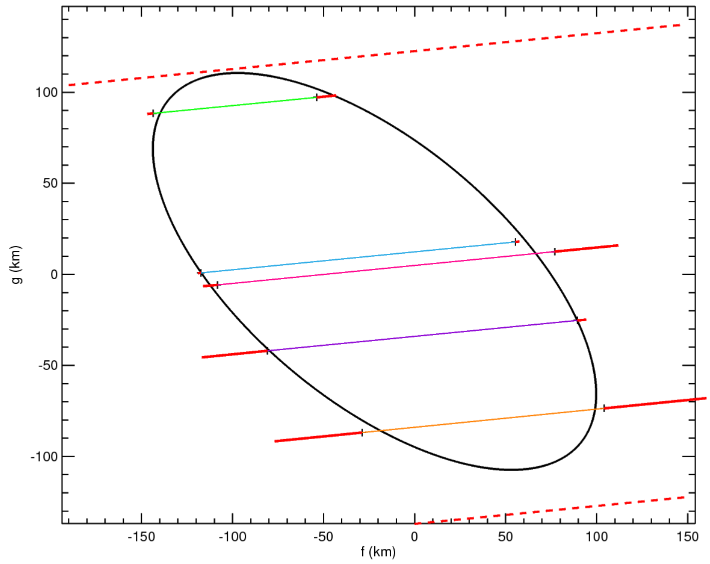


*Fig.1.2.5.2- **Left panel:** result on the stellar occultation by the dwarf planet Haumea with the detection for the first time of a ring around a trans-Neptunian object. These results were published in Ortiz et al. 2017 (Nature). **Right panel:** results on the stellar occultation by the centaur 2002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

Milestones related with WP5:

MS5: "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".

- ➢ This milestone is close to be fulfilled for TNOs/Centaurs, and we expect to make a lot of progress now that the Gaia DR2 has been released (25 April 2018). Some examples of prediction accuracies using GAIA DR1 that should be overcome with GAIA DR2:

  • 19th July 2016 occ. by Pluto (GAIA DR1 + NH ephemeris for Pluto) ~5-7 mas
  • 21st January 2017 occ. by Haumea (Ortiz et al. 2017, Nature) ~11 mas
  • 20th May 2017 occ. by 2002 GZ32 (Santos-Sanz et al. in prep.) ~ 12 mas
  • 28th January 2018 occ. by 2002 TC302 (Ortiz et al. in prep.) ~ 15 mas

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 counted 13 positive stellar occultations by TNOs/Centaurs since April 2016. In total, 46 positive stellar occultations (by 26 TNOs/Centaurs) have been observed by the TNOs/Centaurs occultation community since 2009. The IAA-CSIC team has participated in 36 of them. This means that probably this milestone will be only partially achieved at the end of the project.

Outlook for the third year of the project for WP5:

- Continue with extensive photometric campaigns of asteroids and TNOs/Centaurs from all our observatories (and collaborators).
- Provide/confirm rotational lightcurves (periods and amplitudes) and absolute magnitudes needed for inversion techniques and thermal modelling.
- Improve predictions of stellar occultations by MBAs (easier) and TNOs / Centaurs (challenge) using GAIA DR2. Start to predict radio-occultations by MBAs / TNOs / Centaurs?
- Even using GAIA DR2 very precise relative astrometry few months/weeks prior to the occultation will be needed to refine the prediction due to the uncertainties in the orbits (mainly for TNOs/Centaurs): refine orbits of particularly interesting TNOs/Centaurs using our database images and GAIA DR2.
- Make available to the Planetary Science community observational data of special interest, or not published in regular papers.

1.2.6 Work package 6: Synergies from ground and space

The main goal of this work package (WP) is to make scientific exploitation of the different techniques and tools used and developed in the other work packages in combination. To that end, it is 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 is 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 and D6.7 scheduled for the second year period (Apr 2017 - Mar 2018). We also include 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 is framed in the synergetic frame of WP6 and has materialized in the many publications accepted or submitted for review during these second year (see Sec. 1.3).

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

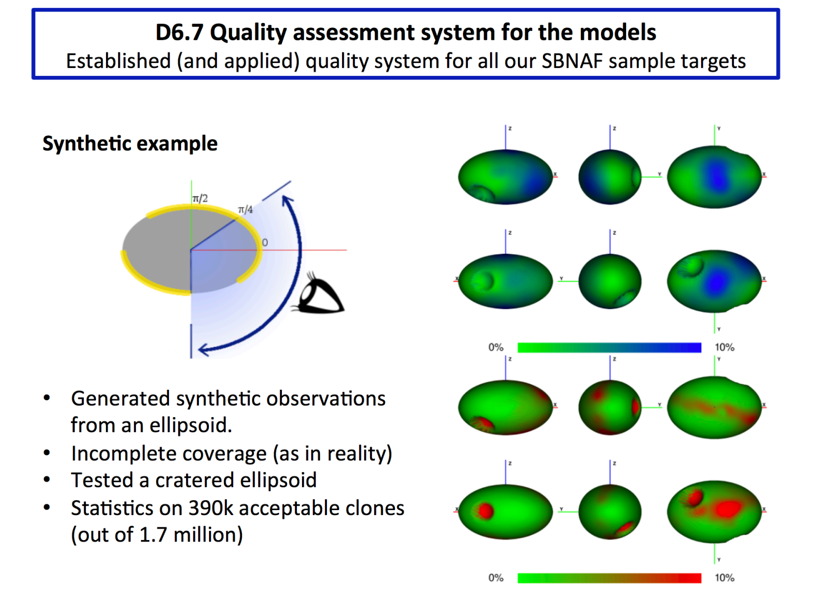
Our external referee requested the reopening of D6.5 on the grounds that it was insufficient to assess whether the SAGE model had been robustly validated. The reason for this is that, at the time of submission of Version 1 (March 2017), all our works were featured in articles that had been submitted to journals for peer-review or were in preparation, so we opted to omit details from the deliverable given it was a public report. As of today, all those works have been published, so Version 2 now contains 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 have 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 is summarized in Table 3 in the deliverable.

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

This deliverable summarizes 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 expands 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 discuss 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 serves 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 present the fundamental aspects of a quality assessment system developed (Bartczak & Dudziński, in prep.) 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.



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, in prep.). Right: cratered ellipsoid to which the method is applied and corresponding positive and negative deviations from the original shape.

Outlook: In WP6 there is only one deliverable remaining: "D6.8 3-D shape models for large MBAs" (Sep 2018). In our mid-term report (D1.3) we already addressed some of the critical points and problems when combining data from very different sources and with very different information content. Considering also the difficulties in producing high-quality 3-D models with reliable size, spin, shape information, and also the delay with the computer cluster setup, **we propose to shift the deadline for D6.8 to the end of 2018.**
In the third year we will continue to exploit the possibilities and limitations of combining multiple techniques and data. We will summarize our findings in publications and upgrade our tools and methods accordingly.

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.

On basis of our target sample we identified open points and a range of specific scientific questions that we want to address in the SBNAF project (Table 1.1 in the SBNAF proposal). Some of these questions are already discussed, and partly answered, in the SBNAF-related publications.

In the second project year (Apr 2017 to Mar 2018) we published (or contributed to) the following articles:

1) 02/2018: Main-belt Asteroids in the K2 Uranus Field, Molnár, L.; Pál, A.; Sárneczky, K.; Szabó, R.; Vinkó, J.; Szabó, Gy. M.; Kiss, Cs.; Hanyecz, O.; Marton, G.; Kiss, L. L., ApJS 234, 37M (2018); arXiv; DOI: 10.3847/1538-4365/aaa1a1

2) 02/2018: Photometric survey, modelling, and scaling of long-period and low-amplitude asteroids, A. Marciniak, P. Bartczak, T. Müller, et al., A&A 610, A7 (2018); arXiv; DOI: 10.1051/0004-6361/201731479
3) 02/2018: Shaping asteroid models using genetic evolution (SAGE), P. Bartczak & G. Dudziński, MNRAS 473, 5050B (2018); arXiv; DOI: 10.1093/mnras/stx2535
4) 01/2018: Spin states of asteroids in the Eos collisional family, J. Hanuš, M. Delbo', V. Alí-Lagoa, B. Bolin, R. Jedicke, J. Ďurech, H. Cibulková, P. Pravec, P. Kušnirá, R. Behrend, F. Marchis, P. Antonini, L. Arnold, M. Audejean, M. Bachschmidt, L. Bernasconi, L. Brunetto, S. Casulli, R. Dymock, N. Esseiva, M. Esteban, O. Gerteis, H. de Groot, H. Gully, H. Hamanowa, H. Hamanowa, P. Krafft, M. Lehký, F. Manzini, J. Michelet, E. Morelle, J. Oey, F. Pilcher, F. Reignier, R. Roy, P.A. Salom, B.D. Warner, Icarus 299, 84H (2018); arXiv; DOI: 10.1016/j.icarus.2017.07.007
5) 12/2017: The thermal emission of Centaurs and trans-Neptunian objects at millimeter wavelengths from ALMA observations, A&A 608, A45; Lellouch, E.; Moreno, R.; M&uum;ller, T.; Fornasier, S.; Santos-Sanz, P.; Moullet, A.; Gurwell, M.; Stansberry, J.; Leiva, R.; Sicardy, B.; Butler, B.; Boissier, J.; arXiv; DOI: 10.1051/0004-6361/201731676
6) 11/2017: "TNOs are Cool": A survey of the trans-Neptunian region. XIII. Statistical analysis of multiple trans-Neptunian objects observed with Herschel Space Observatory, A&A 608, A19, Kovalenko, I. D.; Doressoundiram, A.; Lellouch, E.; Vilenius, E.; Müller, T.; Stansberry, J.; ResearchGate; DOI: 10.1051/0004-6361/201730588
7) 10/2017: Size and shape of Chariklo and its rings reflectivity from multi-epoch stellar occultations, Leiva, R.; Sicardy, B.; Camargo, J. I. B.; Ortiz, J.-L.; Desmars, J.; Bérard, D.; Lellouch, E.; Meza, E.; Kervella, P.; Snodgrass, C.; Duffard, R.; Morales, N.; Gomes-Júnior, A. R.; Benedetti-Rossi, G.; Vieira-Martins, R.; Braga-Ribas, F.; Assafin, M.; Morgado, B. E.; Colas, F.; De Witt, C.; Sickafoose, A. A.; Breytenbach, H.; Dauvergne, J.-L.; Schoenau, P.; Maquet, L.; Bath, K.-L.; Bode, H.-J.; Cool, A.; Lade, B.; Kerr, S.; Herald, D., AJ 154, 159, 23pp (2017); arXiv; DOI: 10.3847/1538-3881/aa8956
8) 10/2017: The structure of Chariklo's rings from stellar occultations, Bérard, D., Sicardy, B., Camargo, J.I.B., Desmars, J., Braga-Ribas, F., Ortiz, J.-L.; Duffard, R.; Morales, N.; Meza, E.; Leiva, R.; Benedetti-Rossi, G.; Vieira-Martins, R.; Gomes Júnior, A.-R.; Assafin, M.; Colas, F.; Dauvergne, J.-L.; Kervella, P.; Lecacheux, J.; Maquet, L.; Vachier, F.; Renner, S.; Monard, B.; Sickafoose, A. A.; Breytenbach, H.; Genade, A.; Beisker, W.; Bath, K.-L.; Bode, H.-J.; Backes, M.; Ivanov, V. D.; Jehin, E.; Gillon, M.; Manfroid, J.; Pollock, J.; Tancredi, G.; Roland, S.; Salvo, R.; Vanzi, L.; Herald, D.; Gault, D.; Kerr, S.; Pavlov, H.; Hill, K. M.; Bradshaw, J.; Barry, M. A.; Cool, A.; Lade, B.; Cole, A.; Broughton, J.; Newman, J.; Horvat, R.; Maybour, D.; Giles, D.; Davis, L.; Paton, R. A.; Loader, B.; Pennell, A.; Jaquiery, P.-D.; Brillant, S.; Selman, F.; Dumas, C.; Herrera, C.; Carraro, G.; Monaco, L.; Maury, A.; Peyrot, A.; Teng-Chuen-Yu, J.-P.; Richichi, A.; Irawati, P.; De Witt, C.; Schoenau, P.; Prager, R.; Colazo, C.; Melia, R.; Spagnotto, J.; Blain, A.; Alonso, S.; Román, A.; Santos-Sanz, P.; Rizos, J.-L.; Maestre, J.-L.; Dunham, D., AJ 154, 144, 21pp (2017); arXiv; DOI: 10.3847/1538-3881/aa830d

9) 10/2017: **The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation, Ortiz et al. 2017, Nature 550, 219-223**, OpenAccessLink; DOI:10.1038/nature24051
10) 10/2017: A new non-convex model of the binary asteroid (809) Lundia obtained with the SAGE modelling technique, Bartczak, P.; Kryszczyńska, A.; Dudziński, G.; Polińska, M.; Colas, F.; Vachier, F.; Marciniak, A.; Pollock, J.; Apostolovska, G.; Santana-Ros, T.; and 5 coauthors, MNRAS, 471, 941; arXiv; DOI: 10.1093/mnras/stx1603
11) 09/2017: Properties of the irregular satellite system around Uranus inferred from K2, Herschel and Spitzer observations, Farkas-Takács, A.; Kiss, Cs.; Pál, A.; Molnár, L.; Szabó, Gy. M.; Hanyecz, O.; Sárneczky, K.; Szabó, R.; Marton, G.; Mommert, M.; Szakáts, R.; Müller, T.; Kiss, L. L., AJ, 154, 119 (2017); arXiv; DOI:10.3847/1538-3881/aa8365
12) 09/2017: Statistical analysis of the ambiguities in the asteroid period determinations, Butkiewicz-Bąk, M., Kwiatkowski, T.; Bartczak, P.; Dudziński, G.; Marciniak, A., MNRAS, 470, 1314 (2017); arXiv; DOI: 10.1093/mnras/stx1343
13) 08/2017: The EURONEAR Lightcurve Survey of Near Earth Asteroids, Vaduvescu, O.; Macias, A. Aznar; Tudor, V.; Predatu, M.; Galád, A.; Gajdoš, S.; Világi, J.; Stevance, H. F.; Errmann, R.; Unda-Sanzana, E.; Char, F.; Peixinho, N.; Popescu, M.; Sonka, A.; Cornea, R.; Suciu, O.; Toma, R.; Santos-Sanz, P.; Sota, A.; Licandro, J.; Serra-Ricart, M.; Morate, D.; Mocnik, T.; Alfaro, M. Diaz; Lopez-Martinez, F.; McCormac, J.; Humphries, N., EM&P, 120, 41 (2017); pdf; DOI:10.1007/s11038-017-9506-9
14) 08/2017: "TNOs are Cool": A survey of the trans-Neptunian region. XII. Thermal light curves of Haumea, 2003 VS2 and 2003 AZ84 with Herschel/PACS", P. Santos-Sanz, E. Lellouch, O. Groussin, P. Lacerda, T. G. Müller, J. L. Ortiz, C. Kiss, E. Vilenius, J. Stansberry, R. Duffard, S. Fornasier, L. Jorda, A. Thirouin, A&A, 604, A95 (2017); arXiv; DOI: 10.1051/0004-6361/201630354
15) 08/2017: 3-D shape of asteroid (6) Hebe from VLT/SPHERE imaging: Implications for the origin of ordinary H chondrites, Marsset, M.; Carry, B.; Dumas, C.; Hanus, J.; Viikinkoski, M.; Vernazza, P.; Müller, T. G.; Delbo, M.; Jehin, E.; Gillon, M.; Grice, J.; Yang, B.; Fusco, T.; Berthier, J.; Sonnett, S.; Kugel, F.; Caron, J.; Behrend, R., A&A, 604, A64; arXiv; DOI: 10.1051/0004-6361/201731021
16) 07/2017: Study of the Plutino Object (208996) 2003 AZ84 from Stellar Occultations: Size, Shape, and Topographic Features, Dias-Oliveira, A., Sicardy, B., Ortiz, J. L., Braga-Ribas, F., Leiva, R., Vieira-Martins, R., Benedetti-Rossi, G., Camargo, J. I. B., Assafin, M., Gomes-Júnior, A. R., and 53 coauthors, AJ 154, 22D (2017); arXiv; DOI: 10.3847/1538-3881/aa74e9
17) 07/2017: Asteroid shapes and thermal properties from combined optical and mid-infrared photometry inversion, Ďurech, J., Delbo', M., Carry, B.; Hanuš, J.; Alí-Lagoa, V., A&A 604, 27D (2017); arXiv; DOI: 10.1051/0004-6361/201730868
18) 07/2017: Sizes and albedos of Mars-crossing asteroids from WISE/NEOWISE data, Alí-Lagoa, V., Delbo', M., A&A 603, 55A (2017); arXiv; DOI: 10.1051/0004-6361/201629917
19) 07/2017: Thermal Infrared Imaging Experiments of C-Type Asteroid 162173 Ryugu on Hayabusa2, T. Okada, T. Fukuhara, S. Tanaka, M. Taguchi, T. Imamura, T. Arai, H.

Senshu, Y. Ogawa, H. Demura, K. Kitazato, R. Nakamura, T. Kouyama, T. Sekiguchi, S. Hasegawa, T. Matsunaga, T. Wada, J. Takita, N. Sakatani, Y. Horikawa, K. Endo, J. Helbert, T. G. Müller, A. Hagermann, Space Science Reviews 208, 255-286 (2017); Open Acess Article; DOI: 10.1007/s11214-016-0286-8

20) 06/2017: Assessment of different formation scenarios for the ring system of (10199) Chariklo, Melita, M. D., Duffard, R., Ortiz, J. L. and Campo-Bagatin, A. A&A 602, A27 (2017); arXiv; DOI: 10.1051/0004-6361/201629858
21) 05/2017: Shape and spin distributions of asteroid populations from brightness variation estimates and large databases, H. Nortunen, M. Kaasalainen, J. Ďurech, H. Cibulková, V. Alí-Lagoa, J. Hanuš, A&A 601, A139 (2017); arXiv; DOI: 10.1051/0004-6361/201629850
22) 04/2017: Physical properties of centaur (54598) Bienor from photometry, Fernández-Valenzuela, E.; Ortiz, J. L.; Duffard, R.; Morales, N.; Santos-Sanz, P., 2017, MNRAS 466, 4147F; arXiv; DOI: 10.1093/mnras/stw3264

The second-year public deliverables and publications contribute substantially to the expected impacts. In addition, some of the NEA publications will also be relevant for projects like Hayabusa2 and for small-body exploitation and mining projects. The JWST-related work started recently and it will be one of the focus projects for the third year.

New elements in the SBNAF project were (i) the phasing in of Kepler-K2 lightcurve observations of MBAs, Trojans, Centaurs, and TNOs; and (ii) the collaboration with AO imaging experts for the characterization of MBAs. Both aspects will have significant impact in the field of small-body and TNO research.

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

No update of the original plan is needed. The SBNAF team is 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 are presented in many public events, like the "Asteroid Day" (every year on June 30), the Marie Skłodowska-Curie action "European Researchers Night (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 are presented in English and available worldwide from our public web page. The SBNAF public talks and articles are 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 is meanwhile 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 are related to our project.

3. Update of the data management plan (if applicable)

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 1st-year external review

Our 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. The reason for this is that, at the time of submission (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. As of today, all those works have been published, so we have included some relevant details and references to the official publications in Version 2. In addition, in response to the feedback and suggestions from the referee 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 deliverable.

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 naturally continue and will continue to work in this direction until the end of the project.

4.2 Clarification: Lucky Star project collaboration and synergy

The EU H2020 'LuckyStar' project (ERC Programme under Grant Agreement no. 669416) is totally focused on stellar occultations by selected distant Solar System small bodies (i.e. Centaurs and TNOs). On the contrary, the SBNAF project is 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...) are complementary and allow us to physically characterize our selected targets. Stellar occultations are thus one particular technique among the list used within SBNAF. These are fundamental structural differences between the projects.

Regarding the overlap, the team in Granada (IAA-CSIC) produces its own refined stellar occultation predictions and also obtains and processes the very relevant and necessary input (e.g. very precise astrometry of selected targets). We then share these predictions and data 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 do their own refinements with their own techniques using our data, but the workload of refinement is mostly on our shoulders.

Finally, we emphasize that 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, is not only desirable, but also inevitable if we want to maximize the scientific results of these activities. It is in this sense that the SBNAF and Lucky Star collaboration leads to very important scientific synergies. This is visible in the author list of some of the occultation publications where members of both teams are included. There is no budget overlap because none of the SBNAF personnel is paid via the Lucky Star project.

5. Deviations from Annex 1 and Annex 2 (if applicable)

5.1 Tasks

Currently, we do not see any changes for the tasks described in the six different work packages.

5.2 Use of resources

The funding distribution between the four beneficiaries does not require any changes right now. At the end of the second year, all 4 beneficiaries together have spent 64.8% of the total budget according to our financial expert at MPE, perfectly in line with the budget plan. 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) 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							
	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	1.0	2.0	2.0	0.0	10.0	11.0	26.0
	3							
	GA	1.0	3.6	3.6	0.0	25.2	24.2	57.6
MTA CSFK	1	0.3	33.8	0.0	0.6	4.0	4.0	42.7
	2	0.3	19.8	0.0	0.6	4.0	4.0	28.7
	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							
	GA	1.0	0.0	45.5	1.2	40.2	56.1	144.0

5.2.1 Unforeseen subcontracting (if applicable)

Not applicable. No subcontracting was done in the second year.

5.2.2 Unforeseen use of in kind contribution from third party against payment or free of charges (if applicable)

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