Herschel Science Centre

Herschel Pointing Product Specification

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Document history

Date	Issue	Pages	Reason for Change
01 September 2005	0.1 Draft	All	First version
23 September 2005	0.2 Draft	All	Multiple changes, including: *(a)* rewritten as an URD; *(b)* Identification of the pointing record improved, including features to handle composite modes: *(c)* Comments and suggestions raised in HPDG teleconf #1 included; *(d)* An annexe describing the different pointing modes included
06 June 2006	1.0 Draft	All	Title changed. Modification history (this table) included. Many changes as specified below:
		5	Purpose of the document rephrased, since the format specification is no longer a proposal. List of acronyms included
		7	Definitions of attitude and rate errors included
		8	Sampling rate and TM bandwith issues clarified
		9	Information on the quality index provided within the AHF included
		10	The use of quaternions to represent the attitude within the pointing product motivated
		11	The meaning "filtered" (uncorrected) and "gyro-propagated" (corrected) attitude explained in the framework of AHF ICD v3.0
		12	Product format changed, now containing multiple table datasets (one per pointing full ID). Attitude data changed to quaternions. Data column names modified accordingly
		16	Section removed and replaced by a reference to the applicable AHF ICD
		21	An appendix with (supposed) useful formulae added.
22 September 2006	1.1	12	Reviewed for comments from HPDG.
2 November 2006	1.2	15	Reviewed for comments from C. Porret (HSCDT).
13 December 2006	1.3	15	Reviewed for comments from M.J. Riketts (SPIRE).
07 Februray 2007	1.4	15	Footnote about the format for the on-board time field
11 October 2007	1.5	12	Equinox header parameter changed to DoubleParameter (for compliance with FITS standard).
		15	UTC time field converted to recordTime to reflect the final agreement that all time columns within products represent TAI.
		15	OBT column format changed from Double1d to Long1d.
06 June 2008	1.6	15	recordTime field removed from the definition.
30 July 2008	1.7	12	odNumber added to common metadata section.
05 February 2009	1.8	15	several column names changed according to SPR-4907.
		14	several metadata fields (slewFlag, onTargetFlag, outOfFieldFlag, offPosFlag) converted into columns to avoid a large number of datasets per product (> 1000)
		14	Cross scan number identifier added
		14	Custom map pointing number identifier added
		12	Product split per observation explicitly stated
		12	obsId added to common metadata section.
26 July 2009	1.9	15	Note clarifying the contents of the gyro-propagated columns where no ground improvement is performed.

Date	Issue	Pages	Reason for Change
10 January 2013	1.10	15	A new column, `uncorrFilterQuat`, included to store the original filtered quaternion produced by the ACMS and down-linked in telemetry. The column `filterQuat` now contains the ground-recomputed filtered quaternion when this correction is available, otherwise contains the same value as the former column, the filtered quaternion produced by the ACMS.
10 January 2013	1.10	12	New metadata items, version and versionNumber, added.
09 April 2013	1.11	15	A new column, `solarAspectAngle`, included to store the Solar Aspect Angle (SAA) from the AHF.
		25	AHF ICD version updated.
13 November 2013	1.12	12	FITS keyword `VERNOTES` changed to `VER_NOTE` to comply with the products' metadata convention.
		14	Metadatum `bbId` changed to `bbid`
		14	FITS keyword `ACMS_MOD` changed to `AMCSMODE` to comply with the products' metadata convention.
20 October 2014	1.13	15	The "filtered attitude" contains the most accurate ground-processed estimate, namely the gyro-reconstructed attitude. Hence, a new column holding the simple-corrected attitude quaternion has been added. Quality estimation fields for the gyro-reconstructed attitude added.
		11	Further explanation of the meaning of the different attitude fields provided.
19 November 2014	1.14	15	Explanation of the contents of the `gyroPropQuat` and `gyroQuality` fields corrected. A new column, `filterQuatFlag` containing a flag related to the origin of the contents of the filtered quaternion field, added.
		11	Definition of "uncorrected filtered" quaternion improved and updated.
16 December 2014	1.15	14	A new meta-datum added to indicate the STR in use.
05 March 2015	1.16	12	Several meta-data keywords related to gyro-reconstructed attitude added.

Contents

1 Introduction

The purpose of this document is to specify the contents and format of the Herschel pointing product . The document is structured as follows: first, some basic background information on ACMS TM is provided. Second, a review of those requirements set by the instruments' teams that can impact in the contents of the pointing products is performed[1]. These requirements have been collected from e-mails and technical notes[2]. Third, the specification of the contents and format of the pointing product is presented. A full listing of the collected requirements related to pointing is presented in Appendix A. The definition of Herschel pointing modes is summarised in Appendix B.

1.1 Acronyms

The following acronyms are used throughout the document:

Acronym	Meaning
ACA	Attitude Control Axes
ACMS	Atttitude Control & Measurement System
AHF	Attitude History File
API	Application Programming Interface
CUS	Common Uplink System
DCM	Direction Cosine Matrix
DEC	Declination
DTM	Diagnostic Telemetry
ETM	Essential Telemetry
FDS	Flight Dynamics System
ICD	Interface Control Document
MTM	Mode Telemetry
OBT	On-Board Time
PA	Position angle
PCF	Parameter Characteristics File (SCOS-2000)
POS	Planned Observation Sequence
RA	Right Ascension
SAM	Sun Acquisition Mode
SBM	Stand-By Mode
SCM	Science Mode
SCOS-2000	Spacecraft Control Operating System
SIAM	Spacecraft-Instrument Alignment Matrix
STR	Star Tracker (also referred as ASTR, Autonomous Star Tracker)
TAI	International Atomic Time scale
TC	Telecommand
TM	Telemetry
UTC	Universal Time Coordinated

[1]Therefore those related to the precision of measurements are not included.

[2]It should be taken into account that this note has been based on requirements written in 2002. A carefully review to check that these requirements are still valid is strongly recommended.

2 ACMS Telemetry

All the information presented here has been collected from [RD.1]. Parameter names and descriptions come from the corresponding fields in the PCF table in the H/P SCOS-2000 database.

2.1 ACMS Modes

The following H/P ACMS modes have been identified:

1. Nominal Modes (NOM):
   (a) Science Mode (SCM)
   (b) Angular Momentum Control Mode (HCM). This mode is not present in the Herschel S/C.
   (c) Orbit Control Mode (OCM, for delta-V maneuvers).
2. Standby Mode (SBM, launch)
3. Sun Acquisition Mode (SAM)
4. Survival Mode (SM)

2.2 ACMS TM categories

ACMS TM falls in four categories, namely:

1. Essential TM (ETM):
   - Mode-independent
   - Single packet
   - Geared towards acquisition modes
   - Compatible with low TM rate downlink
   - Periodic TM (period 16 sec).
2. Mode TM (MTM, includes ARD TM)
   - Mode-dependent
   - No essential data for acquisition modes
   - Periodic TM (period 2 sec).
3. Diagnostic TM (DTM)
   - Not required for nominal operations
   - Periodic TM (any period).
4. Asynchronous TM (ATM): all non-periodic TM (e.g. Service 1 -TC verification reports).

ETM & MTM will be down-linked as TM(3,25). DTM as TM(3,26).

2.2.1 ACMS Essential TM (ETM)

S/C attitude quaternion is downloaded as part of ETM data. So far, it has been identified the AEXA0001 parameter (Main STR Attitude Quaternion) as part of STR Essential TM. This parameter is sampled once in a source packet (i.e. parameter sample frequency is 1/16 Hz). Attitude errors[3] are provided within TM parameter AESB0001 (Attitude errors). Angular velocity (AESV0001) and velocity error[4] (AESW0001) are also downloaded in ETM. All these parameters are sampled at 1/16 Hz.

2.2.2 ACMS Mode TM (MTM)

Mode TM (MTM) is sampled every two seconds. The following attitude information has been identified so far:

- Estimated S/C Attitude is provided in parameter AESA5002. This parameter is present in Science Mode (SCM) and Orbit Control Mode (OCM). In both modes, the parameter is sampled eight times per source packet (i.e. sample frequency is 4 Hz)
- Main STR Attitude is provided in parameter AEXA0001 (Main STR Attitude Quaternion). This parameter is also super-commutated, sampled eight times per packet (4 Hz) in SCM and OCM. This parameter is also downloaded in diagnostic TM.
- Attitude errors are provided within TM parameter AESB0001. This parameter is sampled at 4 Hz in SCM and OCM and at 1 Hz in SASM.
- S/C angular velocity and velocity error are downloaded in parameters AESV0001 and AESW0001, respectively. These parameters are sampled at 4 Hz in SCM and OCM.

2.2.3 ACMS Diagnostic TM (DTM)

STR stars' information is downloaded as diagnostic TM (common to Herschel and Planck). Diagnostic TM will be used whenever additional data is required, e.g. in calibrations or non-nominal situations. So far, the following relevant parameters have been identified in DTM (all of them supercommutated, sampled eight times per diagnostic packet): AEXA0001 (main STR attitude quaternion), AEXN0001 (STR output catalogue identification of stars 01-09), AEXE0001 (STR output coordinates of stars 01-09), AEXM0001 (STR raw output magnitude of stars 01-09).
Note: Diagnostic information is not considered when computing the required ACMS TM budget.

3 Requirements on the Pointing Products

A number of pointing requirements affecting products have been gathered from the different instruments' teams and summarised below. Most requirements have been gathered from e-mails sent to PST. Those from PACS have been collected from [AD.1]. The full listing of pointing requirements (i.e. including those not affecting products) is presented in Appendix A.

[3] The attitude error is computed following algorithm 8.05 in [RD.11] as per requirement SWR-118, as $q_{err} = q_T^* \otimes q_A$, where q_T is the target (demanded) attitude quaternion and q_A is the attitude quaternion; the resulting error quaternion is further multiplied by -1 if the sign of its scalar part is negative; this 4-component magnitude is not representative of the pointing uncertainty but just of the pointing stability. Therefore a different figure should be used to assess the accuracy of provided attitude measurement. This is provided by the STR quality index provided by the STR in SCM mode TM (see page 12).

[4] Computed as prescribed in algorithm 8.05 in [RD.11] as $e_n = \omega_n^{demanded} - \omega_n^{estimated}$, where $n = x, y, z$.

PT-REQ-001
The pointing product shall provide the information needed to identify each attitude record, including:

1. Observation ID
2. Building Block ID
3. Current raster line number (from PACS-PTREQ-R01; = 0 if N/A)
4. Current raster column number (from PACS-PTREQ-R01; = 0 if N/A)
5. Current scan line number (from SPIRE-PTREQ-L01 and PACS-PTREQ-L01; = 0 if N/A)
6. Slew flag (from SPIRE-PTREQ-G07 and PACS-PTREQ-G09; = 0 if in stare pointing or scanning, = 1 if slewing or accelerating/deccelerating for scanning, = 2 if tracking a Solar System Object)
7. On-target flag (collected from SPIRE-PTREQ-001 and PACS-PTREQ-G08)
8. Off-position flag (from PACS-PTREQ-R03, PACS-PTREQ-L03; = 1 if pointing to OFF position, = 0 otherwise or N/A)
9. Switching/nodding cycle number (= 0 if N/A) plus A_{pos} or B_{pos} identifier
10. Pointing mode identifier: a numerical identifier associated with the basic or composite mode in use, as given in Appendix B.

PT-REQ-002
UT time, RA, DEC, commanded RA & DEC, Roll Angle and on-target flag shall be available in the pointing product (from SPIRE-PTREQ-G01, PACS-PTREQ-G06, PACS-PTREQ-G07, HIFI-PTREQ-G05).

PT-REQ-003
The parameters referred in the requirement above shall be sampled at a frequency of 16 Hz (from SPIRE-PTREQ-G01).

Comment: ACMS working frequency is 4 Hz. Attitude data is downloaded at the same rate: mode TM packets are downloaded at a rate of 1 packet every two seconds. Attitude information is sampled eight times per packet; therefore on-ground attitude sampling frequency is 4 Hz (this figure partially drives the ACMS TM budget limit of 4500 bps).In order to sample TM at higher frequency, the appropriate propagation method must be applied, based on the attitude data and the angular rate information provided by the gyroscopes (see appendix C).

PT-REQ-004
The attitude measurements shall be provided at a rate that fully samples the temporal behaviour of the S/C. An upper limit of 10 Hz is set, but it must be faster than 1 Hz in any case. (from PACS-PTREQ-G06, HIFI-PTREQ-G01).
Moreover, the attitude information shall be delivered at a frequency at least doubling the bandwidth of the ACMS (HIFI-PTREQ-G04).

Comment: See previous comment.

PT-REQ-005
The pointing product shall include a "quality flag" in addition to the on-target flag already downloaded in ACMS telemetry (from SPIRE-PTREQ-G06).

Comment: As referred in 12, within the STR software, a weighted sum of the error state covariance matrix is computed, which in turn is used to compute a quality index. This number will be provided within the AHF to assess the quality of any attitude data derived on-board via measurements from the ASTR. In addition to this quality index is an entry for the number of stars used in the on-board attitude determination.

PT-REQ-006
The pointing product shall include, in the line scan mode, the associated S/C scan velocity (from SPIRE-PTREQ-L02)

Comment: This information (angular velocity and velocity error) is included in the ACMS TM data (regardless of the mode) and provided within the AHF.

PT-REQ-007
The Herschel orbit data (in the phase space) shall be available available at the same time resolution as the pointing history data (from SPIRE-PTREQ-G08).

Comment: Orbit data are provided in a separate product, described in [RD.12].

PT-REQ-008
The ACMS mode in which the pointing data were obtained shall be flagged in the pointing product (from PACS-PTREQ-G13).

It will be possible to unambiguously associate a TM packet ID with the ACMS mode in which it was generated. A field containing a string or numeric identifier of the mode (i.e. "SCM", "OCM", "SBM", "SAM", "SM") can be added to the product definition.

PT-REQ-009
The STR information (guide stars, positions etc.) shall be provided (from PACS-PTREQ-G13).

Comment: STR information is part of the diagnostic TM and not included in the available TM budget. If required, the needed TM budget should be deducted elsewhere.

PT-REQ-010
The pointing product shall include a flag indicating the moment when the S/C reaches or leaves constant velocity during line scanning (from PACS-PTREQ-L04).

Comment: The on-target flag provided within the AHF indicates when the scan rate has settled, as indicated in paragraph 4.8.7.4, item B31 ASWTC-H-4.8.7-130 of [RD.1].

PT-REQ-011
The ephemerides used by the spacecraft for tracking a given SSO shall be available (from PACS-PTREQ-T01).

Comment: This can be packed in a separate product. ToDo: Find out where this information is stored.

PT-REQ-012
The pointing product shall include a flag for out-of-field reference attitude measurements (from HIFI-PTREQ-G05).
scanning.

Comment: Does it refer to position references (peak-up mode) or flux references? In any way, this information should be gathered in a similar way as a raster point or an off-position.
ToDo: Investigate how this information can be gathered from TM

4 The Contents and Format of the Pointing Product

The use of quaternions (see Appendix C) to represent the S/C attitude has been adopted, implying a fundamental change with respect to earlier versions of this document. While formerly it was intended to include the attitude as a set of two equatorial coordinates, RA, DEC plus the Position angle (PA)[5], soon became clear that the requirement of having a high attitude sampling rate implies an efficient way to propagate the S/C attitude. The recommended propagation method, using a kinematical equation (see C) implies the use of quaternions. Therefore, rather than storing the attitude data in (RA, DEC, PA) format and converting them to quaternions upon propagating the attitude, it has been envisaged as more appropriate to store the attitude directly in quaternion format and provide with methods to pass the quaternion to (RA, DEC, PA) in the pointing product API.

Note: All attitude data contained within the pointing product are referred to the ACA frame. To convert attitude data to a given instrument's boresight the appropriate SIAM matrix must be applied.

4.1 Contents of the Pointing Product

The pointing product will be built using information provided in the AHF ([AD.2]). The data contained therein includes information gathered from TM plus the HSCCOM keyword copied from the POS. The purpose of this keyword is to help interpretation of the data by the Herschel DP system, indicating the position within an observation that constructs a composite pointing pattern from a sequence of primitive pointing request, raster request or line scan request commands. For instance, it will serve to determine the raster point plus nodding cycle within a "nodding-in-raster" composite command (see Appendix B).

Here follows a list of the minimum contents of the pointing product (all attitude information is expected to be provided in the J2000.0 reference):

1. On-board time (OBT)
2. Full pointing ID:
   - observation ID
   - Building Block ID
   - Raster line number
   - Raster point number
   - Scan line number
   - Slew flag
   - On-target flag
   - OFF-position flag

[5] The Roll Angle.is defined as the angle between two planes: the first defined by the Sun vector and the S/C **X** axes and the second, defined by the S/C **Z** and **X** axes. Therefore, the roll angle has operational signficance since the S/C **Z** axis must be maintained pointing towards the Sun, within certain limits. Nevertheless, it is defined with respect to a non-inertial coordinate system. The position angle (PA) is the inertial equivalent to the roll angle, defining the position of the S/C **Z** axis with respect to the celestial coordinate system. Therefore, is a better choice when representing the S/C attitude

- Switching/nodding cycle number
- A/B position identifier (only applicable to switching/nodding modes)
- Out-of-field flag
- Pointing mode identifier
- Instrument's aperture in use (prime instrument in parallel modes, if any)
- SPIRE serendipity mode
- ACMS mode

3. Expected (commanded) pointing quaternion ($q_1, ..., q_4$)
4. Uncorrected filtered pointing quaternion
5. Filtered pointing quaternion
6. STR quality index
7. Gyro-propagated pointing quaternion
8. Gyro-propagated attitude quality index
9. S/C angular velocity
10. S/C angular velocity error
11. Constant velocity flag
12. STR interlacing status
13. Gyro propagation flag

The definitions of "uncorrected filtered", "filtered" and "gyro-propagated" attitude are described below following [AD.2]:

- The "filtered" attitude refers to the attitude recomputed on-ground based on the most accurate improvement algorithms. As of end of 2014, the most evolved algorithm is that known as "gyro-reconstruction" method, based on an improved STR attitude estimation plus propagation using gyroscopes. Otherwise the column contains the same values as those stored in the "simple-corrected" attitude.

- The "simple-corrected" attitude refers to the attitude recomputed on-ground based on the naïve improvement algorithm, i.e. that correcting the filtered attitude information computed on-board for the systematic, though position-dependent, STR offets. If this information is not available, the column contains the same values as those stored in the "uncorrected filtered" attitude.

- The "uncorrected filtered" attitude refers to the attitude derived by the on-board filter from the STR quaternion provided either by the prime STR or prime+redundant STR together with the gyro outputs in telemetry at a rate of 4 Hz.

- The "gyro propagated" attitude (formerly referred as "corrected" attitude) refers to the attitude derived by FDS using the gyro outputs in telemetry to propagate an attitude quaternion derived from the on-board filtered attitude quaternion at an OFF-position prior to the execution of a raster or line scan. This was only done for those observations flagged in the POS file with the `HSCOMM` record `ATT_PROP`. Otherwise, the "gyro propagated" attitude field contained the attitude quaternion computed by FDS using the nominal estimator (hence, equivalent to the "uncorrected filtered" attitude described above).

The attitude errors are described by means of numeric quality indexes; the STR quality index is related to the attitude solution provided by the STR. It is downloaded in SCM Mode TM. This quality index is a function of the covariance of the errors for the raw quaternion provided by the STR[6]. This quality index can be used as an error measurement for the filtered attitude. A quality index based on gyro propagation ([RD.14]) will be derived based on the standard deviation of the various gyro noise processes and a derived standard deviation for the error in the calibrated gyro biases. These deviations, together with the time elasped when propagating the attitude using gyro outputs will be used to provide some form of quality index here. The details of the calculations are given in [AD.2].

It represents a weighted sum of the diagonal elements of the covariance matrix computed with the STR software. The gyro-propagated quality index is TBD.
In addition, a number of STR information items could be included in a separated product. Those items would include:

1. STR output catalogue identification of stars 01-09
2. STR output coordinates of stars 01-09
3. STR output raw magnitude of stars 01-09

It has been pointed out that there should be a continuous data stream showing the spacecraft pointing, and per active instrument a dedicated pointing file. This is not actually needed since the pointing for a given instrument boresight can obtained by applying the corresponding SIAM. A reference to the applicable SIAM shall be included as product meta-data.

4.2 Format of the Pointing Product

The proposed product will be **split per observation** and shall consist of a sequence of TableDataset items. There will be one TableDataset per block of attitude records with the same "full pointing ID", defined by a series of items in Section 4.1 above. Attitude data records will be ordered by UTC time key within each TableDataset. The proposed keywords follow guidelines for standard metadata names within Herschel DP (see for instance [RD.9]). The FITS equivalents are shown in parentheses.

4.2.1 Pointing info - Common Metadata

These are the common product metadata items (equivalent to the keywords in the primary HDU in a FITS file):

1. version (VERSION): StringParameter. Version of the product[7].
2. versionNotes (VER_NOTE): StringParameter Notes specific to this version. A comment explaining the reason of the new version, e.g. changes in the format of the product or in the computation algorithms.
3. author (AUTHOR): StringParameter. Author of data (site)
4. creator (CREATOR): StringParameter. Name of the software creating the data
5. creationDate (DATE): LongParameter [8].Product creation date
6. startDate (DATE-OBS): LongParameter. First product time key

[6]Notice that it is not computed from the filtered quaternion coming out of the on-board estimator that combines STR and gyro measurements
[7]Start with v2.0 for products compliant with version 1.10 of this document
[8]All dates are HCSS FineTime values (microseconds since TAI epoch 1958). However, upon exporting these fields to FITS, the corresponding header keywords will be ASCII-format UTC dates.

7. endDate (DATE-END): LongParameter. Last product time key

8. raDecSys (RADESYS): StringParameter. Coordinate reference frame for the RA and DEC axis columns (e.g. 'FK5')

9. equinox (EQUINOX): DoubleParameter. Equinox of reference system (set to 2000.0)

10. telescope (TELESCOP): StringParameter. Set to 'Herschel'

11. instrument (INSTRUME): StringParameter. Set to 'ACMS'

12. siamId (SIAM_ID): StringParameter. Reference to the applicable SIAM. Suggested format as in [RD.4] (*ddddvvvvSIAM*, where *dddd* represents the operational day-count and *vvvv* is the version of the file).

13. odNumber (ODNUMBER). longParameter. Operational day (OD) number count.

14. Observation ID: obsId (OBSID). LongParameter. As specified in [RD.10].

The following metadata keywords are included to ease the evaluation of the quality of the gyro-reconstructed attitude (provided in the `filterQuat` column). These keywords are intended for observation-based pointing products. For OD-based pointing products, default fixed values are to be used (as specified below):

15. gyroAttQuality (GYR-QUAL): DoubleParameter. It is computed as $1 - N_{bad}/N_{gyr}$, where $N_{bad}$is the number of "bad samples" (such as the value in the column `gyroAttProb` is less than than certain threshold value `probThreshold` recorded in the meta-datum below) and N_{gyr} is the total number of samples used for the computation. Default value for OD-based pointing products is 1.0.

16. probThreshold (PROBTHRE): DoubleParameter. Probability threshold used for computing N_{bad} (see the `gyroAttQuality` parameter above). Default value for OD-based pointing products is 1.0.

17. gyroAttCoverage (GYR-COV): DoubleParameter. Gyro-reconstructed attitude coverage as given by the fraction N_{gyr}/N_{tot}, where N_{gyr} is the number of samples with gyro attitude (fulfilling certain conditions, generally that the on-target flag is "True" and/or slew-flag is "False") and N_{tot} is the total number of samples (fulfilling the same conditions). Default value for OD-based pointing products is 1.0.

18. probBad (PROB-BAD): DoubleParameter. Recommended threshold value for `gyroAttQuality`. Default value for OD-based pointing products is 0.0.

19. coverageThresh (COVTHRE): DoubleParameter. Recommended threshold for `gyroAttCoverage`. Default value for OD-based pointing products is 0.0.

The following metadata keywords record the parameters used in the gyro-reconstruction process (i.e. input parameters to `calcAttitude`:

20. calcAttProbThres (CA-PRTHR): DoubleParameter. Probability threshold used for `calcStrAttitude`.

21. calcAttRefThres (CA-REFTRH): DoubleParameter. Threshold for updating the reference attitude. Unit: arcsec.

22. calcAttWindLen (CA-WINLEN). DoubleParameter. Time window within which the gyro drift rates are assumed as constant. Unit: sec.

23. calcAttRotLimit (CA-ROTLIM): DoubleParameter. Allowed limit on rotations from reference attitude. Unit: deg.

24. calcAttTOffStar (CA-TOFFST): DoubleParameter. Time offset to be added to the on-board time of the STR attitude measurements. Unit: sec.
25. calcAttExclGyro (CA-EXCGYR): ShortParameter. GYR number from which measurements are to be excluded in the computations.

4.2.2 Pointing info - TableDataset

There will be a TableDataset per block of attitude records sharing a common set of values defining the "full pointing ID" as described in Section 4.1 above. These values shall be written as MetaData of the TableDataset, as described below.

1. **MetaData:**

   i Observation ID: obsId (OBSID). LongParameter. As specified in [RD.10].[9]

   ii Building block ID: bbid (BB_ID). LongParameter. As specified in [RD.10].

   iii Raster line number: rasterLineNum (RSLINNUM). LongParameter. As given in the (composite) mode command.

   iv Raster column number: rasterColumnNum (RSCOLNUM). LongParameter. As given in the (composite) mode command.

   v Scan line number: scanLineNum (SCLINNUM). LongParameter. As given in the (composite) mode command.

   vi Cross scan number count: crossScanNum (XSCANNUM). Long parameter. Number count of the cross scan. Allowed values are 0 (nominal direction or normal scan mode), 1 & 2 (cross repetition 1, 2).

   vii Custom map pointing number: customMapPointNum (CUSPTNUM). Long parameter. Custom map number count as given by the POS HSCCOM keyword "PMODE POINT n".

   viii Switching/nodding cycle number: nodCycleNum (NOD_NUM). LongParameter. As given in the (composite) mode command.

   ix A/B position identifier: abPosId (ABPOSID): BooleanParameter (e.g. 0 if "A" position, 1 otherwise).

   x Pointing mode identifier pointModeId (POINTID): StringParameter. Enumerated type for each of the following:
   fine_pointing, raster, raster_with_off, line_scan, line_scan_with_off, position_switching, nodding, composite_position_switching, composite_nodding, repeated_line_scan_with_off, nodding_of_raster, nodding_in_raster, repeated_raster_with_hold, nodding_in_raster_with_off, line_scan_with_hold.

   xi Instrument aperture in use: apertureId (APER_ID). StringParameter. Suggest to use the same format as for SIAM matrix [RD.4], i.e.

   Hnn_s for HIFI, $01 \leq nn \leq 10$
   Pnn_s for PACS, $01 \leq nn \leq 12$
   Snn_s for SPIRE, $01 \leq nn \leq 75$

   And $0 \leq s \leq 7$, indicating the possible SAA corrections applied (zero = none).

   xii SPIRE serendipity mode flag: serendipityFlag (SEREN_FL). BooleanParameter. 1 if SPIRE serendipity mode active, 0 otherwise.

[9]From v1.8, the pointing product is split by observation rather than per OD. nevertheless, the obsId is kept in both the common metadata header and in each TableDataset metadata section for backwards compatibility

xiii ACMS mode: acmsMode (ACMSMODE) StringParameter. Possible values: SCM, OCM, SBM, SAM, SM.

xiv startDate (DATE-OBS): LongParameter. First product time key

xv endDate (DATE-END): LongParameter. Last product time key

xvi strInUse (STR-USE): ShortParameter. Either 1 or 2 (for STR-1 or STR-2).

2. **Columns:**

(a) On-board time obt (OBT). Double1d. Unit: microseconds[10]

(b) Commanded pointing quaternion: commandQuat (COMM_Q). Double2d. Contains the four double-precission components of the commanded attitude quaternion[11] in the ACA frame.

(c) Filtered attitude quaternion: filterQuat (FILT_Q). Double2d. Contains the four double-precission components of the filtered attitude quaternion in the ACA frame (see definitions in page 11).

(d) Gyro-propagated attitude quaternion: gyroPropQuat (GYRPROP_Q). Double2d. Contains the four double-precission components of the gyro-propagated attitude quaternion in the ACA frame as furnished within the AHF (see definitions in page 11).

(e) STR quality index: strQuality (STR_QIDX). Double1d. Unit: arcsec.

(f) Gyro-propagated quality index: gyroQuality (GYP_QIDX). Double1d. Unit: arcsec. As furnisehd within the AHF.

(g) S/C angular velocity: angVelocity (ANG_VEL). Double2d: Unit: arcsec/sec

(h) S/C angular velocity error: angVelocityErr (ER_ANGV). Double2d: Unit: arcsec/sec

(i) Constant velocity flag: isConstantVelocity (CVELFLAG). Bool1d.

(j) Quality flag: qualityFlag(QUALFLAG): Int1d.

(k) STR interlacing status: isInterlacing (STR_INTE). Bool1d. 1 if STR interlacing active, 0 otherwise.

(l) Slew flag: isSlew (ISSLEW). Bool1d. Units: n/a

(m) On-target flag: isOnTarget (ISONTARG). Bool1d (units: n/a)

(n) Off-position flag: isOffPosition (ISOFFPOS). Bool1d (units: n/a)

(o) Out-of-field flag: isOutOfField (ISOUTFLD). Bool1d (units n/a)

(p) Uncorrected filtered attitude quaternion: uncorrFilterQuat (UNFILT_Q). Double2d. Contains the four double-precission components of the STR-uncorrected filtered attitude quaternion in the ACA frame (see definitions in page 11).

(q) Solar Aspect Angle: solarAspectAngle (SAA). Double1d: Unit: degrees. Solar Aspect Angle (SAA) as provided in the AHF (item number 23 in tables 3 & 4 of [AD.2])

(r) "Simple–corrected" Filtered attitude quaternion: simpleCorrFilterQuat (UNFILT_Q). Double2d. Contains the four double-precission components of the STR filtered attitude quaternion in the ACA frame, after applying the "simple" attitude correction (see definitions in page 11). If this information is not available (for instance if the redundant STR was used rather than the nominal one) the column will contain the same value as the "uncorrected filtered" attitude.

The following columns are to be taken from the `gyroAttitude` output, and will be set to zero if the information is not available (see filterQuatFlag field below):

[10] All OBT time references are TAI, expressed in microseconds since epoch 1958.001.00.00.00.000

[11] The order of the components in any quaternion array is such as the scalar component goes in the last position, i.e. (q_1, q_2, q_3, q_4) as in equation 1 of Appendix C.

(s) Gyro attitude probability-X: gyroAttProbX (GAPROB_X). Double1d. Probability of such a large value of the minimized cost function (x-axis) occurring at random.

(t) Gyro attitude probability-Y: gyroAttProbY (GAPROB_Y). Double1d. Probability of such a large value of the minimized cost function (y-axis) occurring at random.

(u) Gyro attitude probability-Z: gyroAttProbZ (GAPROB_Z). Double1d. Probability of such a large value of the minimized cost function (z-axis) occurring at random.

(v) Attitude sigma-X: gyroAttSigmaX (GASIGM_X). Double1d. Standard deviation of error about ACA-frame x-axis.

(w) Attitude sigma-Y: gyroAttSigmaY (GASIGM_Y).Double1d. Standard deviation of error about ACA-frame y-axis.

(x) Attitude sigma-Z: gyroAttSigmaZ (GASIGM_Z). Standard deviation of error about ACA-frame z-axis.

(y) Filtered Attitude Quaternion Flag: filterQuatFlag (FILT_QFL). Short1d. A flag indicating he contents of the filtered attitude quaternion: if `filterQuatFlag` = 0 → filterQuat contains the output of `gyroAttitude`. If `filterQuatFlag` = 1 → filterQuat contains the output of the “simple” attitude correction, i.e. the output of `FocalLengthCorrection`. If `filterQuatFlag` = 2 → filterQuat contains the filtered attitude as computed by the on-board filters and furnished within the AHF, i.e. no correction has been applied to the standard filtered attitude produced by the ACMS. In principle, this should only happen when the STR in use was the backup unit (STR2).

5 Information Provided within the AHF

The information provided by FDS within the AHF is described in [AD.2] and therefore no longer described in this document.

A Appendix: Full list of collected instruments' requirements on pointing

The requirements below are labelled as follows: *instrument*-PTREQ-X*nn*, where *instrument* can be either SPIRE, PACS or HIFI and X can be: “G” for General requirements, “R” for Raster pointing requirements, “L” for Line scanning requirements and “T” for SSO Tracking mode requirements.

A.1 SPIRE Requirements

SPIRE-PTREQ-G01 All pointing modes as defined in Annex 4 to the IID-A shall be available.

SPIRE-PTREQ-G02 The pointing accuracy shall be as specified in section 5.12.2 of the IID-A.

SPIRE-PTREQ-G03 Time (UT), RA, Dec, Intended RA, Intended Dec, Roll Angle and the On Target Flag shall be available at a sampling frequency of 16 Hz. Note: If this frequency of sampling is not available then a time resolution that does not introduce significant additional uncertainty into the pointing data will be acceptable.

SPIRE-PTREQ-G04 The estimated errors in the RA, Dec and Roll Angle for the pointing direction shall be available at the same frequency as for requirement SPIRE-PTREQ-G03).

SPIRE-PTREQ-G05 The time associated with the measurement of each pointing sample shall be accurate to 10 milliseconds.

SPIRE-PTREQ-G06 For each pointing sample a quality flag consistent with the pointing accuracy requirements shall be available.

SPIRE-PTREQ-G07 Pointing data where the S/C is slewing shall be flagged with a slew flag identifier

SPIRE-PTREQ-G08 The Herschel orbit data (S/C Position, S/C Velocity) shall be available at the same time resolution as the pointing history data.

SPIRE-PTREQ-G09 The Solar System Object database used by the S/C shall be available to the ICCs.

SPIRE-PTREQ-G10 For observation modes in which nodding is performed each pointing sample shall be labelled with the nodding cycle identifier.

SPIRE-PTREQ-R01 For raster mode observations each pointing sample shall be labelled with the raster point identifier.

SPIRE-PTREQ-L01 For line scan mode observations each pointing sample shall be labelled with the line scan identifier.

SPIRE-PTREQ-L02 For line scan mode observations each pointing sample shall include the associated S/C scan velocity.

A.2 PACS Requirements

PACS-PTREQ-G01 For all pointing data, the accurate time at which the measurement has been sampled shall be available to an absolute precision of better than 25ms.

PACS-PTREQ-G02 For all pointing data their specific errors shall be available and if applicable at full time resolution.

PACS-PTREQ-G03 In case pointing data is obtained during different ACMS modes of operation, these modes shall be indicated (flagged) in the data and their meaning shall be documented.

PACS-PTREQ-G04 The pointing accuracy of the data shall be as defined in the IID-A.

PACS-PTREQ-G05 All pointing modes as specified in IID-A annex 4 shall be available.

PACS-PTREQ-G06 Right Ascension (RA) and Declination (DEC) (or respective measurements which allow their derivation) shall be available at a sampling frequency which fully samples the temporal behaviour of the spacecraft. (i.e. if RA or DEC jitter bandwidth is 3 Hz, the sampling frequency shall be at least 6 Hz). However in the case of PACS, the sampling frequency of RA and DEC does not need to be faster than 10Hz, but must be faster than 1 Hz in any case.

PACS-PTREQ-G07 The roll angle of the spacecraft shall be available.

PACS-PTREQ-G08 An On-Target-Flag (OTF) shall be provided.

PACS-PTREQ-G09 All stews shall be flagged with a “slew” flag.

PACS-PTREQ-G10 An adequate description of the Herschel orbit (orbit file ?) shall be available at a time resolution compatible with the pointing accuracy specified in IID-A

PACS-PTREQ-G11 In case the pointing information is filtered on the way from “raw” data to RA and DEC, the information about the filter shall be available.

PACS-PTREQ-G12 Quality information for every given pointing shall be provided matching to and compatible with the pointing accuracy requirements. A id4

PACS-PTREQ-G13 Star-tracker information (obviously depends on type of star-tracker) shall be available, especially used guide stars, if applicable, and their position(s) on the star-tracker field of view.

PACS-PTREQ-G14 In general, all measurements related to the determination of the actual line of sight of the Herschel telescope, shall be available at a time resolution (either continuously or on request during a limited time), sufficient to allow for correlation studies with PACS science data for analysis of possible systematic effects affecting the science return.

PACS-PTREQ-G15 All measurements required in PTREQ-G13 have to be available in "raw" (digital units) format and in their converted format of physical units(Volts, Degrees, Amps, etc.).

PACS-PTREQ-R01 The raster point identifiers shall be available (M, N) at full time resolution.

PACS-PTREQ-R02 Slews between individual raster positions shall be flagged in the data stream.

PACS-PTREQ-R03 The "off' position in raster observations with off-position shall be flagged in the data stream.

PACS-PTREQ-R04 Raster specific requirements hold also for observations involving position switching and nodding.

PACS-PTREQ-L01 The line number (N) shall be available at full time resolution.

PACS-PTREQ-L02 Slews between individual lines shall be flagged in the data stream.

PACS-PTREQ-L03 The "off" position in line scan observations with off-position shall be flagged in the data stream.

PACS-PTREQ-L04 A flag indicating the moment when the spacecraft reaches or leaves constant velocity during line scanning shall be. available.

PACS-PTREQ-T0l The ephemerides used by the spacecraft for tracking a given SSO shall be available.

PACS-PTREQ-T02 A software tool shall be provided that allows to calculate the accurate Herschel-centric RA and DEC for any SSO, either based on an orbit prediction for calibration planning purposes or based on the true Herschel orbit for the analysis of observations.

PACS-PTREQ-T03 Herschel calibration will be partly based on SSOs where accurate flux predictions are crucial.Therefore it will be necessary to know in advance the true distance between Herschel and the observed object. Additionally, the Herschel solar elongation is important (zodiacal light a influences, visibility constraints) and the phase angles (Sun-object-Herschel) is needed for accurate modelling of SSO calibrators.

A.3 HIFI Requirements

HIFI-PTREQ-G01 Of course HIFI expects the AOCS requirements in IID-A and its appendix concerning scientific pointing modes to be met.

HIFI-PTREQ-G02 HIFI requires that pointings can be specified for at least 14 different instrument boresights (corresponding to "left" and "right" beams for seven mixers). The mechanism for this might employ offsets along satellite axes generated in the CUS.

HIFI-PTREQ-G03 HIFI expects attitude information at least once per second.

HIFI-PTREQ-G04 HIFI expects attitude information at a frequency at least double the bandwidth of the AOCS control system.

HIFI-PTREQ-G05 The attitude information must contain:

- Time
- Intended R.A. and Dec
- Estimated errors on R.A. and Dec
- Roll angle
- Raster point or raster line number
- On-target flag
- Flag for out-of-field reference measurement

HIFI-PTREQ-G06 Estimated errors must be filtered to contain no frequencies beyond half the sampling frequency.

HIFI-PTREQ-G07 There must be absolute clarity about phase shifts between reported times, positions and position errors.

B Appendix: Herschel Pointing Modes

This section describes the Herschel pointing modes and is based on [RD.6] and [RD.7]. Observations are the smallest schedulable entities. It is assumed that one observation contains no more than one pointing command, either basic (standard) or composite. Each observation uses an instance of an observing mode that is defined in the CUS language. The observing mode invokes a pointing mode (e.g. raster) and then issues a sequence of instrument commands to control the instruments.
Note: This section is still to be worked out. The current version is nearly a placeholder and just presents a short definition (verbatim from [RD.7]) of each pointing mode. The command name and its proposed numerical code are shown in parentheses.

B.1 Standard Fixed Modes

1. **Fine pointing** (fine_pointing): Fine pointing is a single fixed pointing at a given RA and DEC, for a duration 'tp'.

2. **Raster** (raster): A raster pointing is a series of fine pointing observations of equal duration that map a rectangular area, with 'n' lines and 'm' points per line.

3. **Raster with OFF position** (raster_with_off): A raster pointing with OFF position is a special form of raster where, after a specified number 'k' raster points, the boresight slews to a predefined OFF position, after which it continues at the next raster point.

4. **Line scan** (line_scan): Line scanning maps a rectangular area with a sequence of (approximately) parallel lines. The spacecraft must slew between lines and acceleration and decceleration periods at the ends of the scan lines must be taken into account.

5. **Line scan with OFF position** (line_scan_with_off): A line scanning with OFF position differs from a simple line-scan in that: *(a)* After each sequence of 'k' lines, the boresight slews to a predefined OFF position for a duration 'top' and *(b)* The maximum length of a scan line is 2 degrees, whereas for a simple line-scan it is 20 degrees.

6. **Position switching** (position_switching): Position switching is a mode where the instrument line-of-sight is periodically switched between a target source (point A) and a position off the source (point B). The orientation of the pattern is specified relative to the sky; its orientation relative to the instrument axes depends on the direction of the Sun and hence

on the time at which the observation is performed. This mode executes a pattern of the form ABBAAB..., such that there are always an equal number of As and Bs. This ensure that the total integration times on the two points are the same. The parameter 'n' specifies the number of AB (or BA) pairs.

7. **Nodding** (nodding): Nodding differs from position switching in that the orientation is specified relative to the instrument boresight axes. This is to ensure that the nodding direction is aligned with the direction of the instrument chopper throw.

B.2 Composite Modes

1. **Composite position switching** (composite_position_switching): This mode differs from basic position switching in the following:
   - The number of switches can be up to 1200, instead of 32.
   - The times at point A and B may be different.
   - On every nload'th switch, a load-slew[12] occurs. If nload=0, no load-slews occur.
2. **Composite nodding** (composite_nodding): This mode differs from basic nodding in the following:
   - The number of switches can be up to 1200, instead of 32.
   - On every nload'th switch, a load-slew occurs. If nload=0, no load-slews occur.
   - After every 'nhold' switches, a hold of duration 'thold' occurs at a fixed pointing for calibration. This occurs between the pair of points AA (or BB). If nhold=0, the holds do not occur.
3. **Repeated line scan with OFF position** (repeated_line_scan_with_off): This mode differs from the basic line-scan-with-off in the following ways:
   - The number of lines can be up to 240, instead of 32.
   - The whole map is repeated 'ncover' times.
   - Every nload'th slew to the OFF position is a load-slew. If nload=0, no load-slews occur.
   - The map always starts and ends at the OFF position.
4. **Nodding of raster** (nodding_of_raster): This mode consists of a raster 'map-1' and a second identical raster 'map-2' that is offset by the chopper throw. The pattern starts with 'k' points of map-1, then switches to map-2 for 2 × k points, then back to map-1 for 2 *times* k points, finally finishing with 'k' points in map 1. In addition:
   - After every 'nload' raster points, a load-slew occurs.
   - The orientation of the raster is always specified relative to the sky (TBC).
5. **Nodding in raster** (nodding_in_raster): Nodding-in-raster can be thought of as a combination of the raster and nodding modes described above, such that 'nnod' nodding switches occuring at each raster point. This mode is required by all three instruments. In addition:
   - After every 'nhold' switches, a hold of duration 'thold' occurs at a fixed pointing for calibration. If nhold=0, no holds occurs.

[12] A load-slew is a 'stretched' slew, with a minimum duration of 'tloadslewmin' to allow load calibration to take place during the slew. The spacecraft slews to the next position and then waits, if necessary, until the requested time has elapsed.

- The orientation of the pattern may be specified relative to either the sky or the instrument boresight axes.
- An additional parameter 'pattnod' specifies the orientation of the nod relative to the instrument boresight axes.

6. **Repeated raster with hold** (repeated_raster_with_hold): This mode differs from a basic raster in the following ways:
   - The whole map is repeated 'ncover' times.
   - After every 'nhold' raster points, a hold of duration 'thold' occurs for calibration at a fixed pointing. If nhold=0, no holds occur.
7. **Nodding in raster with OFF position** (nodding_in_raster_with_off): This mode is similar to 'nodding in raster', except that:
   - Calibration holds are not supported.
   - The pattern goes to an OFF position after every 'k' raster points. If m × n is divisible by 'k', the pattern ends on the OFF position.
   - The raster orientation is always specified relative to the sky.
8. **Line scan with hold** (line_scan_with_hold): This mode differs from a basic line-scan in the following ways:
   - After every 'nhold' lines, a hold of duration 'thold' occurs at a fixed pointing for calibration. If nhold=0, no holds occur.
   - The orientation is always specified relative to the instrument boresight axes.

B.3 Standard Solar System Tracking Modes

SSO Tracking modes are TBD.

B.4 Gyro Propagation Modes

Gyro propagation modes are TBD.

C Appendix: Useful formulae

Important note: this section is for reference only. It is strongly recommended to perform all computations using the Java classes provided within `herschel.share.fltdyn.math`. Please refer to the online documention at:
`ftp://www.rssd.esa.int/pub/HERSCHEL/csdt/releases/doc/api/herschel/mpos/fltdyn/math/package-summary.html`
for more information.

C.1 Quaternions

The quaternions are members of a noncommutative division algebra conceived by W. R. Hamilton. Quaternions are a single example of a more general class of hypercomplex numbers. While the quaternions are not commutative, they are associative, and they form a group known as the quaternion group. By analogy with the complex numbers being representable as a sum of real and imaginary parts, a quaternion can also be written as a linear combination:

$$q = q_1 i + q_2 j + q_3 k + q_4 \equiv (q_1, q_2, q_3, q_4) \tag{1}$$

where $q_i, i = 1, ..., 4$ are real numbers; q_4 is the scalar component of the quaternion. The magnitudes i, j, k satisfy the following relationships:

$$\begin{array}{l} i^2 = j^2 = k^2 = ijk = -1 \\ ij = -ji = k \\ jk = -kj = i \\ ki = -ik = j \end{array} \tag{2}$$

The conjugate of a quaternion is defined as:

$$q^* = -q_1 i - q_2 j - q_3 k + q_4$$

The addition of two quaternions, $p = (p_1, p_2, p_3, p_4)$ and $q = (q_1, q_2, q_3, q_4)$ has the following properties:

$$\begin{array}{l} p + q = q + p = (p_1 + q_1, p_2 + q_2, p_3 + q_3, p_4 + q_4) \\ p + \mathbf{0} = \mathbf{0} + p = p \quad \text{where } \mathbf{0} \equiv (0,0,0,0) \\ -p = (-p_1, -p_2, -p_3, -p_4) \\ p + (-p) \equiv p - p = -p + p = \mathbf{0} \\ p + (q + s) = (p + q) + s \end{array} \tag{3}$$

The product of quaternions is in general non-commutative; it can be expressed in matrix format as follows:

$$p \otimes \ q = \begin{pmatrix} q_4 & q_3 & -q_2 & q_1 \\ -q_3 & q_4 & q_1 & q_2 \\ q_2 & -q_1 & q_4 & q_3 \\ -q_1 & -q_2 & -q_3 & q_4 \end{pmatrix} \begin{pmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{pmatrix} \tag{4}$$

and has the following properties:

$$\begin{array}{l} (p \otimes q) \otimes s = p \otimes (q \otimes s) \\ \mathbf{1} \otimes p = p \otimes \mathbf{1} = p \quad \text{where } \mathbf{1} \equiv (0,0,0,1) \\ p \otimes (q + s) = p \otimes q + p \otimes s \\ (p + q) \otimes s = p \otimes s + q \otimes s \\ p^{-1} = \dfrac{p^*}{\mid p \mid^2} \quad \text{if } p \neq 0 \\ p \otimes p^{-1} = p^{-1} \otimes p = \mathbf{1} \end{array} \tag{5}$$

A positive rotation of an angle θ about a unit axis vector $\hat{\mathbf{e}}$ is described by a unit quaternion as:

$$q = \left(e_x \sin\frac{\theta}{2}, e_y \sin\frac{\theta}{2}, e_z \sin\frac{\theta}{2}, \cos\frac{\theta}{2}\right) \tag{6}$$

Since this is a unit quaternion the four parameters are not independent, but satisfy the constraint relation $\sum_{i=1}^{4} q_i^2 = 1$. The components $q_i,\ i = 1, ...4$ in equation 6 are usually referred as *Euler symmetric parameters* and provide an adequate representation of the S/C attitude (no singularities, no trigonometric functions, convenient product rule for successive rotations).

If $\vec{\mathbf{a}}$ is a vector, we can associate a quaternion $\underline{\vec{\mathbf{a}}} = (a_x, a_y, a_z, 0)$. If $(\theta, \hat{\mathbf{e}})\,\vec{\mathbf{a}}$ is the vector obtained from $\vec{\mathbf{a}}$ by a rotation of an angle θ about a unit axis vector $\hat{\mathbf{e}}$ the following applies:

$$\underline{(\theta, \hat{\mathbf{e}})\vec{\mathbf{a}}} = q \otimes \underline{\vec{\mathbf{a}}} \otimes q^* \tag{7}$$

where q is the unit quaternion given by equation 6.

It is easy to represent the concatenation of rotations in quaternion format. If the quaternion $\mathbf{r}$ represents the concatenation of a rotation $\mathbf{p}$ followed by a rotation $\mathbf{q}$, and the quaternion $\mathbf{q}$ is expressed in the coordinate system rotated by $\mathbf{p}$, it is easy to show that $\mathbf{r} = \mathbf{p} \otimes \mathbf{q}$. This expression is useful to propagate the attitude quaternion with a gyro update.

C.1.1 Converting quaternions into attitude matrices

Attitude can be represented by means of the direction cosine matrix or attitude matrix[13]. The attitude matrix can be expressed in terms of the Euler symmetric parameters as ([RD.13], p. 414):

$$A(q) = \begin{pmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\ 2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & +2(q_2q_3 + q_1q_4) \\ 2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{pmatrix} \tag{8}$$

Inversely, given a direction cosine matrix (DCM) **A**, the quaternion components can be found from the expression ([RD.13], p. 415):

$$\begin{aligned} q_4 &= \pm\frac{1}{2}\left(1 + A_{11} + A_{22} + A_{33}\right)^{1/2} \\ q_1 &= \frac{1}{4q_4}(A_{23} - A_{32}) \\ q_2 &= \frac{1}{4q_4}(A_{31} - A_{13}) \\ q_3 &= \frac{1}{4q_4}(A_{12} - A_{21}) \end{aligned} \tag{9}$$

Note the sign ambiguity in the calculation of these parameters. Of course these formulae are valid as long as $1 + A_{11} + A_{22} + A_{33} \neq 0$

C.1.2 Converting quaternions into RA, DEC & PA

It is possible to derive the relations between the attitude quaternion components and RA (α), DEC (δ) & PA (ϕ) taking into account that the attitude quaternion can be expressed as: $q = q_a \otimes q_b \otimes q_c$, where $q_a = (0, 0, \sin\alpha/2, \cos\alpha/2)$, $q_b = (0, -\sin\delta/2, 0, \cos\delta/2)$ and $q_c = (-\sin\phi/2, 0, 0, \cos\phi/2)$. Applying the rules of multiplication of quaternions in 4 and 5:

$$\begin{aligned} q_1 &= \cos\frac{\phi}{2}\sin\frac{\delta}{2}\sin\frac{\alpha}{2} - \sin\frac{\phi}{2}\cos\frac{\delta}{2}\cos\frac{\alpha}{2} \\ q_2 &= -\cos\frac{\phi}{2}\sin\frac{\delta}{2}\cos\frac{\alpha}{2} - \sin\frac{\phi}{2}\cos\frac{\delta}{2}\sin\frac{\alpha}{2} \\ q_3 &= -\sin\frac{\phi}{2}\sin\frac{\delta}{2}\cos\frac{\alpha}{2} + \cos\frac{\phi}{2}\cos\frac{\delta}{2}\sin\frac{\alpha}{2} \\ q_4 &= \sin\frac{\phi}{2}\sin\frac{\delta}{2}\sin\frac{\alpha}{2} + \cos\frac{\phi}{2}\cos\frac{\delta}{2}\cos\frac{\alpha}{2} \end{aligned} \tag{10}$$

The inverse relations are not very easy to compute from the expressions above. But it is possible to derive a relation between the equatorial coordinates and the quaternion components by taking into account that the attitude matrix is a ZYX (a.k.a. 3-2-1) transformation with Euler angles α, $-\delta$, $-\phi$. Then:

$$\begin{aligned} \alpha &= \tan^{-1}(A_{12}/A_{11}) \\ \delta &= \sin^{-1}(A_{13}) \\ \phi &= -\tan^{-1}(A_{23}/A_{33}) \end{aligned} \tag{11}$$

The A_{ij} coefficients are related to the quaternion components by means of equation 8.

[13]The attitude matrix represents a passive rotation, i.e. that expressing the same vector in two different coordinate systems, while a quaternion represents an active rotation, i.e. that rotating a vector in a fixed coordinate systems. An active rotation is just the inverse of the corresponding passive rotation.

C.1.3 Propagating the attitude

The S/C attitude can be propagated in time using an initial estimation of the attitude and the angular rates provided by the gyroscopes, by means of the kinematic equation of motion (see for instance [RD.13] p. 511):

$$\dot{q} = \frac{1}{2}\Omega q \tag{12}$$

where Ω is a skew-symmetric matrix built from the components of the angular velocity vector in the orthogonal, right-handed triad $(\hat{\mathbf{u}}, \hat{\mathbf{v}}, \hat{\mathbf{w}})$ fixed in the S/C body:

$$\Omega = \begin{pmatrix} 0 & \omega_w & -\omega_v & \omega_u \\ -\omega_w & 0 & \omega_u & \omega_v \\ \omega_v & -\omega_u & 0 & \omega_w \\ -\omega_u & -\omega_v & -\omega_w & 0 \end{pmatrix} \tag{13}$$

Assuming Ω constant, we can formally integrate equation 12 to obtain:

$$q(t) = \exp(\Omega t/2) q(0) \tag{14}$$

The exponential can be solved as ([RD.13], p. 755):

$$\exp(\Omega t/2) = \sum_{n=0}^{\infty} \frac{\left(\frac{1}{2}\Omega t\right)^n}{n!} = \mathbf{1}\cos\left(\frac{1}{2}\omega t\right) + \Omega\omega^{-1}\sin\left(\frac{1}{2}\omega t\right) \tag{15}$$

where $\mathbf{1}$ is the 4×4 identity matrix, $\mathbf{1}_{ij} = \delta_{ij}$

References

[RD.1] Herschel-Planck ACMS Telemetry Definition, H-P-4-DS-TN-025, v4.0 (04/05/06)

[RD.1] Herschel-Planck ACMS Telecommand Definition, H-P-4-DS-TN-024, v3.8 (26/08/05)

[RD.3] Definition of the Flexible Image Transport System (FITS), NOST 100-2.0 (http://archive.stsci.edu/fits/fits_standard)

[RD.4] ICD: Herschel Spacecraft/Instrument Alignment History, PT-HMOC-FD-ICD-2111-OPS-GFT v1.1 (31/01/05)

[RD.5] Herschel/Planck Orbit Data and Access Softfware ICD, PT-CMOC-FD-ICD-2101-OPS-GFI v1.0 (05/07/04)

[RD.6] Pointing command requirements for Herschel, v0.5 Draft (31/05/05)

[RD.7] Herschel Pointing Modes, HERSCHEL-HSC-DOC-624 v0.2 (22/07/05)

[RD.8] Minutes of Meeting, HPDG Teleconference#1, HERSCHEL-HSC-MOM-0648 Issue 1 (12/09/05)

[RD.9] Standard Metadata Names for Herschel Data Processing, SPIRE-RAL-DOC-002388 Issue 0.2 Draft (30/03/05)

[RD.10] Herschel Science Ground Segment to Instruments ICD, FIRST-FSC-DOC-0200 Issue 2.3 (30/09/04)

[RD.11] Herschel/Planck ACC ASW Software Requirements Document, H-P-4-TSAW-RS-0001 Issue 3 (20/12/04)

[RD.12] Herschel Orbit Product Specification, HERSCHEL-HSC-DOC-0767 v1.0 (12/04/06)

[RD.13] Wertz, J. R. (Ed.), Spacecraft Attitude Determination and Control, Kluwer Academic Publishers, 1990

[RD.14] Tuttlebe, M., private communication (e-mail on 09/06/06)

[AD.1] PACS Requirements on Pointing Information, PACS-ME-TN-030, issue 1 (26/02/02)

[AD.2] Attitude History File ICD, PT-HMOC-FD-ICD-2109-OPS-GFT, v2.0 (9/05/08)