Deliverable D2.2

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	**WP2, Infrared observations**
Del.No	**D2.2**
Title	**NEA HSA upload**
Lead Beneficiary	MTA CSFK
Nature	Other
Dissemination Level	Public
Est. Del. Date	31 December 2016
Version	1.0 (as of December 23, 2016)
Date	30 December 2016
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Objectives of the WP: 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. To collect auxiliary infrared data from previous missions (Spitzer, Planck, WISE, Akari, IRAS, ISO, MSX) and published ground-based mid-IR, submm, 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 larger object samples.

The immediate goal of this delivery (D2.2) is to provide the science community with expert reduced data products of Herschel near-Earth asteroid observations. These data products are uploaded to and accessible through the Herschel Science Archive (*http://www.cosmos.esa.int/web/herschel/science-archive*).

Contents

1 Introduction

One of the goals of WP2 Infrared observations is to produce a set of high-quality data products for Herschel observations of Solar System objects for an upload to the Herschel Science Archive (HSA). These new products will then be available for the entire scientific community, in parallel to the standard pipeline-processed Herschel archive data. In the deliverable D2.1 we focused on the general processing tools and scripts for these Herschel Solar System observations and pointed out differences to the standard pipeline processing. Our tools and methods are optimized for moving Solar System targets to account for issues with different apparent motions, issues for faint moving targets on structured background emission, and also for calibration- and photometry-related aspects for faint targets, and also for very bright point-sources.

Here we describe the Herschel measurements of near-Earth asteroids (NEA), the processing and calibration steps, and present the final products which were provided to the Herschel Science Center (HSC) for an upload of these products 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: http://www.cosmos.esa.int/web/herschel/user-provided-data-products These UPDP are publicly available from the HSA for all registered users.

2 Herschel Space Observatory

The Herschel Space Observatory (short: Herschel; Pilbratt et al. 2010) was operational from 2009 until 2013. It had three instruments on board: The Photodetector Array Camera and Spectrometer (PACS) instrument (Poglitsch et al. 2010), the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010), and the Heterodyne Instrument for the Far Infrared (HIFI; de Graauw et al. 2010). All three instruments were used to observe Solar System objects in different photometry and spectroscopy observing modes. The observations cover scientific, as well as calibration measurements. Most of these data are taken in tracking mode, a few also in fixed mode. All Herschel measurements were pipeline processed in a standard way and are available from the HSA. More details about the observations, data reduction, calibration, and HSA data products can be found on the web pages of the Herschel Science Center (HSC) at: *http://sci.esa.int/herschel*

3 Near-Earth asteroid observations

Near-Earth asteroids (NEA) were only observed in very few dedicated small projects, either as part of a Guaranteed Time Programme (GT1_lorourke) or as part of small Director's Discretionary Time projects (DDT_lorourke, DDT_thmuelle). The NEA target list comprises: 433 Eros, 99942 Apophis, 101955 Bennu (1999 RQ36), 162173 Ryugu (1999 JU3), 175706 (1996 FG3), and 308635 (2005 YU55). A summary table of all PACS photometer measurements of NEAs is given below.

All NEA measurements (in total 21 OBSIDs with a combined total observing time of 8.1 hours) were performed with the Herschel-PACS instrument. Neither SPIRE, nor HIFI conducted any dedicated NEA measurements, there are also no calibration measurements on NEAs existing. The PACS Photometer (PacsPhoto observing mode) observations were all taken in "largeScan" mode (with 20″/sec satellite scan speed), in "high gain" detector setting, and in SSO tracking mode. Only the measurements on 308635 (2005 YU55) were taken in “fixed pointing” by simply scanning a pre-calculated field on sky at the time of the NEA crossing: the object simply had a too high apparent motion on the sky for using the nominal SSO tracking option. Typically, a nominal scan (70°scan angle with respect to the instrument reference frame) and a cross-scan (110°) were conducted and all three filters (blue = 70 μm, green = 100 μm, red = 160 μm) were used. In case of Apophis and 175706 (1996 FG3) only one scan direction was performed, Ryugu was only observed in the blue/red filter combination.

4 Data reduction and calibration

The PACS photometer data reduction of moving Solar System objects is described in Kiss, Müller, Vilenius et al. 2013, ExpAstron 37, 161: “ Optimized Herschel/PACS photometer observing and data reduction strategies for moving solar system targets” (https://arxiv.org/abs/1309.4212), with updates documented in SBNAF Deliverable “D2.1 Herschel tools” from September 30, 2016. A specific procedure was applied to the measurements on 308635 (2005 YU55) which were not taken in standard SSO tracking due to its extreme apparent motion at the time of the observations. A detailed description can be found in Müller et al. 2013, A&A 560, 40M: Physical properties of asteroid 308635 (2005 YU55) derived from multi-instrument infrared observations during a very close Earth approach.

For targets whose data can be reduced in a fixed frame and have overlapping backgrounds at different epochs differential and double-differential products can be produced (DIFF and DDIFF, see the D2.1 documentation). For most targets the reduction had to be performed in the co-moving frame using a specific motion correction (dubbed as ’SSO’ in the respective tables). In addition, selection of repetitions and/or scan legs and stacking of multiple images were necessary in most cases as described in the target-specific subsections below, and also in the summary tables in the Appendix.

5 Results

All measurements are from the science program from different projects. Most of the measurements have already been published:

- 101955 Bennu: Müller et al.: Physical properties of OSIRIS-REx target asteroid (101955) 1999 RQ36. Derived from Herschel, VLT/ VISIR, and Spitzer observations, A&A 548, 36M (2012)
- 2005 YU55: Müller et al.: Physical properties of asteroid 308635 (2005 YU55) derived from multi-instrument infrared observations during a very close Earth approach, A&A 560, 40M (2013)
- 162173 Ryugu: Müller et al.: Hayabusa-2 Mission Target Asteroid 162173 Ryugu (1999 JU3): Searching for the Object’s Spin-Axis Orientation, A&A, accepted (2016)
- 99942 Apophis: Müller et al.: Thermal infrared observations of asteroid (99942) Apophis with Herschel, A&A 566, 22M (2014)

OBSID	OD	target	SAA (deg)	Date/time	Band	Prog.	Dur. (sec)	Re.	Map pars.	P.A.
1342228379	849	101955 Bennu	5.3	Sep 09 19:09:01 2011	B	DDT_lorourke_16	1685	5	$3.0'/10/4.0''$	inst 70
1342228380	849	101955 Bennu	5.4	Sep 09 19:40:19 2011	G	DDT_lorourke_16	2012	7	$3.0'/10/4.0''$	inst 70
1342228381	849	101955 Bennu	5.4	Sep 09 20:09:38 2011	B	DDT_lorourke_16	1448	5	$3.0'/10/4.0''$	inst 110
1342228382	849	101955 Bennu	5.4	Sep 09 20:38:57 2011	G	DDT_lorourke_16	2012	7	$3.0'/10/4.0''$	inst 110
1342231945	906	433 Eros	-19.9	Nov 06 03:19:39 2011	B	GT1_lorourke_9	890	1	$3.0'/4/4.0''$	inst 70
1342231946	906	433 Eros	-19.8	Nov 06 03:28:49 2011	B	GT1_lorourke_9	137	1	$3.0'/4/4.0''$	inst 110
1342231947	906	433 Eros	-19.8	Nov 06 03:31:50 2011	G	GT1_lorourke_9	137	1	$3.0'/4/4.0''$	inst 70
1342231948	906	433 Eros	-19.8	Nov 06 03:34:50 2011	G	GT1_lorourke_9	152	1	$3.0'/4/4.0''$	inst 110
1342232729	910	2005YU55	-18.8	Nov 10 14:50:58 2011	B	DDT_thmuelle_5	373	1	$14.0'/4/4.0''$	sky 59.8
1342232730	910	2005YU55	-18.9	Nov 10 14:56:44 2011	G	DDT_thmuelle_5	284	1	$14.0'/4/4.0''$	sky 59.7
1342232383	917	175706 (1996 FG3)	25.1	Nov 16 18:09:10 2011	B	GT1_lorourke_9	1084	2	$2.5'/10/4.0''$	inst 70
1342232384	917	175706 (1996 FG3)	25.0	Nov 16 18:23:32 2011	G	GT1_lorourke_9	583	2	$2.5'/10/4.0''$	inst 70
1342233222	928	175706 (1996 FG3)	-14.1	Nov 27 19:21:36 2011	B	GT1_lorourke_9	998	2	$2.5'/10/4.0''$	inst 70
1342233223	928	175706 (1996 FG3)	-14.2	Nov 27 19:35:15 2011	G	GT1_lorourke_9	583	2	$2.5'/10/4.0''$	inst 70
1342243716	1057	162173 Ryugu	-19.2	Apr 05 01:02:31 2012	B	GT1_lorourke_9	2021	7	$3.0'/10/4.0''$	inst 70
1342243717	1057	162173 Ryugu	-19.2	Apr 05 01:36:37 2012	B	GT1_lorourke_9	2012	7	$3.0'/10/4.0''$	inst 110
1342258557	1333	99942 Apophis	-24.6	Jan 06 00:10:08 2013	B	GT1_lorourke_9	1928	6	$3.0'/10/4.0''$	inst 70
1342258558	1333	99942 Apophis	-24.6	Jan 06 00:43:27 2013	G	GT1_lorourke_9	2012	7	$3.0'/10/4.0''$	inst 70
1342258559	1333	99942 Apophis	-24.6	Jan 06 01:15:07 2013	B	GT1_lorourke_9	1730	6	$3.0'/10/4.0''$	inst 70
1342258560	1333	99942 Apophis	-24.7	Jan 06 01:46:47 2013	G	GT1_lorourke_9	2012	7	$3.0'/10/4.0''$	inst 70
1342267456	1400	99942 Apophis	-16.7	Mar 14 07:08:53 2013	B	DDT_thmuelle_8	4967	18	$3.0'/10/4.0''$	inst 70

Table 1: Summary table of Herschel near-Earth asteroid observations. The columns of the table are: (1) OBSID; (2) operational day; (3) target name or designation; (4) solar aspect angle; (5) date and time of observation; (6) filter combination used (B = 70/160 μm, G = 100/160 μm); (7) program ID; (8) duration; (9) number of repetitions; (10) map parameters (scan leg length [arcmin]/ number of scan legs/ cross-scan steps [arcsec]); (11) map position angle ("inst" and "sky" indicate angles with respect to instrument or sky coordinate system)

- 175706 (1996 FG3): O'Rourke et al.: Herschel observations of the Marco-Polo-R asteroid 175706 (1996 FG3), EPSC 2012, conference poster.

Only 433 Eros and 175706 (1996 FG3) are not yet covered by refereed publications.

Below we give a more detailed description of the observations and derived data products for all near-Earth targets. Due to its high brightness observations of 433 Eros does not require special processing, the "standard product generation (SPG)" products available in the Herschel Science Archive are sufficient for any scientific applications.

5.1 (101955) Bennu

The reduction of Bennu observations were performed following the standard scan-map processing scheme, also considering proper apparent motion correction, but using the the asteroid-optimised data reduction pipeline (see a detailed description in D2.1). These final products are different from the standard SPG products in high-pass filter width parameters (12, 15 and 30 in the 70, 100 and 160 μm bands, respectively) and pixel sizes ($1\overset{''}{.}1$, $1\overset{''}{.}4$ and $2\overset{''}{.}1$) that allows an optimal sampling of the respective point spread functions. In the final step the measurements taken at the two position angles are combined, using stacking at the target's apparent position (combination of two images in the 70 and 100 μm and a combination of four images in the 160 μm band). In the case of the 160 μm band the first observation (OBSID = 1342228379) was excluded due to the presence of a very bright background source along the track of Bennu. The three final products (70, 100 and 160 μm) were used for science purposes (Müller et al., 2012) and are provided through the Herschel Science Archive (files map_101955_Bennu_sso_{70,100,160}).

5.2 175706 (1996 FG 3)

As in the previous case, 1996 FG3 observations were performed following the standard scan-map processing scheme, also considering proper apparent motion correction, but using the the asteroid-optimised data reduction pipeline and applying the same high-pass filter and pixel size options and in the case of Bennu. Due to the fast apparent motion of the target and large time separation of the two epochs combined data products (DIFF or DDIFF) could not be derived. We provide single 70 and 100 μm images for both epochs (map_175706_1996FG3_sso_70_{1/2}) and map_175706_1996FG3_sso_100_{1/2}) and one stacked 160 μm image for both epochs that uses the red channel information of the respective OBSIDs at a specific visit (map_175706_1996FG3_sso_160_{1/2}).

5.3 308635 (2005 YU 55)

The asteroid 2005 YU55 crossed the entire visibility window ($\sim$60° to $\sim$115° solar elongations) from the Herschel Space Observatory during its close Earth-encounter on November 10, 2011, in about 16 h. Its apparent motion was between 2.8°/h and 3.8°/h, far outside the technical tracking limit of the satellite. Therefore two standard scan-map observations were performed with 240 s length each, one in the 70/160 μm (Nov. 10 14:52–14:56, 2011 UT, OBSID 1342232729) and one in the 100/160 μm filter combination (Nov. 10 14:57–15:01, 2011 UT, OBSID 1342232730), at fixed times at pre-calculated positions on the sky. Each scan-map consisted of four scan-legs of 14′ length and separated by 4″ parallel to the apparent motion of the target and with a scan-speed of 20″/s. During both scan-map observations

2005 YU55 crossed the observed field of view and the target was seen in each scan-leg. We re-centred/stacked all frames where the satellite was scanning with constant speed (about 1700 frames in each of the two dualband measurements) on the expected position of 2005 YU55. This technique worked extremely well and the final results agrees well with the image of standard point sources in each Herschel/PACS bands, allowing accurate photometry. For the 70 and 100 μm bands we provide single stacked images (map_308635_2005YU55_sso_70 and map_308635_2005YU55_sso_100). For the 160 μm band two separate images are provided for the two OBSIDs (map_308635_2005YU55_sso_160_1 and map_308635_2005YU55_sso_160_2).

5.4 (162173) Ryugu

PACS observed the asteroid in early April of 2012 for approximately 1.3 h, split into two separate measurements and taken in solar-system-object tracking mode. The target at this time moved at a Herschel-centric apparent speed of 34″/h, corresponding to 19.3″ movement between the mid-times of both observations. The observations were performed in the 70/160 μm filter combination, using seven repetitions in each of the two scan-directions. The PACS measurements were reduced and calibrated with our standard SSO-pipeline, further processing was then performed as follows. We produced single repetition images from both scan direction measurements: scanA1...scanA7, scanB1...scanB7, not correcting for the apparent motion of the target (it is slow enough that the movement is not visible in a single 282s repetition). We then subtracted from each scanAn image the respective, single repetition scanBn image: diff_1 = scanA1-scanB1,...diff_7=scanA7-scanB7, producing differential (DIFF) images. At this point, we co-added the DIFF images in such a way that each DIFF image was shifted by the corresponding apparent motion, relative to the first DIFF image. We produced the double-differential image and then performed the photometry and determined the noise using the implanted source method (Kiss et al. 2014 and references therein, also D2.1) on the final image. We provide the double-differentail 70 and 160 μm images (map_162173_Ryugu_ddiff_{70/160}), as well as the single-repetition differential images (for repetitions from 1 to 7), for both bands (map_162173_Ryugu_diff_{70/160}_1...7).

5.5 (99942) Apophis

Apophis observations with Herschel/PACS took place on January 6, 2013 (four individual observations) and on March 14, 2013 (one individual observation). Each individual observation consisted of several repetitions of a mini scan-map. During the first epoch all three PACS filters at 70, 100, and 160 μm were used, while in the second epoch only the 70/160 combination was observed. Each measurement consisted of a mini scan-map with ten scan-legs of 3′ length and separated by 4″, the scan direction was 70° (along the diagonal of the detector arrays), with a scan-speed of 20″/s. Each scan-leg was centred on the true object position at scan mid-time. The total duration of our Herschel-PACS observations was about 2 h during the first epoch, split into four measurements of about 30 min each: 2x6 map repetitions in the blue, 2x7 map repetitions in the green band, each time with the red channel in parallel. During the second visit only a single, 1.4 h measurement was executed, corresponding to 18 map repetitions in the 70/160 filter setting. In this latter case we split the data into six individual data sets with three repetitions each.

A set of images are produced by stacking all frames of a given band on the source position in the first frame. The background structures in these figures are not real and are related to background-source artefacts caused by the re-centring of images on the rapidly changing Apophis position. During the first visit Apophis was moving in a clean part of the sky without any significant sources along the object path. During the second visit the source moved across faint objects located in a field of diffuse background emission that we were not entirely able to eliminate in the reduction process. We followed the object flux (in the background-subtracted images) and noticed a 1–2 mJy residual background emission in parts of the object trajectory. In addition to the six sub-images, we also combined all background-free and clean images (repetitions 4–9, 16–18) to obtain a final object-centred map for high-quality photometry. We provide this final combined map (map_99942_Apophis_sso_70_2), as well as the images obtained by decomposing the measurements into 3-repetition blocks (map_99942_Apophis_sso_70_2_rep{[1-3,4-6,7-9,10-12,13-15,16-18]}).

References

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– O'Rourke et al., 2012, Herschel observations of the Marco-Polo-R asteroid 175706 (1996 FG 3), EPSC 2012, conference poster

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Appendix

Summary of uploaded data products

Target	Band	Filename	OBSID(s)	Type
(101955) Bennu	70	map_101955_Bennu_sso_70	1342228379/81	SSO /Stacked
(101955) Bennu	100	map_101955_Bennu_sso_100	1342228380/82	SSO /Stacked
(101955) Bennu	160	map_101955_Bennu_sso_160	1342228379/80 /81/82	SSO /Stacked
175706 (1996 FG 3)	70	map_175706_1996FG3_sso_70_1	1342232383	SSO
175706 (1996 FG 3)	70	map_175706_1996FG3_sso_70_2	1342233222	SSO
175706 (1996 FG 3)	100	map_175706_1996FG3_sso_100_1	1342232384	SSO
175706 (1996 FG 3)	100	map_175706_1996FG3_sso_100_2	1342233223	SSO
175706 (1996 FG 3)	160	map_175706_1996FG3_sso_160_1	1342232383/84	SSO /Stacked
175706 (1996 FG 3)	160	map_175706_1996FG3_sso_160_2	1342233222/23	SSO /Stacked
308635 (2005 YU 55)	70	map_308635_2005YU55_sso_70	1342232729	SSO
308635 (2005 YU 55)	100	map_308635_2005YU55_sso_100	1342232730	SSO
308635 (2005 YU 55)	160	map_308635_2005YU55_sso_160_1	1342232729	SSO
308635 (2005 YU 55)	160	map_308635_2005YU55_sso_160_2	1342232730	SSO

Table 2: List of data products uploaded to the Herschel Science Archive for the asteroids (101955) Bennu, 175706 (1996 GF 3) and 308635 (2005 YU 55), related to the deliverable D2.2. The columns of the table are (1) Target; (2) wavelength (μm); (3) file name; (4) OBSID(s) used; (5) product type. See the main text for a detailed description of the data products.

Target	Band	Filename	OBSID(s)	Type
(162173) Ryugu	70	map_162173_Ryugu_ddiff_70	1342243716/17	DDIFF
(162173) Ryugu	160	map_162173_Ryugu_ddiff_160	1342243716/17	DDIFF
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep1	1342243716/17	DIFF /Rep.1-1
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep2	1342243716/17	DIFF /Rep.2-2
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep3	1342243716/17	DIFF /Rep.3-3
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep4	1342243716/17	DIFF /Rep.4-4
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep5	1342243716/17	DIFF /Rep.5-5
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep6	1342243716/17	DIFF /Rep.6-6
(162173) Ryugu	70	map_162173_Ryugu_diff_70_rep7	1342243716/17	DIFF /Rep.7-7
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep1	1342243716/17	DIFF /Rep.1-1
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep2	1342243716/17	DIFF /Rep.2-2
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep3	1342243716/17	DIFF /Rep.3-3
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep4	1342243716/17	DIFF /Rep.4-4
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep5	1342243716/17	DIFF /Rep.5-5
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep6	1342243716/17	DIFF /Rep.6-6
(162173) Ryugu	160	map_162173_Ryugu_diff_160_rep7	1342243716/17	DIFF /Rep.7-7

Table 3: List of data products uploaded to the Herschel Science Archive for (162173) Ryugu (continutation of Table 2)

Target	Band	Filename	OBSID(s)	Type
(99942) Apophis	70	map_99942_Apophis_sso_70_1	1342258557/59	SSO /Stacked
(99942) Apophis	100	map_99942_Apophis_sso_100_1	1342258558/60	SSO /Stacked
(99942) Apophis	160	map_99942_Apophis_sso_160_1	1342258557/58 /59/60	SSO /Stacked
(99942) Apophis	70	map_99942_Apophis_sso_70_2	1342267456	SSO
(99942) Apophis	70	map_99942_Apophis_sso_70_2_rep1_3	1342267456	SSO /Rep.1−3
(99942) Apophis	70	map_99942_Apophis_sso_70_2_rep4_6	1342267456	SSO /Rep.4−6
(99942) Apophis	70	map_99942_Apophis_sso_70_2_rep7_9	1342267456	SSO /Rep.7−9
(99942) Apophis	70	map_99942_Apophis_sso_70_2_rep10_12	1342267456	SSO /Rep.10−12
(99942) Apophis	70	map_99942_Apophis_sso_70_2_rep13_15	1342267456	SSO /Rep.13−15
(99942) Apophis	70	map_99942_Apophis_sso_70_2_rep16_18	1342267456	SSO /Rep.16−18

Table 4: List of data products uploaded to the Herschel Science Archive for (99942) Apophis (continutation of Table 2)

Summary of additional FITS keywords

OBS_ID	Herschel observation identifier number / single observation used for data product
OBSID001, OBSID002, ... OBSIDnnn	Herschel observation identifier number / multiple observations used for data product
OBSDAY	Herschel operational day / single observation used for data product
OBSDAY01, OBSDAY02, ... OBSDAYnn	Herschel operational day / multiple observations used for data product
PROPOSAL	Herschel proposal ID of the observations used
LAYER0, LAYER1	Type of data in a specific data layer of the FITS cube ("image" or "coverage")
EQLEVEL	Equivalent level of SPG processing
TARGET	Name or designation of the target
INSTRUME	Main Herschel instrument
SUBINSTR	Subinstrument
FILTER	Nominal wavelength of the filter used (mircometer)
DATAPRID	Type of data product
PROJECT	Project identifier
LEGS	Legs used for data product generation
REPETIT1, REPETIT2, ..., REPETITn	Repetition(s) used from the respective OBSID(s)

Table 5: List of keywords added to the header of the data product FITS files. Note that not all keywords apply to a specific data product type.