Deliverable

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

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WP	**WP4 Asteroid-related calibration**
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Lead Author	T. Müller, MPE, tmueller@mpe.mpg.de

WP4 Asteroid-related calibration
Objectives: To transport 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.

Description of deliverable D4.4
Testing and validation of secondary asteroids completed; model predictions (version 1) for secondary asteroids placed on web.

Description of deliverable

I. Introduction

The context for using asteroids as far-IR/submm/mm calibration purposes was presented and discussed in D4.1. As a first step (in D4.2) we provided preliminary model predictions (model version 0) for 20 asteroids for the time period 2016 to 2020. These predictions are only meant for planning purposes: to find a good-quality calibrator in the required flux regime for specific calibration applications. These predictions are used worldwide by all major far-IR/submm/mm projects (ground-based, airborne, and space observatories). In D4.3 we focused on high-quality model prediction of asteroid fluxes (at far-IR/submm/mm wavelengths) for direct calibration purposes. These flux predictions (called asteroid model version 2) are based on sophisticated models for selected asteroids, and including daily and seasonal variations due to rotation, changing Sun-observer-target distances, phase and aspect angles. Predictions were done for four asteroids (1 Ceres, 2 Pallas, 4 Vesta, and 21 Lutetia), for the time period 2014 to 2020 (also to be used for past ALMA/SOFIA/IRAM/etc. calibration observations). In addition, the deliverable D4.3 included also specific TPM calculations (FITS files with model SEDs) for all Herschel PACS and SPIRE photometric observations of the asteroids 1 Ceres, 2 Pallas, 4 Vesta, and 21 Lutetia (calibration and science observations; one model FITS file for each OBSID) for direct upload to the Herschel Science Archive. These Herschel model requests include the detailed model and observing parameters, as well as the observation-specific parameters (OD, OBSID, instrument and observing mode) as FITS header keywords.

In D4.6 we discussed the selection process for secondary calibrators, trying to fulfil the calibration requirements of different projects. We also tried to establish criteria for the final selection. Here, in D4.4, we apply the selection recipes to more than 10 asteroids, resulting in 7 good-quality secondary calibrators: (3) Juno, (6) Hebe, (7) Iris, (8) Flora, (9) Metis, (24) Themis, (65) Cybele. These objects complement our primary calibrators (1) Ceres, (2) Pallas, (4) Vesta, and (21) Lutetia (see D4.3). Several of our earlier candidates (see D4.6) had to be rejected at this stage due to the lack of high-quality thermal data, poor or ambiguous spin/shape solutions, or problems in finding acceptable and unique model solutions (spin, shape, size, albedo, thermal inertia, surface roughness, emissivity).

Predictions for more asteroids (also model versions 1 and higher) for direct calibration applications are part of deliverable D4.5 (which will complete WP4) and connected to the on-going work (and deliverables) in WP2, WP3, WP4, WP5, and WP6 of the SBNAF project.

II. Good-quality secondary calibrators: requirements & potential problems

The following aspects were considered for selecting asteroids as potential calibrators:

- Intermediate to large main-belt asteroids without satellites (or very small satellites with negligible contributions at thermal IR wavelengths).
- Objects with known shape and spin information, with no signs of albedo variegation, based on rich datasets of dense, high quality lightcurves, avoiding objects with large-amplitude or exotic lightcurves (see "D3.3 Shape & spin solutions for secondary calibrators").
- Availability of high-quality, multi-epoch, multi-wavelength thermal data (see Table 1 in D4.6).
- Availability of high-quality absolute magnitudes and phase slopes (see "D5.4 High-precision photometry measurement table").
- Availability of occultation and/or AO imaging data and/or "ground truth" from interplanetary missions (information on some potentially relevant targets are given in D6.5)

Overall, our 7 new secondary calibrators matched these requirements. However, we also encountered various problems:

- There are often several shape models available: standard convex shapes (typically based on lightcurve inversion only), non-convex shapes (where also occultation or AO information was used in addition).
- Also the spin-axis orientation and rotation periods differ slightly from model to model.
- The decision about potential albedo variations is not easy and often not possible. It would require high-quality AO imaging or multi-colour lightcurves or a good coverage of spectra for different rotational phases.
- Some shape models cover only a very limited range of aspect angles and the shape models have regions with larger uncertainties and other areas which are very well determined (see also the work done in D6.7 on the quality assessment).
- The available thermal data (for testing specific spin-shape solutions and to determine the object's radiometric size, albedo and thermal properties) varies from object to object. Some asteroids have very limited thermal data (limited in wavelengths, phase angle, aspect angle, quality, rotational phases, etc.).
- The test of the object's submm/mm emissivity properties is challenging: there only very few data available (Herschel-SPIRE, ALMA, APEX, CSO, etc.), but these data have large error bars, are calibrated in very different reference systems, or suffer from atmospheric effects which are not included in the error bars.

III. Input parameters and testing procedure

We used spin-shape solutions from the following sources:

- The DAMIT database (Ďurech et al. (2010), *DAMIT: a database of asteroid models*, A&A, 513, A46, ADS: 2010A&A...513A..46D): http://astro.troja.mff.cuni.cz/projects/asteroids3D/web.php
- Convex models from Kaasalainen et al. (2002a), Torppa et al. (2003), Ďurech et al. (2011), Hanuš et al. (2013b), Franco and Pilcher (2015)
- ADAM models from Viikinkoski et al. (2015), Hanuš et al. (2016), Hanuš et al. (2017b)
- KOALA models from Marsset et al. (2017)
- SAGE models from Bartczak & Dudziński (2018)
- In addition, we used spherical shape solutions with exactly the same spin properties as reference test cases.

For consistency, we took H-G values from "Online multi-parameter phase-curve fitting and application to a large corpus of asteroid photometric data", Oszkiewicz et al. 2011, Journal of Quantitative Spectroscopy & Radiative Transfer, 112, p1919-1929; DOI: 10.1016/j.jqsrt.2011.03.003

The thermal data were already described in previous deliverables (D4.1, D4.6).

For each of the spin-shape solutions we applied well-established radiometric techniques to find the object's size (size of an equal-volume sphere), the geometric albedo, thermal inertia, and surface roughness. We tested the stability of these solutions against subsets of thermal data (high/low quality, short/long wavelengths, individual project data, sorting by aspect angle, etc.) to determine the validity of the solution and to estimate error bars.

In the following figures we demonstrate the procedure for the asteroid (65) Cybele and show the comparison between the final TPM predictions and the available mid-IR, far-IR, submm/mm observations. As a first step we test different spin-shape models against the available thermal data: a sphere, a convex solution from the DAMIT database, and the ADAM solution from Viikinkoski et al. (2017), also available in the DAMIT database. The ADAM shape solution fits the data best for a thermal inertia of around 25 SI-units.

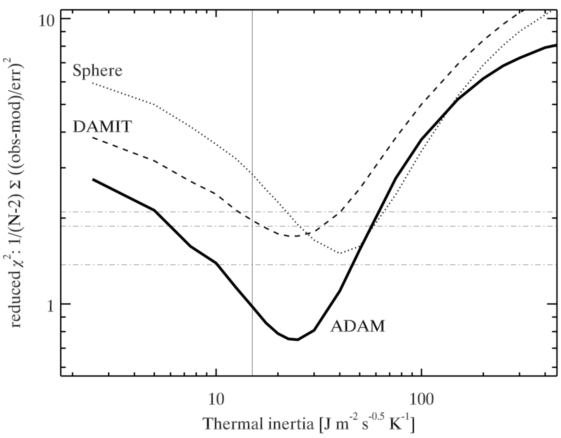
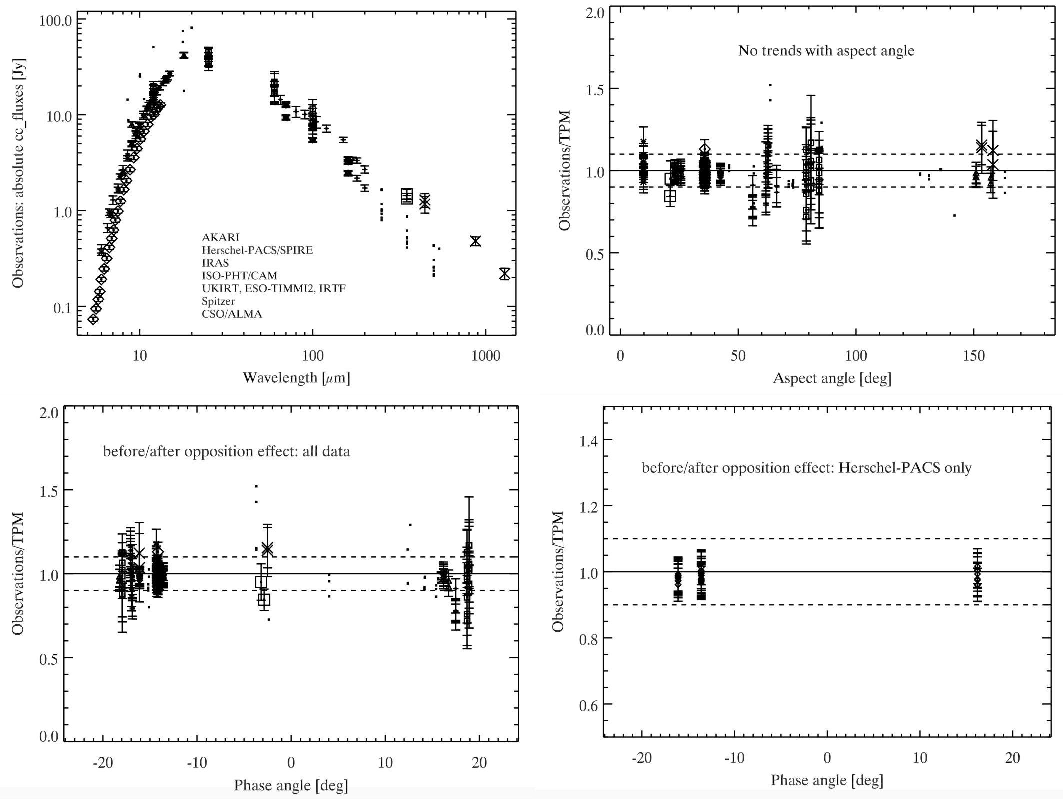


Figure 1: *Reduced χ^2 versus thermal inertia for the sphere (dotted line), convex (dashed line), and ADAM (solid line) models..*

Using the ADAM shape solution, together with the radiometric size, albedo, thermal inertia and surface roughness, we make now flux predictions for the epochs and observing geometries of all observations in our database. The ratios between observations and TPM predictions are shown in the following figures (again for 65 Cybele).



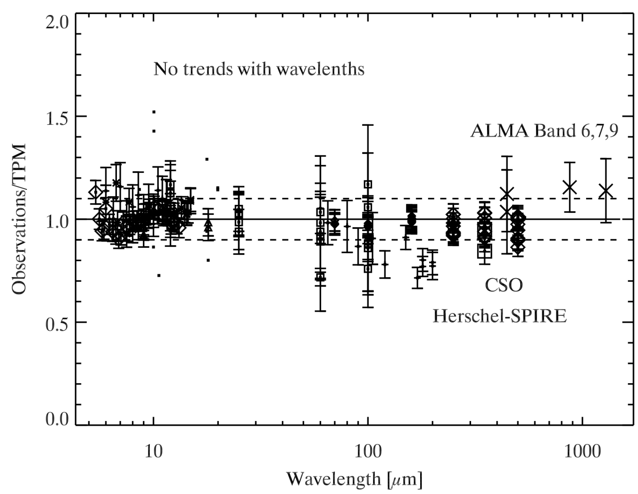


Figure 2: *All available thermal measuements for 65 Cybele. Top left: absolute observed and calibrated fluxes as a function of wavelengths. Top right: observed fluxes divided by the corresponding TPM predictions as a function of aspect angles: showing that the TPM solution works very well for a wide range of aspect angles. Middle: observed fluxes divided by the corresponding TPM predictions as a function of phase angles before and after opposition: all data on the left side, only PACS data on the right side. Bottom left: Test of TPM solution against the submm/mm data. This is critical for the long-term predictions.*

IV. Results

(3) Juno:

a. General info: Newest model from Viikinkoski et al. (2015) is based on 38 lightcurves obtained in the years 1954-1991, and one new lightcurve from 2015. Auxiliary data were VLT/Sphere images, rotationaly resolved ALMA interferometry, and one 16-chord occultation from 1979 (with large errorbars). Shape model is detailed and reliable, with a slight misfit between it and some of AO (Adaptive Optics) images. However, each intermediate model based on subset of available data (eg. lightcurves + ALMA, but without AO and occultation) has notable differences in topography. Northern hemisphere topography is less constrained than southern, and the vertical dimension is stable. The density was determined as: 3.32 ± 0.40 g/cm^3, implying a porosity of 7 ± 1% and a negligible macroporosity of 2 ± 2%, which is consistent with an intact internal structure (based on comparison to L ordinary chondrites).

b. Radiometric analysis: the ADAM shape worked fine, but only for aspect angles > 70°, at smaller aspect angles the shape model has severe problems. The submm/mm range (CSO, SPIRE, ALMA) is explained reasonably well. We estimated absolute accuracy in the submm/mm range of about 5% (for aspect angles > 70°) and 5-10% for the smaller aspect angles.

(6) Hebe:

a. General info: New lightcurves, model and termophysical analysis (TPM) are in the paper by Marsset et al. (2017). There are many high-resolution AO images used for this model, and it fits them well. Last lightcurve data come from 2016, however the fit of this ADAM model to many lightcurves is not good, looking like a phase shift. The shape model and the data are now available in DAMIT. Comparing to the previous model by Hanuš et al. 2013, the pole and size uncertainty is much smaller, while the values for the pole are similar, but the size is 30 km larger.

b. Radiometric analysis: solution (KOALA with radiometrically derived thermophysical properties) was published in Marsset et al. 2017. There is a slight trend of changing thermal inertia with heliocentric distance, but this is of minor importance for the submm/mm predictions. Estimated accuracy at submm/mm: 5%.

(7) Iris:

a. General info: The newest ADAM model available in DAMIT is from Viikinkoski 2017, however DAMIT gives different values for the spin axis than the cited paper: 20 and +9 degrees, while the paper gives 18 and +19, for λ and β respectively. Also, the sizes differ: 223 ± 7 km in DAMIT, and 217 ± 7 in Viikinkoski 2017. The model is made with ADAM algorithm, fits well the lightcurves (with the last one from 2013), and a few high-resolution AO images. This model, unlike all the previous one, gives only one solution for the spin axis. The density is given in V2017: ρ = 2.4 ± 0.5 g/cm^3, consistent with the S type.

b. Radiometric analysis: the analysis suffered from the lack of thermal data (no PACS, no WISE W3/W4, no MSX), but the overall fit to the existing data was perfectly fine. There is a mismatch between radiometric size and AO/occultation-derived size of almost 10% which is unexplained. Our radiometric solution (based on ADAM spin-shape solution) fits the submm/mm data (SPIRE) very well, but there might be an issue at very high aspect angles (seen at 150°-160°). Estimated accuracy at submm/mm: 5-10%.

(8) Flora:

a. General info: ADAM shape model for Flora from H2017 is available in DAMIT. It fits well both the lightcurves, with the last data from 2009, and fuzzy AO images as well. 6 images from adaptive optics and small addition of new lightcurves have been used to improve previous model using ADAM algorithm. Model should be reliable. This is an S-type asteroid with the density $\rho = 4.4 \pm 0.6$ g/cm^3 ("unlikely to be realistic"), the value of which is influenced by discrepant mass estimates from the literature.
b. Radiometric analysis: radiometric and AO-related sizes are almost identical. High-quality solution (based on ADAM spin-shape solution), but the thermal data set is not very large (IRAS, PACS/SPIRE, AKARI). There is a slight trend of changing thermal inertia with heliocentric distance, but this is of minor importance for the submm/mm predictions. Estimated accuracy at submm/mm: 5-10%.

(9) Metis:

a. General info: Strongly nonconvex KOALA model of Metis (the previous model, from Hanuš et al., 2013) is spurious. It gives relatively good lightcurve and occultation fits. However, it does not fit AO images. Last lightcurves come from 1988, but the overall lightcurve quality is very good. The new ADAM model (H2017) is based on the same lightcurve dataset, but with the addition of 8 AO images and 2 occultation data incorporated in the modelling (however, there are also other multi-chord occultations available). The estimated density $\rho = 3.4 \pm 0.7$ g/cm^3 is typical for the S-type composition. The new model is reliable, but with a low pole (see the discussion in the last section). Another reliable nonconvex model was obtained by Bartczak & Dudziński (2018) and is available in the internal version of ISAM service.
b. Radiometric analysis: problematic object due to the lack of thermal data (no IRAS, no Herschel, WISE: saturated, poor-quality ground-based data) and only poor coverage in the submm/mm (CSO). The convex DAMIT solution looks superior to the ADAM spin-shape solution. Overall, the χ^2-fit worked well, and the derived properties are within the expected range, but there might be albedo variations on the surface which make a clean solution problematic. Estimated accuracy at submm/mm: 10%.

(24) Themis:

a. General info: The newest model of Themis was constructed by Viikinkoski et al. (2016) and is available at DAMIT. It's fit to the lightcurves is a large improvement compared to the previous model by Hanuˇs et al. 2016. The body non-typical shape, produces lightcurves of multiple extrema, instead of double-sine wave, diplayed by smooth ellipsoid-like shapes. However, the ADAM model does not fit the AO images well. The density is given in V2017: $\rho = 1.1 \pm 0.4$ g/cm^3 and the spectral type is C or B.

b. Radiometric analysis: there are still two spin solutions compatible with the existing data and a spherical shape solution is explaining the data on a similar level. We use the DAMIT (second convex solution with (l, b)=(137°, +59°)) for the submm/mm predictions and used default emissivity properties. The estimated accuracy at submm/mm: 10%.

(65) Cybele:

a. General info: Cybele is a low-amplitude and also low-pole asteroid which lightcurves get even flatter when it is observed pole-on. However, thanks to rich lightcurve dataset (with the last one from 2014) the shape model is smooth and should be reliable (V2017). It fits the data well, also the fuzzy AO images. We are observing this target in SBNAF project, but the lightcurve we obtained in 2016 had only 0.02 mag amplitude with scatter at the same level. In the next years, apparitions it should display larger amplitudes. We might be able to improve or at least confirm this model. V2017 gives its density: 1.0 ± 0.3 g/cm^3 consistent with it being a C type.

b. Radiometric analysis: rich and high-quality thermal data set. The ADAM spin-shape explains the thermal data well. The test of the solution at submm/mm was done against SPIRE, CSO, ALMA data. Estimated submm/mm absolute accuracy of the model predictions: 5%.

Others:

We have tested several other objects (see also lists in D4.1 and D4.6) but could not find robust solutions at this stage. The target list in D3.3 is still our baseline for this project. We updated this document internally and use it for future tests and applications, with the goal to have acceptable solutions for D4.5 (end of SBANF project).

The model predictions for all the targets for the time period 2018-2020, with a 15-min time resolution, can be found at:
http://www.mpe.mpg.de/~tmueller/sbnaf/results/bProducts.html.
The predictions are done at 10 reference frequencies/wavelengths between 30 and 1000 GHz (10,000 to 300 micron). Figure 3 shows the absolute fluxes of all 7 asteroids over the entire 3-year period. The overall flux change is mainly related to a change in observing geometry (asteroid's helio- and geo-centric distance, and phase angle). Figure 4 shows the same data, but just for the first day (Jan 1, 2018). Here, the variations are related to the object's shape and spin properties.

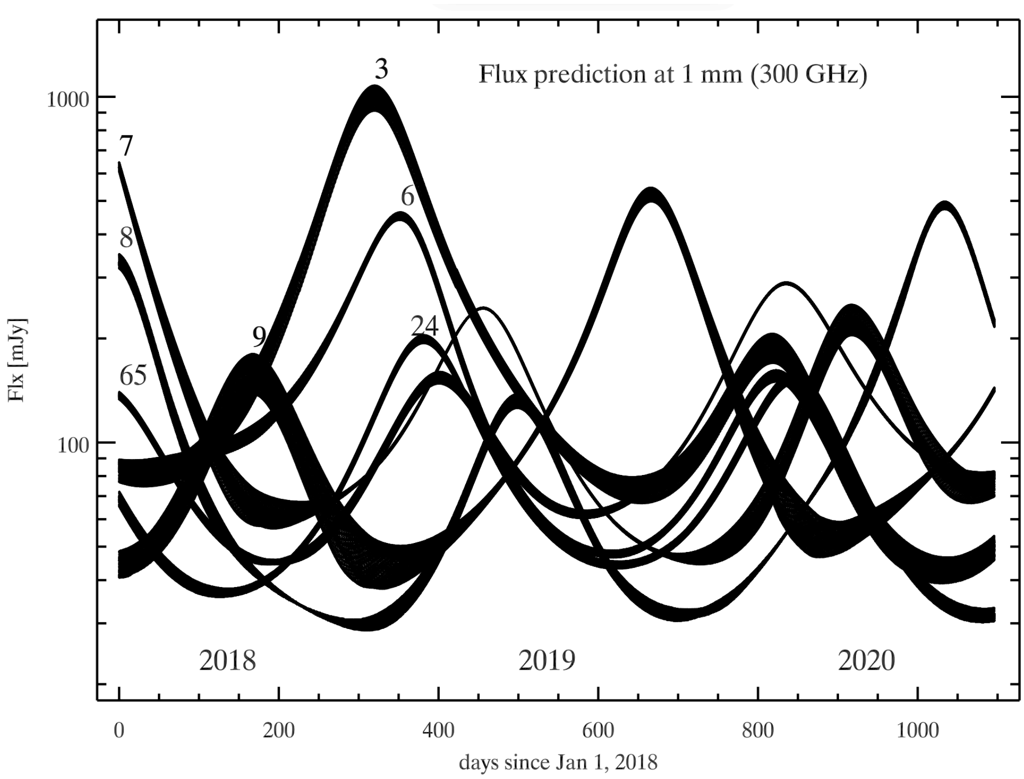


Figure 3: *The 1-mm (300 GHz) flux predictions for our current list of secondary asteroid calibrators. The overall change in flux is related to the changing observing geometry. The line width shows the amplitude of the short-term variations due to the object's shape and rotation.*

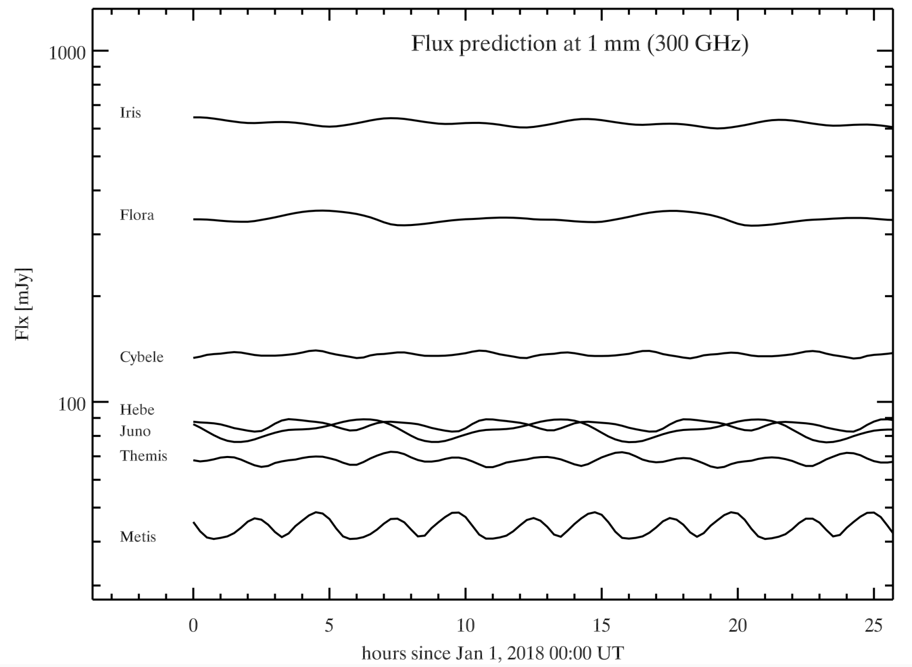


Figure 4: *The 1-mm (300 GHz) flux predictions are shown for Jan 1, 2018. The absolute flux scale is accurate on a 5-10% level. The variations shown for each object are related to the object's shape and spin properties. Calculations are done for the ALMA site (observatory code: -7).*

The current set of secondary asteroids covers (at 1-mm wavelengths) a flux range from a few 10 mJy up to about 1 Jy. At shorter wavelengths (higher frequencies) the objects are brighter, at longer wavelengths (lower frequencies) the objects are fainter, following roughly a Rayleigh-Jeans spectral energy distribution.

V. Outlook

We will continue to produce flux predictions for more candidate large main-belt asteroids covering a similar flux regime until the end of the SBNAF project. Based on the needs and requirements of the users (typically the calibration teams of observatories or instruments), we will make long-term predictions beyond 2020 and include more targets. As a byproduct of the careful testing and verification of the final model solution for each target, different shape models have to be vetted against the thermal data. We would also like to include more APEX/ALMA/IRAM fluxes in our test, but the feedback from the various calibration teams is currently very slow. This accumulated experience is relevant to assessing shape quality and assigning quality codes (MS8) based purely on the thermal infrared data. In some cases, this work also leads to an improved/consolidated knowledge of the thermo-physical properties of the targets relevant to the scientific exploitation in WP6, and the derived radiometric solutions will be published in a dedicated paper in the mid-term future.

VI. Products

The products generated for D4.4 are available on the internal and public SBNAF web pages:

- D4.4 Secondary asteroid models (31 Mar 2018)
  These secondary asteroid model predictions (2018-2020, 15-min time resolution) are based on new spin-shape solutions (derived from combined lightcurve, occultation, AO observations), combined with radiometrically derived size, albedo, and thermal properties. The models have been tested against available and well-calibrated submm/mm data from Herschel-SPIRE, CSO, ALMA, APEX. Estimated absolute model accuracy in the submm/mm range: +/- 5-10%
  - (3) Juno: 2018, 2019, 2020 (txt files)
  - (6) Hebe: 2018, 2019, 2020 (txt files)
  - (7) Iris: 2018, 2019, 2020 (txt files)
  - (8) Flora: 2018, 2019, 2020 (txt files)
  - (9) Metis: 2018, 2019, 2020 (txt files)
  - (24) Themis: 2018, 2019, 2020 (txt files)
  - (65) Cybele: 2018, 2019, 2020 (txt files)

  The detailed model solutions are available on request.