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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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 D4.2
Preliminary model predictions (model version 0) for 10-20 asteroids for planning of submm/mm calibration observations; deliveries to ALMA, SOFIA, IRAM, APEX, etc.

Description of deliverable

I. Introduction

The context for using asteroids as far-IR/submm/mm calibration purposes was presented and discussed in D4.1. Here, we focus on model prediction of asteroid fluxes (at far-IR/submm/mm wavelengths) for **calibration planning purposes**. These flux predictions (called asteroid **model version 0**) are based on simplified models using spherical shapes for the asteroids, and including only seasonal variations due to changing Sun-observer-target distances and phase angles. Changes due to the object's shape and rotation are not considered here. Predictions were done for the time period 2016 to 2020. Predictions of higher quality (model versions 1 and higher) for direct calibration applications are part of upcoming deliverables and connected to the ongoing work (and deliverables) in WP2, WP3, WP4, WP5, and WP6 of the SBNAF project.

II. List of asteroids as potential calibrators

Following up on the successful usage of asteroids as calibrators for Herschel, a list with 20 asteroids was established to support on-going and future ground-based and airborne project. The following list of asteroids – all large main-belt asteroids with well-known object properties - has been established for planning of calibration applications (see also D4.1, section III):
(1) Ceres, (2) Pallas, (3) Juno, (4) Vesta, (6) Hebe, (7) Iris, (8) Flora, (9) Metis, (10) Hygiea, (12) Victoria, (19) Fortuna, (23) Thalia, (29) Amphitrite, (52) Europa, (54) Alexandra, (88) Thisbe, (471) Papagena, (511) Davida, (532) Herculina, (704) Interamnia.

III. Simple model predictions for calibration planning purposes

For planning of far-IR/submm/mm calibration observations it is important to know the sky availability of a given object and its approximate flux density at a given wavelength and time. In addition, it is also useful to have basic information about the expected background level at the position of the asteroid. For specific applications it is also useful to know the object's apparent sky motion. The predictions should also cover several years into the future to facilitate long-term planning activities. The model version 0 predictions here are generic for typical far-IR/submm/mm projects. Model v0 predictions are accurate on a 10-30% level, depending on object, and observing geometry. Higher model versions (1, 2, 3, ... see D4.1) are usually done for specific projects at agreed reference wavelength/frequencies, with much higher time resolution, and much higher flux accuracies.

For the model v0 predictions, we used a simple thermal model to predict asteroid fluxes. The model merges aspects from the Standard Thermal Model (STM, Lebofsky et al. 1986, Icarus 68, 239-251) and the Near-Earth-Asteroid Thermal Model (NEATM, Harris 1998, Icarus 131, 291-301). It assumes a spherical object in instantaneous equilibrium with solar insolation. We applied a NEATM beaming parameter $\eta = 1.25$, a phase angle correction factor of 0.01 mag/° and a submm/mm emissivity of $\varepsilon = 0.8$ (Müller & Lagerros 1998, A&A 338, 340-352). The geometric V-band albedo is calculated by:

$$p_V = 6.259 - 2 \log D_{eff} - 0.4\, H,$$

where D_{eff} is the (effective) diameter, and H the absolute magnitude in V-band. For the calculation of the bolometric Bond albedo we used a phase integral of

$$q_{phase} = 0.29 + 0.684\, G,$$

where G is the slope parameter (Bowell et al. 1989, Asteroids II, pp 524-556).

Solar system targets regularly cross sky regions with high background levels at far-IR/submm/mm wavelengths (like star forming regions or the galactic plane). In these cases, the source-to-background signal level can drop dramatically and sometimes even the brightest asteroids become poor calibrators. We calculated for each epoch the expected background confusion level, including galactic and extra-galactic contributions (Kiss et al. 2005: "Determination of confusion noise for far-infrared measurements", A&A 430, p.343-353), at the specific asteroid position. The calculations are based on COBE-DIRBE and ISO-ISOPHOT data ("skynoise_pacs110_wdirbe_csi.fits", "skynoise_pacs175_wdirbe_vsi.fits"). Band 2 refers to a reference wavelength of 110 µm, band 3 to 175 µm, values are given in mJy per Herschel-PACS beam. These values are useful to judge the background ground level at a given asteroid position. The confusion noise level at 110 µm (band 2) is typically below 1 mJy. A larger value means that the object is located in a region with high (far-IR/submm/mm) background values. The values at 175 µm (band 3) are typically higher (just below 2 mJy). Here, values above approximately 3 mJy indicate more problematic regions in the sky. The calculation of the true observatory-instrument-wavelength specific background is more complex, but the values here allow already to do a useful judgement of the potential background issues.

The model flux predictions are done for all 20 asteroids (all large main-belt asteroids), for the time period January 2016 to January 2020 (time steps of 5 days), at reference wavelengths of 200.0, 350.0, 450.0, 850.0, 1300.0, and 3000.0 µm (or frequencies of 1499.0, 856.5, 666.2, 352.7, 230.6, and 99.9 GHz). The predictions (confusion noise and flux) were added to JPL/Horizons (http://ssd.jpl.nasa.gov/horizons.cgi) output files with astrometric RA & Dec, rates in RA and Dec, heliocentric and observer-centric distances, and the Sun-Target-Observer (phase) angle. The gzipped tar-file with the long-term predictions for all 20 asteroids is available on the password-protected SBNAF web page at: http://www.mpe.mpg.de/~tmueller/SBNAF/DELIVERABLES/-D4_2_20asteroids_model0.tar.gz

These predictions were provided to all interested parties (see next section).

IV. Calibration teams & projects: contact points

The following projects and teams supported the WP4-related work in the SBNAF proposal preparation phase:

- Prof. Dr. Takashi Onaka, P.I. of the Infrared Camera onboard **AKARI**, The University of Tokyo; AKARI is an infrared astronomy satellite developed by JAXA, in cooperation with institutes of Europe and Korea
- Dr. Francisco Montenegro, Head of Sciops Group at **APEX** (ESO), Vitacura, Santiago, Chile; APEX is the Atacama Pathfinder EXperiment, located in Chile
- Drs. J. Boissier, M. Krips, R. Neri (**IRAM-NOEMA**); Drs. C. Kramer, S. Leclerc, H. Ungerechts (**IRAM-30m telescope**), Institut de Radioastronomie Millimétrique, Domaine Universitaire de Grenoble, Saint Martin d'Hères, France
- Dr. Erick Young, Director, **SOFIA** Science Mission Operations, SOFIA Science Center, NASA Ames Research Center, Moffett Field CA, USA: SOFIA is the Stratospheric Observatory For Infrared Astronomy, a joint project of NASA and the German Aerospace Center (DLR)
- Dr. Anthony Marston, **Herschel** Instrument and Calibration Scientist Team Lead and Chair of the Herschel Calibration Steering Group, Herschel Science Centre, ESAC, Villanueva de la CaÒada, Spain; More than 200 h of Herschel observing time was spent on selected asteroids for calibration purposes
- Dr. Pierre Cox, Director **ALMA** observatory, & Dr. Rüdiger Kneissl, Calibration contact point, Atacama Large Millimeter/submillimeter Array, Llano de Chajnantor, Atacama desert, Chile: high-quality asteroid model solutions are very important for ALMA calibration.

In the calibration context the following contact points have been established:

SOFIA:
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V. Model details

Model input values are mainly taken from JPL/Horizons (http://ssd.jpl.nasa.gov/horizons.cgi). The key object properties are summarized in the following table:

Asteroid Number & Name	H_V mag	G_{slope}	D_{eff} [km]	p_V
(1) Ceres	3.34	0.12	952.4	0.09
(2) Pallas	4.13	0.11	532.0	0.16
(3) Juno	5.33	0.32	233.8	0.24
(4) Vesta	3.20	0.32	530.0	0.42
(6) Hebe	5.71	0.24	185.2	0.27
(7) Iris	5.51	0.15	199.8	0.28
(8) Flora	6.49	0.28	135.9	0.24
(9) Metis	6.28	0.17	190.0	0.12
(10) Hygiea	5.43	0.15	407.0	0.07
(12) Victoria	7.24	0.22	112.8	0.18
(19) Fortuna	7.13	0.10	200.0	0.04
(23) Thalia	6.95	0.15	107.5	0.25
(29) Amphitrite	5.85	0.20	212.2	0.18
(52) Europa	6.31	0.18	302.4	0.06
(54) Alexandra	7.66	0.15	165.7	0.06
(88) Thisbe	7.04	0.14	232.0	0.07
(471) Papagena	6.73	0.37	134.2	0.20
(511) Davida	6.22	0.16	326.0	0.05
(532) Herculina	5.81	0.26	222.2	0.17
(704) Interamnia	5.94	-0.02	316.6	0.07

VI. Output statistics

Based on the JPL/Horizons ephemerides we calculated the following minimal and maximal values for the specified time period from Jan 2016 until Jan 2020 (the detailed values for the covered 2016-2020 time period are given in the above mentioned tar-file):
The minimum and maximum values for the object's apparent sky motion in arcsec per hour, the Sun-target-observer phase angles in degrees, the heliocentric and geocentric distances in astronomical units.

		apparent motion ["/h]		phase angle [°]		heliocentric distance [AU]		geocentric distance [AU]	
No	Name	min	max	min	max	min	max	min	max
1	Ceres	3.00	68.25	0.2	23.2	2.56	2.98	1.60	3.95
2	Pallas	4.67	83.37	0.2	27.6	2.13	3.41	1.23	4.28
3	Juno	4.54	87.25	0.3	29.1	1.98	3.35	1.04	4.30
4	Vesta	0.33	80.88	0.4	28.0	2.15	2.57	1.14	3.58
6	Hebe	0.61	89.54	0.7	31.6	1.93	2.92	0.98	3.89
7	Iris	1.42	92.91	0.2	31.4	1.83	2.94	0.85	3.91
8	Flora	1.85	92.26	0.3	32.1	1.86	2.55	0.94	3.53
9	Metis	1.47	81.78	0.3	28.6	2.09	2.68	1.14	3.66
10	Hygiea	0.63	64.45	0.1	21.3	2.77	3.50	1.77	4.50
12	Victoria	0.82	96.77	0.6	33.8	1.82	2.85	0.90	3.85
19	Fortuna	0.52	84.21	0.3	27.8	2.05	2.83	1.25	3.77
23	Thalia	0.87	86.99	0.7	29.1	2.01	3.24	1.05	4.21
29	Amphitrite	1.80	71.25	0.6	24.9	2.37	2.74	1.39	3.72
52	Europa	1.06	62.99	0.4	21.1	2.76	3.43	1.81	4.41
54	Alexandra	2.40	82.17	0.5	27.1	2.17	3.25	1.18	4.25
88	Thisbe	1.74	77.50	0.6	25.3	2.31	3.22	1.32	4.22
471	Papagena	3.60	75.22	0.3	26.3	2.21	3.56	1.29	4.49
511	Davida	1.85	67.39	0.8	22.8	2.57	3.76	1.63	4.74
532	Herculina	0.94	76.90	0.6	26.2	2.28	3.26	1.35	4.23
704	Interamnia	2.65	68.59	0.1	22.9	2.59	3.53	1.66	4.45

In addition, we also calculated the expected background confusion noise level (in milli-Jansky per Herschel-PACS photometer beam) at 110 and 175 µm and the minimal and maximal flux density (in Jansky) of a given object during the entire period 2016 to 2020 (again, details are given in the tar-file):

		Confusion noise at 110 µm [mJy]		Confusion noise at 175 µm [mJy]		Flux prediction at 850 µm [Jy]	
No	Name	min	max	min	max	min	max
1	Ceres	0.535	963.139	1.772	219.048	1.167	7.525
2	Pallas	0.534	162.417	1.767	80.080	0.278	4.111
3	Juno	0.535	261.725	1.772	105.907	0.054	1.144
4	Vesta	0.536	274.301	1.772	107.980	0.450	4.904
6	Hebe	0.535	274.301	1.771	107.980	0.045	0.826
7	Iris	0.537	274.625	1.778	107.531	0.052	1.385
8	Flora	0.536	277.246	1.771	107.531	0.032	0.499
9	Metis	0.536	311.084	1.771	118.545	0.057	0.671
10	Hygiea	0.537	277.246	1.776	104.404	0.153	1.121
12	Victoria	0.535	264.027	1.776	106.272	0.017	0.368
19	Fortuna	0.537	274.625	1.775	107.531	0.059	0.581
23	Thalia	0.535	963.139	1.771	219.048	0.012	0.244
29	Amphitrite	0.536	979.679	1.771	229.457	0.068	0.522
52	Europa	0.536	190.365	1.771	84.813	0.089	0.590
54	Alexandra	0.537	979.679	1.780	229.457	0.029	0.462
88	Thisbe	0.534	267.256	1.770	105.094	0.059	0.717
471	Papagena	0.534	979.679	1.766	229.457	0.016	0.230
511	Davida	0.534	327.058	1.770	120.936	0.085	0.844
532	Herculina	0.534	130.079	1.767	61.299	0.052	0.576
704	Interamnia	0.536	545.113	1.776	157.067	0.093	0.739

These tables help to see if a given object might be useful in a given calibration context. For the detailed planning of a specific observations one should use the more detailed values in the gzipped tar file connected to this deliverable D4.2.

VII. Important reference articles in this context

- Müller & Lagerros (1998), A&A, 338, 340: Asteroids as far-infrared photometric standards for ISOPHOT
- Müller & Lagerros (2002), A&A, 381, 324: Asteroids as calibration standards in the thermal infrared for space observatories
- Müller et al. (2005), ESA SP-577, 471: The Asteroid Preparatory Programme for HERSCHEL, ASTRO-F & ALMA
- Müller et al. (2014), Exp. Astron, 37, 253: Herschel celestial calibration sources. Four large main-belt asteroids as prime flux calibrators for the far-IR/sub-mm range
- Harris (1998), Icarus 131, 291-301: A Thermal Model for Near-Earth Asteroids

- Lebofsky et al. (1986), Icarus 68, 239-251: A refined 'standard' thermal model for asteroids based on observations of 1 Ceres and 2 Pallas
- Bowell et al. (1989 in R.P. Binzel, T. Gehrels and M.S. Matthews (eds.), Asteroids II, pp 524-556, The University of Arizona Press: Application of photometric models to asteroids
- Kiss et al. (2005), A&A 430, 343-353: Determination of confusion noise for far-infrared measurements