Attitude History File ICD

DMS Document ID : PT-PMOC-FD-ICD-2110-OPS-GFT

PTGS Document ID: PGS-ICD-006

Version: Issue 2.6

24/07/09

The present document defines the PLANCK Attitude History File (AHF) Interface. The AHF is provided by the MOC (FDD). The interface is designed to be used inside the DPCs and the PSO for the extraction of the attitude and orientation of the spacecraft for a given operational day as a function of time.

Document Approval

Prepared by	
Name	**Affiliation**
M. J. Tuttlebee (Custodian)	SciSys

	Signature	Date		
Agreed:	Eduardo Valido Cabrera	Digitally signed by Eduardo Valido Cabrera DN: cn=Eduardo Valido Cabrera, o=ESA, ou=OPS-GDS, email=eduardo.valido.cabrera@esa.int, c=DE Date: 2009.12.01 12:40:11 +01'00'	G. Di Girolamo	OPS-GDS
		Digitally signed by Steve Foley DN: cn=Steve Foley, o=ESA, ou=ESOC, email=steve.foley@esa.int, c=DE Date: 2009.11.27 10:32:01 +01'00'	C. J. Watson	OPS-OAP
		Laurent Vibert 2009.08.04 15:02:01 +02'00'	L. Vibert	DPC/HFI
		Digitally signed by Andrea Zacchei Date: 2009.08.06 08:52:51 +02'00'	A. Zacchei	DPC/LFI
		Digitally signed by Damien Texier Date: 2009.07.28 09:55:54 +02'00'	D. Texier	PSO
Approved:		Gottlob Gienger 2009.08.10 11:25:49 +02'00'	G. Gienger	OPS-GFM
			U. Feucht	OPS-GF
Released:		Digitally signed by Andreas Rudolph DN: cn=Andreas Rudolph, o=ESA, ou=ESOC, email, c=<n Date: 2009.12.01 17:19:10 +01'00'	~~J. Dodsworth~~	~~OPS-HS~~

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Document Status Sheet

DOCUMENT TITLE	Attitude History File ICD
DMS DOCUMENT ID:	PT-PMOC-FD-ICD-2110-OPS-GFT
PTGS DOCUMENT ID :	PGS-ICD-006

VERSION	REV.	DATE	OVERALL REASON FOR CHANGE
Draft 1	0	17/10/03	Initial draft for internal review
Draft 2	0	09/03/04	Updates after external review comments from DPC-HFI and DPC-LFI
Draft 3	0	10/05/04	Updates after comments from G. Gienger, J. Palmer, and DPC-HFI
1	0d	21/07/04	Updates after comments from PSO, DPC-HFI and DPC-LFI
1	0	21/07/04	Included updates for Issue 1.0
2	0d	19/10/05	Included updates for Issue 2.0
2	0	13/06/06	Final updates for Issue 2.0
2	1d	19/09/06	Updates based on detailed design and implementation
2	1	13/10/06	Final updates for Issue 2.1
2	2d	08/11/07	updates for Issue 2.2
2	2	04/12/07	Final updates for Issue 2.2
2	3	06/06/08	updates for Issue 2.3
2	4	31/07/08	Final updates for Issue 2.4
2	5d	17/12/08	updates for Issue 2.5
2	5	17/12/08	Final updates for Issue 2.5
2	6	26/07/09	updates for Issue 2.6

Document Change Record	DCR NO	1
	DATE	09/03/04
	ORIGINATOR	M. Tuttlebee

1. DOCUMENT TITLE:	Attitude History File ICD
2. DMS - DOCUMENT REFERENCE NUMBER:	PT-PMOC-FD-ICD-2110-OPS-GFT
3. PGS - DOCUMENT REFERENCE NUMBER:	PGS-ICD-006
4. DOCUMENT ISSUE/REVISION NUMBER:	Draft 2 Rev 0

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p.2		New reference added for Planck reference coordinate system conventions
p.7		Updated text to reflect new requirement PGS-IR-4.1-315 and added text to describe what data is provided.
p.9		Corrected location of LFI DPC
p.13		Updated file size to be compatible with maximum frequency of high frequency data records.
p.15		Updated text to correct decription of inertial reference and proposal that time records are represented by On-Board Time.
p.16		High frequency data can be provided at the same frequency as ACC data. Various other changes to text
p.17		High frequency data record structure updated including the new representation of time and the use of quaternion to represent the instantaneous attitude
p.18		Spin period frequency data record structure updated including the new representation of time together with time duration for an observation period. Change spin axis to angular momentum vector
p.19		Observation frequency data record structure updated including the new representation of time. Change spin axis to angular momentum vector
p.20		Update note [2] to define NNNN
p.20		Add note [4] to quaternion components and re-number subsequent notes
p.20		Update notes [5], [6], and [7] to cater for new format for attitude
p.21		Update note [17] to clarify the meaning of nutation damping time constant.
p.25		Add appendix to describe derivation of 3-axes attitude from data in the Observation frequency data record structure

annex 1-2		Annex A added to clarify reference syatems and dynamical parameters in spin period and observation period data records

Document Change Record		DCR NO	2
		DATE	10/05/04
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Draft 3 Rev 0	
5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE	
All		Major update to the document in particular the Annex which describes in more detail the data records within the observation frequency records and the algorithms required to process them.	

Document Change Record		DCR NO	3
		DATE	20/07/04
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 1.0d	
5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE	
p.10		Updated text to reflect new requirement PGS-IR-4.1-315 and added text to describe what data is provided.	
p12		AHF size change because of change in AHF record length	
p13		Change AHF record length from 235 to 211 bytes	
p13,15,16, 17		Change character string length of 6 byte OBT to A12	

p15,16,17, 18		Update offsets in Tables 2, 3, 4 to reflect corrected OBT representation.
p14,17,18		Change nominal duration of spin frequency (nominally 60 seconds) and observation frequency (30 to 60 minutes) data
p.17		Add definition of the observation frequency duration
p.18		Correct frequency of high frequency records
p.18		Insert a definition of the quaternion and a cross reference to the planck body reference system definition into Note [4]
p.19		Add a cross reference to the spin phase zero point definition into Note [7].
p.20,21		Added an example attitude history file

Document Change Record	DCR NO	4
	DATE	21/09/04
	ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD	
2. DMS - DOCUMENT REFERENCE NUMBER:	PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:	PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:	Issue 1.0	

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p.i-ii		Updated front page formats
p.1,2		Updated issue numbers of ADs and RDs
p4		New acronym
p7		Add footnote
p13		Record length changed due to changes to data records
p15,16,17		Update offsets in Tables 2, 3, 4 to reflect updated data records.
p15,16,17		Change format of differences between reconstituted and target right ascension/declination
p.17,19		Changed format of observation duration
p.21		Add corrected AHF example based on changes to data records
annex.2		Clarify definition of DCMs

annex.5		Correct nutation damping formula

Document Change Record	DCR NO	5
	DATE	13/04/06
	ORIGINATOR	M. Tuttlebee

1. DOCUMENT TITLE:	Attitude History File ICD
2. DMS - DOCUMENT REFERENCE NUMBER:	PT-PMOC-FD-ICD-2110-OPS-GFT
3. PGS - DOCUMENT REFERENCE NUMBER:	PGS-ICD-006
4. DOCUMENT ISSUE/REVISION NUMBER:	Issue 2.0

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
All		Corrected DMS Document reference 2210 ->2110
pi		Update abstract text
pii-iii		Updated signature and distribution lists
p1-3		Added/Updated issue numbers of ADs and RDs
p9		Add references to related interfaces
p10		Correction to wrapper file name
p12,14,15, 18		Updated to reflect science mode TM availability at 8 Hz
p12		Updates to text in Sections 6.2 and 6.3. Record length changed due to changes to data records
p14		Remove references to processing raw star data and add text related AHF contents during OCM and contingencies
p15		Changed references to define spin phase zero point. Removed items 14 and 16 from Table 2. Added scalar part of the quaternion based on numerical considerations.
p17		Cross references to notes changed as a result of updates on Page 15
p19		Removed Note 14 since raw star positions are no longer present in the science mode TM packet
p20		Updated example basedc on changes to the high frequency records.
p21		Updated to include a more realistic example
annex 2		spin phase mentioned explicitly in text

annex 3		Updated introductory text
annex 5		Included algorithm to compute the spin phase angle

Document Change Record		DCR NO	6
		DATE	13/10/06
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 2.1	

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p12		Recompute the file size and storage requirements
p13		Increase record length by 4 bytes to accomodate additional data in data records.
p14		Updates to text describing the different phases covered within an AHF. Combined Post slew and stable pointing phases.
p15,16		Updated explanatory text of high frequency records. Added ACMS mode, right ascension and declination of the angular momentum vector expressed in the ecliptic inertial reference system, spin phase, principal axis tilts, nutation angle, body and inertial nutation phase to high frequency record structure.
p16,17		Updated explanatory text of spin frequency records. Added principal axis tilts, nutation angle, body and inertial nutation phase to spin frequency record structure.
p18,19		Added body nutation phase to observation frequency record structure.
p19,20		Various additions and major updates to notes.
p21		Updated text describing file examples.
p22		Updated example to reflect latest high frequency record structure.
p23		A second example added of a stable pointing containing all AHF record types.
annex 1,7		Update subscript for ecliptic inertial reference system
annex 2,3,4		Various updates and additions to text. In particular descriptions on how the data is derived and used to compute the rotation matrices

Document Change Record	DCR NO	7
	DATE	04/12/07
	ORIGINATOR	M. Tuttlebee

1. DOCUMENT TITLE:	Attitude History File ICD
2. DMS - DOCUMENT REFERENCE NUMBER:	PT-PMOC-FD-ICD-2110-OPS-GFT
3. PGS - DOCUMENT REFERENCE NUMBER:	PGS-ICD-006
4. DOCUMENT ISSUE/REVISION NUMBER:	Issue 2.2

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p.ii		Modified delete/add new names
p.iii		Modified delete/add new names
p.iv		Document Status Sheet changes
p.x		New Document Change Record added
pp.1-3		Updated references to reflect latest document issues.
pp.4-5		Added several acronyms that were missing
p.10		Updated wrapper file name to be in line with FTS ICD
pp.15-19		Removed units from data description fields since this is given in the notes section. The units for the principal axis tilts were arcsec in the data field description and arcmin in the notes section. The unit arcmin is the correct unit.
pp.19-21		Remove constraint about the quaternion scalar component. Notes have been clarified where necessary. Added notes [15] and [21]
pp.21-22		Changed file examples to a file generated based on Day 3 of P-SVT-0
annex 2,3		Transformations and text in A.2.2 corrected
annex 3,4		Text in A.2.3 and expressions for principal axis tilts corrected.
annex 5		Correct formula give in A.3.1
annex 8		Rewrite A.3.9 and remove references to the Cluster mission

Document Change Record		DCR NO	8
		DATE	06/06/08
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 2.3	

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p.xi		New Document Change Record added
pp.1-3		Updated references to reflect latest document issues.
p.10		Corrected AHF wrapper file specification
p.16		Changed high frequency record item 22 from slew start time to time of first thruster pulse.
p.17		Correct description for items 10 and 11
p.20		Changed Note [13] from HCM mode entry time to the time of the first thruster firing after transition to HCM
p.21		Minor editorial change
pp.21-22		Updated example based on the RMS rerun.
Annex A.3	annex. 5-6	Added description on how to recover the inertia tensor from data in the observation frequency record.
Annex A	annex. 2-10	Equation numbers added for clarity

Document Change Record		DCR NO	9
		DATE	31/07/08
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 2.4	
5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE	
p.xi		New Document Change Record added	
p.1		Updated references to reflect latest document issues.	
p.10		Added text to describe the gzipped AHF	
p.13		Added file size requirements for gzipped AHFs	
p.17		Added clarification about spin averaged record validity time	
p.19		Added clarification about observation averaged record validity time	

Document Change Record		DCR NO	10
		DATE	17/12/08
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 2.5d	
5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE	
p.xii		New Document Change Record added	
p.4		Add acronym	
p.13		Updated file size requirements due to increased high frequency record size.	
p.14		Updated record length and added processing interval start and stop times to header record definition	

p.15		Added Figure to describe clearly the structure of the AHF record.
p.16		Added Figure to clarify AHF processing interval definition for CPV phase (20 hour pointing duration)
p.17		Added Figure to clarify AHF processing interval definition for routine phase (30 to 70 minute pointing duration)
p.18		Added Figure to clarify AHF processing interval definition for CPV phase (48 hour pointing duration)
p.19		Text added to describe selection of filter cutoff frequency, how data is split into batches prior to filtering including the handling of data gaps
pp.20-23		Reorganised the sections to describe the detailed contents of each data record.
p.21		Added an integer identifier for the attitude data filtering batch number
p.22		Increased the length of item 17 to account for new record lengths
p.23		Added to the record the X-axis principal moment of inertia and modified the length of item 23 to account for this addition and the new record lengths
p.25		Added note [16] for data batch number
p.26		Added note [23] for X-axis principal moment of inertia.
pp.26-27		Updated file example from SOVT-1

Document Change Record		DCR NO	11
		DATE	26/02/09
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 2.5	

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p.xiii		New Document Change Record added
p.2		Updated reference
p.19		Remove TBC from list of important points concerning AHF records
p.21		Changed item 25 format from I2 to A2

p.25		Changed text in Note [16]
p.27		Updated example to reflect updated batch number format

Document Change Record		DCR NO	12
		DATE	24/07/09
		ORIGINATOR	M. Tuttlebee
1. DOCUMENT TITLE:	Attitude History File ICD		
2. DMS - DOCUMENT REFERENCE NUMBER:		PT-PMOC-FD-ICD-2110-OPS-GFT	
3. PGS - DOCUMENT REFERENCE NUMBER:		PGS-ICD-006	
4. DOCUMENT ISSUE/REVISION NUMBER:		Issue 2.6	

5. PAGE	5. PARAGRAPH	6. REASON FOR CHANGE
p.xiv		New Document Change Record added
p.23		Increased observation duration Format from F7.1 to F8.1. Updates to Offsets as a result of format change
p.25		Update to Note [17]

Table of Contents

1. *Introduction*

1.1. *Purpose*

This Interface Control Document (ICD) describes the low-level interfaces between the Planck Flight Dynamics System (FDS) developed by the Flight Dynamics Division (FDD) at ESOC, the Planck Mission Control System (MCS) and the Planck Science Office (PSO) and Data Processing Centres (DPCs) for the delivery of the following products, to be generated by Flight Dynamics (FD):

- the attitude history file (AHF) providing the attitude and orientation of the spacecraft as a function of time

These files are generated on the FDS and notified to the MCS via FTS. Transfer to the PSO and DPCs takes place via the FTS.

The relevant high-level ICD covering the flow of information from MOC to PSO and DPCs is described in [AD.4]

1.2. *Scope*

The attitude history file will be used during the payload verification and routine mission-phases. This ICD chapter is applicable to these phases. Prior to launch, this ICD chapter is applicable for the validation of the interfaces during Ground Segment integration and testing and for simulations of operations.

1.3. *Applicable Documents*

	Document Project ID	**Title**		
	Author	**Affiliation**	**Issue**	**Date**
[AD.1]	QMS-EIMO-GSEG-DRD-1207-OPS	OPS QMS Document Requirements Definition for Flight Dynamics Documentation		
	A. Schütz, R. E. Münch	OPS-GF	Issue 2.0	30/05/2008
[AD.2]	PT-CMOC-FD-RC-2001-OPS-GFT	Herschel/Planck Flight Dynamics Support Requirements Compilation		
	J. B. Palmer et. al.	OPS-GFT	Issue 3.3	25/06/2008
[AD.3]	PT-CMOC-FD-IA-2002-OPS-GFT	Herschel/Planck Flight Dynamics Implementation Analysis		
	J. B. Palmer et. al.	OPS-GFT	Issue 2.0	31/07/2008
[AD.4]	PT-CMOC-MDS-ICD-3107-OPS-GDS	Herschel+Planck File Transfer System ICD		
	HPMCS Development Team	OPS-GDS	Issue 1.7	June 2008
[AD.5]	PLANCK/PSO/2002-003	PLANCK Ground Segment Interface Requirements Document		
	PGSSG	ESA/PSO	Issue 3 rev. 0	05/10/2004

1.4. Reference Documents

	Document Project ID	Title		
	Author	**Affiliation**	**Issue**	**Date**
[RD.1]	Journal of the Astronautical Sciences	A Survey of Attitude Representations		
	M. D. Shuster		Vol 41, No. 4, pp 439-517	Oct-Dec 1993
[RD.2]	PLANCK/PSO/2002-007	PLANCK Ground Segment list of ICDs		
	M. Bremer	ESA/PSO	Issue 0 rev. 1	11/11/2002
[RD.3]	PLANCK/PSO/2004-008	PLANCK Science Ground Segment : Low level ICD list		
	M. McKinnell	ESA/PSO	Issue 2 rev. 0	03/10/2006
[RD.4]	PLANCK/PSO/2001-001	PLANCK Operations Scenario Document		
	J. Tauber	ESA/SCI-SA	Issue 1 rev 0.0	June 2003
[RD.5]	PT-PMOC-TN-6602-OPS-OGH	PLANCK Mission Planning Concept		
	C. J. Watson, R. Biggins	OPS-OGH	Issue 2.3	July 2005
[RD.6]	PT-CMOC-FD-ICD-2104-OPS-GFT	Planning Skeleton File ICD		
	P. Mahr	OPS-GFT	Issue 1.5	04/08/2008
[RD.7]	PLANCK/PSO/2003-007	PSO-MOC/PSO-DPC : Preprogrammed Pointing List (PPL)		
	M. McKinnell	ESA/PSO	Issue 1 rev. 1	22/10/2007
[RD.8]	PT-PMOC-FD-ICD-2108-OPS-GFT	PLANCK Augmented Preprogrammed Pointing List / Attitude Parameter File		
	A. McDonald	OPS-GFT	Issue 3.2	02/10/2008
[RD.9]	PLANCK/PSO/2005-015	DPC-PSO : Spacecraft/Instrument Alignment Matrices (SIAM)		
	D. Taylor	ESA/PSO	Issue 1.3	01/07/2008
[RD.10]	PT-CMOC-MDS-ICD-3102-OPS-GDS	HERSCHEL-PLANCK MCS Time Correlator ICD		
	T. Ulriksen	Terma	Issue 2 rev. 6	20/11/2008
[RD.11]	H-P-4-DS-TN-025	ACMS Telemetry Definition		
	J. A. Meijer	Dutch Space	Issue 5.0	13/10/2008
[RD.12]	OG-URD-001-ASTR	ASTR SW User Requirements Document		
	S. Gigli	Galileo Avionica	Issue 7 rev. 0	12/12/2002
[RD.13]	H-P-4-GAF-UR-0002	ASTR SW User Requirements Document for Planck		
	G. Berrighi	Galileo Avionica	Issue 6 rev. 0	September 2004
[RD.14]	H-P-4-GAF-SR-0002	P-ASTR SW Requirements Document		
	R. Marchi	Galileo Avionica	Issue 7 rev. 0	30/06/2005

	Document Project ID	Title		
	Author	**Affiliation**	**Issue**	**Date**
[RD.15]	H-P-4-SEN-TN-0004	Planck ACMS Nomenclature and Conventions		
	J. M. Del Cura, C. Cazorla	Sener	Issue 2 rev. 0	31/01/2003
[RD.16]	H-P-4-SEN-TN-0002	Planck Attitude Determination Algorithms Description		
	C. Cazorla et. al.	Sener	Issue 2 rev. 2	07/04/2006
[RD.17]	H-P-4-SEN-TN-0017	Planck Attitude Determination Design Simulations Report		
	A. Agenjo et. al.	Sener	Issue 1 rev. 0	01/01/2003
[RD.18]	H-P-4-DS-MA-001	ACMS User Manual		
	ACMS Team	Dutch Space	Issue 4.4	12/02/2009

1.5. Acronym List

ACA: Attitude Control Axes reference system
ACC: Attitude Control Computer
ACMS: Attitude Control and Measurement System
AD: Applicable Document
AHF: Attitude History File
AHFG: Attitude History File Generation Task in FDS
APPL: Augmented Planned Pointing List
APF: Attitude Parameter File
ASCII: American Standard Code for Information Interchange
ASTR: Autonomous Star Tracker
ASW: Application Software

CCD: Charge Coupled Device
CPU: Central Processing Unit
CPV: Commissioning and Performance Verification Phase

DCM: Direction Cosine Matrix
DPC: Data Processing Centre

ED: Event Designator
ESA: European Space Agency
ESAC: European Space Astronomy Centre (ESAC)
ESOC: European Space Operations Centre (ESA)

FDD: Flight Dynamics Division (at ESOC)
FDS: Flight Dynamics System
FDWS: Flight Dynamics Workstation
FM: Flight Model
FOV: Field Of View
FTS: File Transfer System

HCM: Angular Momentum Control Mode
HF: History File
HFI: High Frequency Instrument
HK: Housekeeping Telemetry Packet

ICD: Interface Control Document

LEOP: Launch and Early Operations Phase
LFI: Low Frequency Instrument

MCS:	Mission Control System
MIRD:	Mission Implementation Requirements Document
MOC:	Mission Operations Centre
MP:	Mission Planning
OAD:	Orbit and Attitude Division (Old acronym for FDD)
OBT:	On-Board Time
OCM:	Orbit Control Mode
OD:	Operational Day
ORATOS:	ORbit and ATtitude Operating System
POS:	Preferred Observation Schedule
PPL:	Planned Pointing List
PSF:	Planning Skeleton File
PSO:	Planck Science Office
QR:	Qualification Review
RD:	Reference Document
SCM:	Science Mode
SPACON:	Spacecraft Controller
SVT:	System Validation Test
TBC:	To be confirmed
TBD:	To be done
TM:	Telemetry
UTC:	Universal Time Coordinated

2. Operational Assumptions and Constraints

2.1. Communications

TBD

2.2. Hardware

TBD

2.3. Software

TBD

2.4. User

Initiation of traffic on this interface is available only to authorised users of the FDS. Access restrictions apply.

2.5. Timing

TBD

3. Requirements

3.1. Functional Requirements

The functional requirements in terms of data delivery are covered in [AD.2] and [AD.5][1].

These requirements can be summarised as follows:-

PGS-IR-4.1-310 The MOC shall make available to DPCs and PSO the Spacecraft Attitude data corresponding to the given operational period.

The DPCs will use this data for scientific data reduction and for calibration on top of the raw attitude data included in the S/C HK TM. The S/C attitude history will allow to reconstitute the pointing of the S/C at any given time of the operational period. The DPCs will have to reconstruct the detector LOS pointing from the S/C attitude data, the PSO will use the data to assess survey status.

PGS-IR-4.1-315 The MOC shall make available to DPCs and the PSO the reconstituted pointing information:-

- the positions on the sky of the three axes bound to the ACMS system (ASTR) every second (quaternions or equivalent information). The accuracy of this information must comply with the requirements (and hopefully the goals) stated in the SRS document
- For each circle (i.e. nominally a 60 second observation period), the spin axis position on the sky and spin velocity averaged over this circle plus the spin phase.
- For each ring (i.e. nominally a 3600 second observation period), the spin axis position on the sky, spin velocity and nutation parameters averaged over this ring
- Any information the MOC will have that might help the DPCs in assessing the quality of the above information.

The attitude history file shall contain high frequency data for slews, post slew and stable pointing periods at a maximum frequency of one record every 0.25 seconds. It shall also contain data averaged over a spin period and data averaged over an observation period. For the spin period and observation period, the information used to construct these data records shall be restricted to stable pointing periods.

PGS-IR-4.1-320 The MOC shall make available to DPCs when available an up-to-date time dependent model of the spacecraft inertial properties.

3.2. On-Line Delivery Requirements

The AHF delivery from MOC to PSO and DPCs (via the FTS) is initiated from the FDS, at most 8 hours after the end of the current operational day.

1. The updates of [AD.5] are pending.

3.3. *Off-Line Delivery Requirements*

N/A.

3.4. *Performance Requirements*

The performance requirements in terms of data quality are covered in [AD.2] and [AD.5].

These requirements can be summarised as follows:-

PGS-IR-4.1-350 The reconstructed accuracy shall be consistent with the pointing requirements in the System requirements specification

PGS-IR-4.1-355 The MOC shall make updates of the complete mission attitude history data as justified by incremental knowledge of inertial satellite behaviour

4. Interface Characteristics

4.1. Interface Location and Medium

The FDS and MCS are both components of the Planck Mission Operation Centre (MOC) based at ESOC, Darmstadt (D).

The Planck Science Office (PSO) is based at ESAC, Villafranca (E).

There are two Planck Data Processing Centres (DPCs), one for LFI which is located in Trieste (I) and the other one for HFI, which is located in Paris (F).

Details are given in [AD.4]

4.2. Hardware Characteristics and Limitations

Details are given in [AD.4]

4.3. Data Source, Destination and Transfer Mechanism

The attitude history file and the associated products are generated and recorded on the FDS. They are transferred to the PSO and DPCs via the FTS.

Details of the transfer mechanism are given in [AD.4]

4.4. Node and Device Addressing

See table 5.3-2 of [AD.4].

4.5. Relationship with other Interfaces

Detailed interfaces, describing the format and content of the following types of files that are passed during mission planning, are covered elsewhere in the following documents:

- Planning Skeleton File (PSF). (See [RD.6])
- Planned Pointing List (PPL). (See [RD.7])
- Augmented Preprogrammed Pointing List/Attitude Parameter File (APPL/APF). (See [RD.8])
- Time Correlator. (See [RD.10])

5. Access

5.1. Programs Using the Interface Data

Using the Attitude History File and Instrument alignment matrices

- PSO will monitor execution of pointings and monitor sky coverage progress
- DPC will perform instrument attitude reconstruction

5.2. Failure Protection, Detection and Recovery Procedures

TBD

5.3. File Naming Conventions

The AHF name and extension will take the form:

`dddd_vvvv.AHF`

where:

- **AHF** is the three character designator for every attitude history file
- **dddd** is the four digit operational day number in the range
  0001 ≤ rrrr ≤ 9999
- **vvvv** is the four digit FDS-specific version number in the range
  0001 ≤ nnnn ≤ 9999
- the separating character "_" is explicitly part of the name

Note: **dddd** and **vvvv** always contain leading zeros.

Prior to file transfer using FTS, the AHF will be gzipped and the name of the resulting file will be:

`dddd_vvvv.AHF.gz`

The gzipped AHF will be put into a wrapper file. The name and extension of the wrapper file will follow the convention given in [AD.4] and is given as follows.

Table 1: FTS wrapper file specification for AHF

01234567890123456789012345678901234567
AHF__FDSPGT_D_dddd_vvvv_____nnnnn.PLAN

where:

- **nnnnn** is the wrapper version number (integer in the range 00000 to 99999) under the control of the FTS

5.4. Storage and File Deletion Requirements

No requirements on physical storage (e.g. tape racks, etc.) are associated with this interface.

5.5. Security Requirements

N/A

5.6. Data Integrity Checks

TBD

5.7. Backup Requirements

All AHFs which are transferred to the PSO and DPCs will be archived by the FDS.

5.8. Input/Output Protocols, Calling Sequences

TBD

5.9. Synchronisation Requirements

5.9.1. Timing and Sequencing Characteristics

Data file transfers are initiated automatically. One AHF per operational day will be transferred from the MOC to the PSO and DPCs via the FTS

5.9.2. Attitude History File

The notification of the AHF to the FTS (for transfer to the PSO and DPCs) is initiated from the FDS, at most 8 hours after the end of the current operational day.

5.9.3. Effective Duration

Provided all relevant systems for a particular transfer are operational (PSO, DPCs, FTS, FDS): neither the SW of a system involved in the transfer nor the network load shall prevent the transfer of a file from being able to complete within 2 (desirable) to 15 (mandatory) minutes from initiation to receipt at its final destination. See also chapter on FTS.

5.9.4. Priority Interrupts

The priorities of data file transfers shall be such that the time constraints above can be met.

5.10. Error Handling

TBD

6. Detailed Interface Specifications

6.1. Data Structure

ISO (Unix) format ASCII file

6.2. Generation Method

One AHF per operational day will be generated by the attitude determination and attitude history file generation subsystem of the PLANCK FDS.

Note: A planning period always covers the time interval from one operational day to the next. In line with the established ESA terminology this time is consistently referred to in this document as a "Operational Day".

6.3. Data Passed Across the Interface & Transfer Direction

Data file transfers are initiated automatically. One AHF per operational day will be transferred from the MOC to the PSO and DPCs via the FTS. The notification of the AHF to the FTS (for transfer to the PSO and DPCs) is initiated from the FDS, at most 8 hours after DTCP.

6.4. Size and Frequency of Transfers

On any given system it is assumed that the following resources will be needed in order to maintain an adequate and convenient attitude history file:

File type	Typical size (per file)	Max. number of coexisting files	Disk space
AHF	149.0 MB	10	1.490 GB
gzipped AHF	31.4 MB	10	0.314 GB

"Maximum number of coexisting files" refers to the maximum number of gzipped files which must be capable of coexisting on the source and target systems. In other words, the respective system must be capable of hosting this number of files - this does not prohibit that at any given time more or fewer files might actually be present on a given system.

The above figures are based on the possibility of having to provide attitude entries over the period of a 24 hour operational day for the following cases [1]:-

- one header record
- one record every 0.125 second. (i.e. 691200 records)
- one record every spin period (i.e. 1440 records)
- one record every observation period[2] (i.e. 48 records)

1. See chapter on data definition
2. Assuming the minimum obervation period (dwell time) of 30 minutes.

7. Data Definition (Files)

7.1. File Characteristics

The AHF will consist of one header followed by several data records. These records will be time ordered according to Item 4 in the data records.

All records will be 215 bytes long and in ISO (Unix) format ASCII file.

Attitude information will be expressed with respect to the mean ecliptic reference system of Equinox J2000.0.

In what follows the conventions listed below apply:

- record numbering starts at record 1
- offsets are defined in terms of 8-bit words, starting at offset 0
- item "types" are defined in terms of standard FORTRAN FORMAT edit descriptors
- Unless otherwise indicated, all times are expressed in the A12 form:
  - 6 byte OBT in Hexadecimal representation

7.2. Header Records

The header record is the first record in the file. It will contain the following items:

Table 2: AHF Header Record Structure

Item	Offset	Note	Type	Description
1	0	[1]	A20,1X	Start time of interval covered by this file
2	21	[1]	A20,1X	End time of interval covered by this file
3	42	[1]	A20,1X	PSF start time
4	63	[1]	A20,1X	PSF stop time
5	84	[1]	A20,1X	Time of generation of this file
6	105		I4.4,1X	Operational day number
7	110		I6,1X	Number of records in this file (including this one)
8	117		I4.4,1X	AHF version number
9	122		A5,1X	AHF SW version number
10	128		A87	Space reserved for comments

Notes:

[1] All header times are expressed in the A20 form yyyy-mm-ddThh:mm:ssZ

7.3. Data Records

In order to provide attitude information in a single and self contained interface file, it is proposed that the Planck AHF contains 3 different data record structures that are chronologically ordered and therefore interlaced. This is mainly due to the requirement PGS-IR-4.1-315. The relevant data record structure can be identified via a dedicated field.

The different data structures are identified as follows:-

- high frequency data (0.25 seconds (HCM,OCM) and 0.125 seconds for (SCM))
- spin frequency data (nominally 60 second = 1 revolution)
- observation frequency data (between 30 and 60 minutes)

In what follows, the 'notes' listed in each table are collected together in Section 7.3.5.

Data records start with record number 2. They will contain the items listed in the following subsections. Figure 1 shows graphically the organisation and contents of the various AHF data records described previously. Figures 2, 3 and 4 show how the AHF processing intervals are defined as a function of the various mission phases.

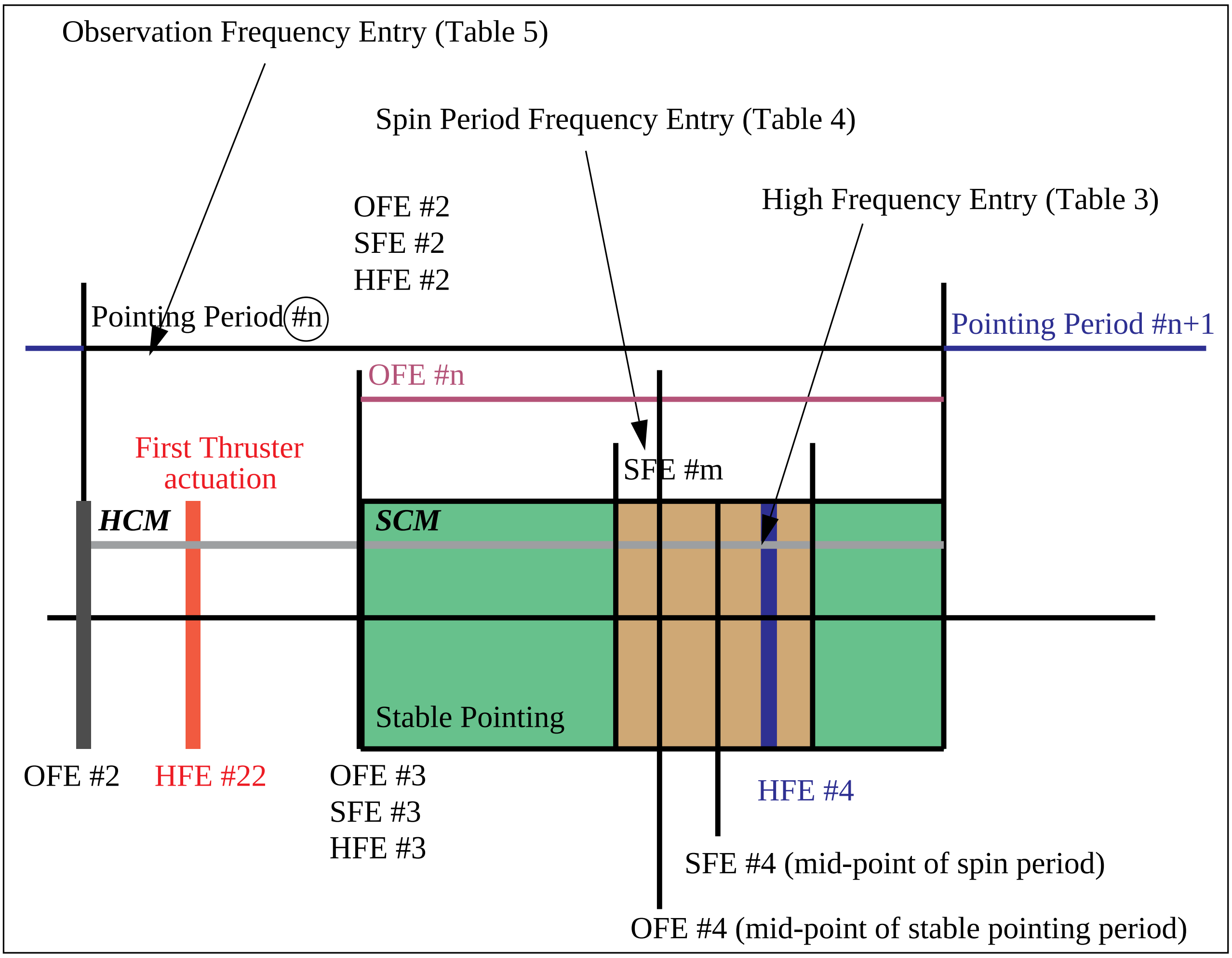


Figure 1: Graphical representation and description of the various AHF records

Figure 2: CPV Phase AHF records organisation (20 hour pointings)

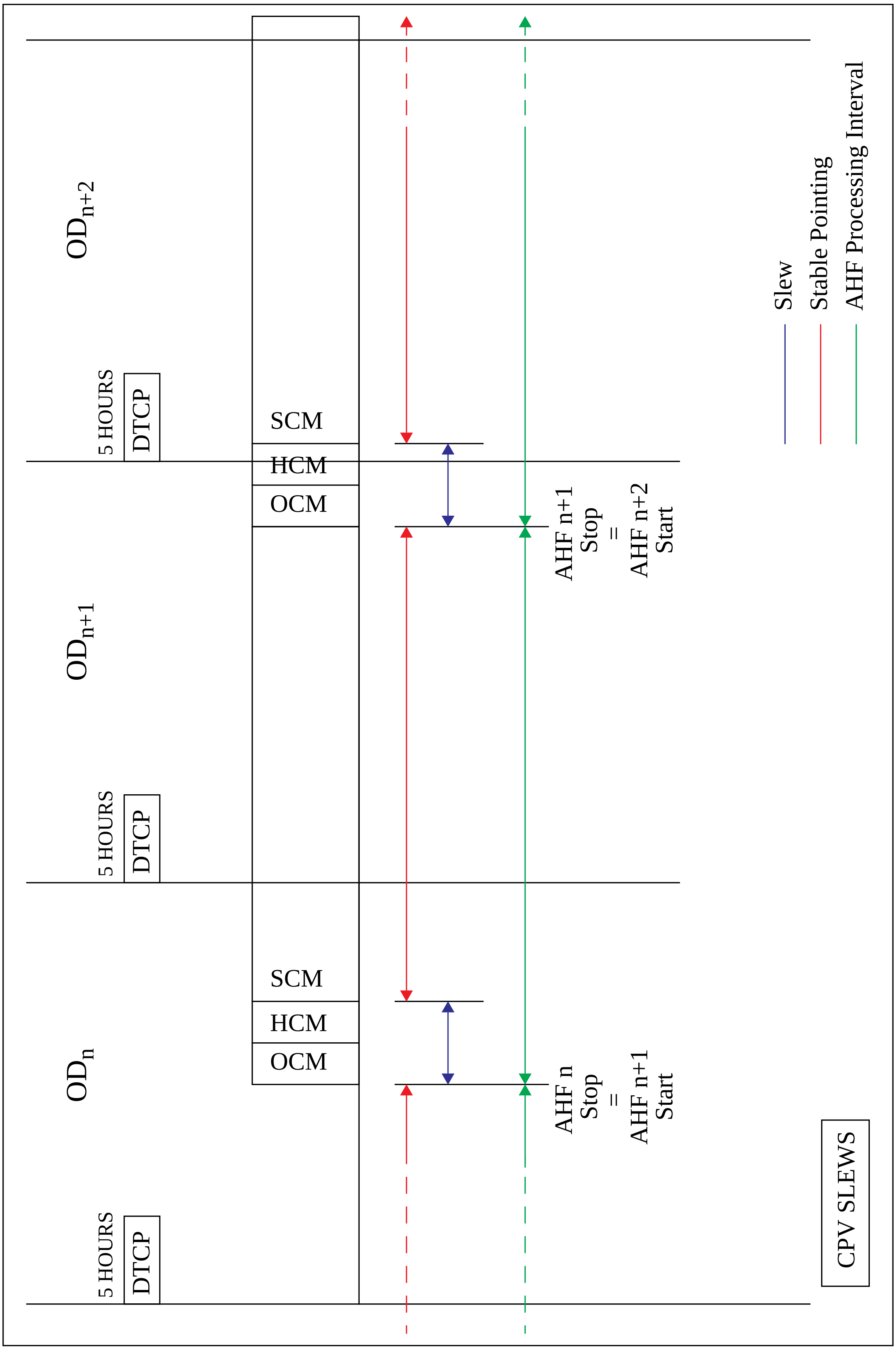


Figure 3: Routine Phase AHF records organisation (30-70 minute pointings)

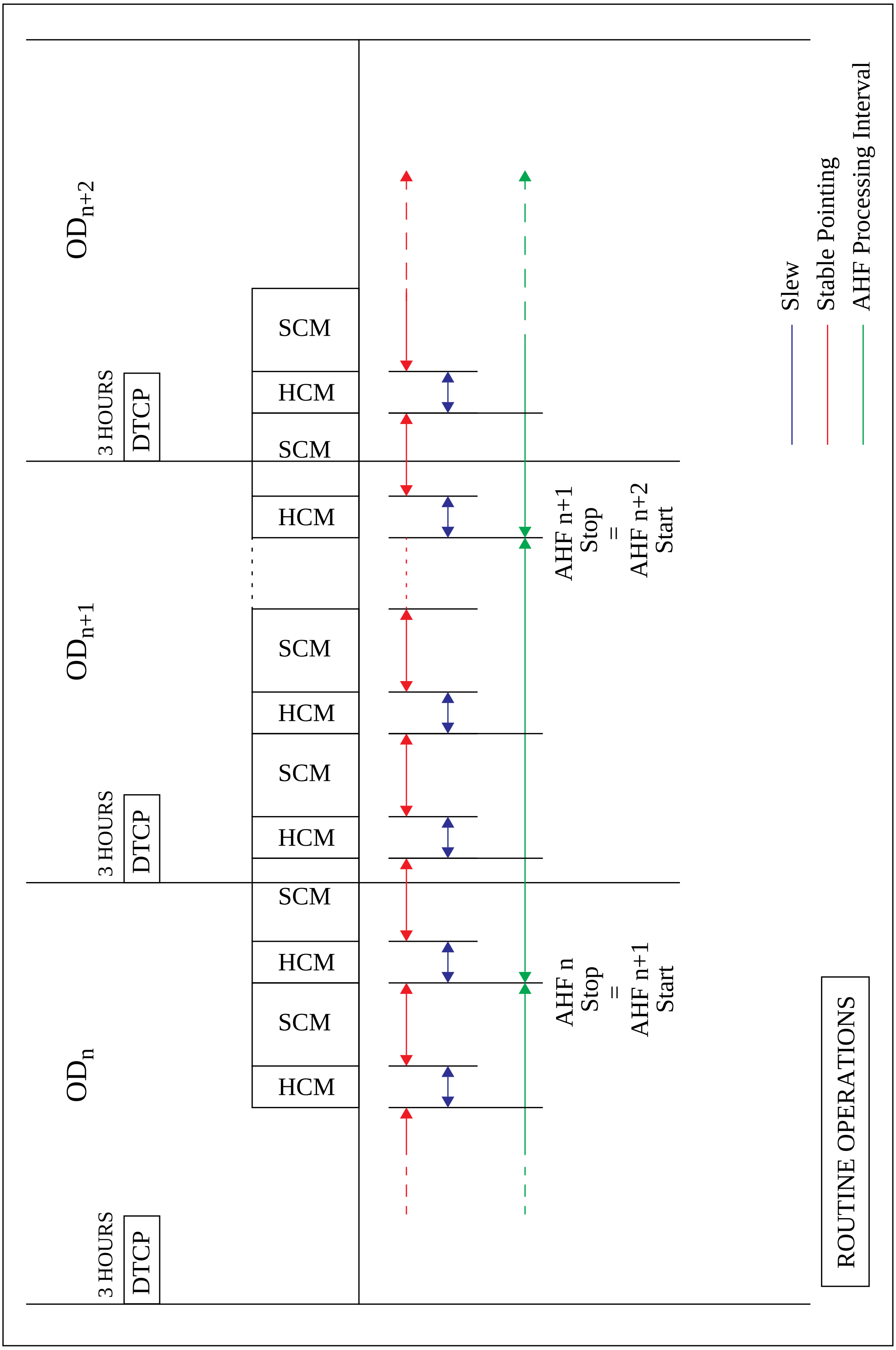
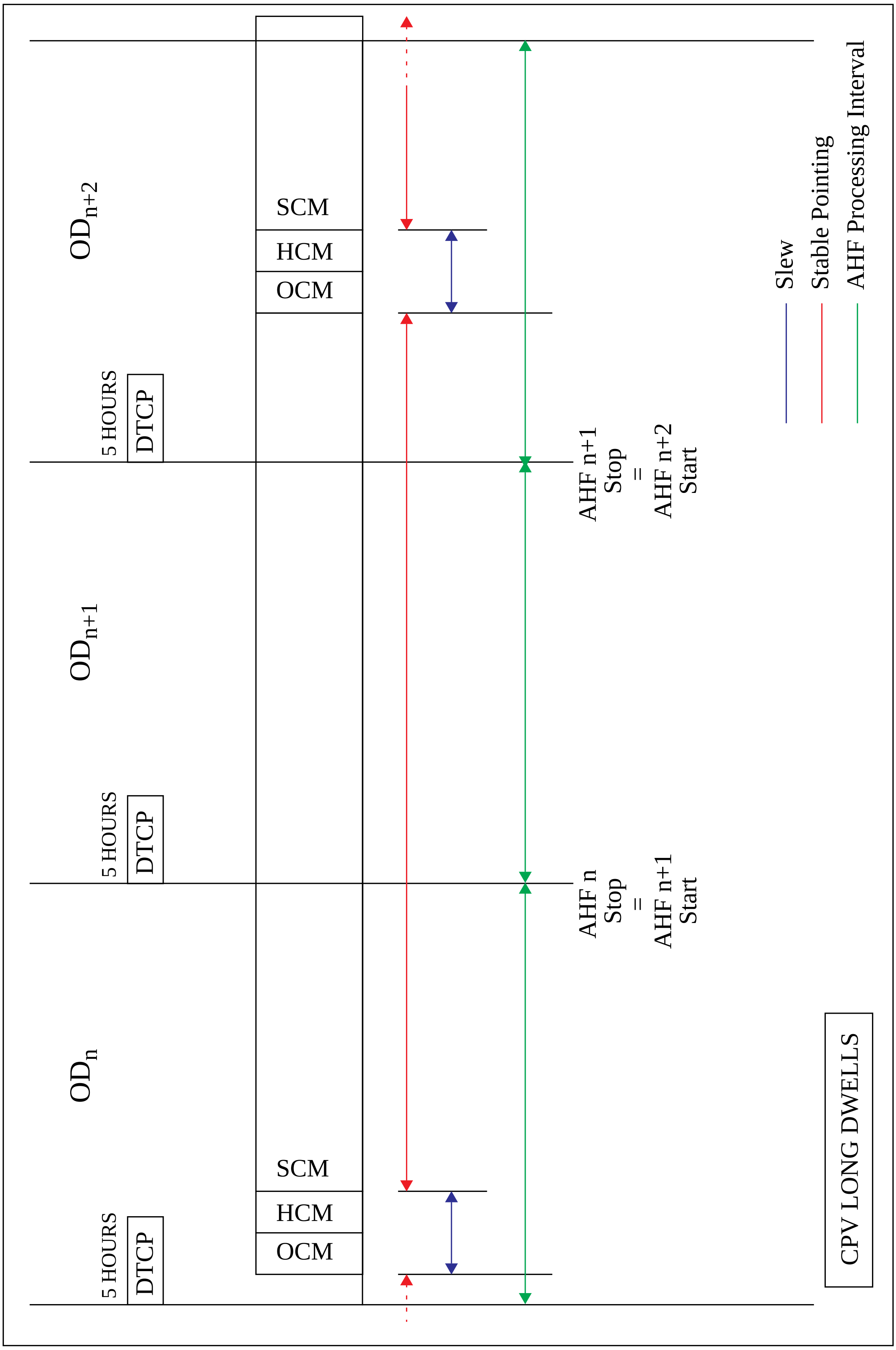


Figure 4: CPV Phase (Long Dwells) AHF records organisation (48 hour pointings)



7.3.1. Attitude History Background

The attitude history will cater for 3 distinct “phases” which are identified in the following table. This does not include contingencies where the spacecraft has entered into survival mode. This is also the case in the event or telemetry gaps or that the ASTR has lost it’s inertial reference. In such cases, where attitude data from the ASTR is unavailable, there are no reliable means for attitude data replacement.

	Phase	**Description**
I	Slew[1]	For spin axis reorientation manoeuvres, attitude entries in the AHF will be an average of two 8 Hz samples of the attitude quaternion provided by the ASTR[2] during the manoeuvre. This data is provided in the Planck ACC HCM mode HK telemetry (See [RD.11]). The time resolution of AHF entries generated will be 0.25 seconds.
II	Post slew and Stable pointing[3]	There will be several entries with different record structures in the AHF for a nominal stable pointing period. High frequency attitude entries in the AHF will be the result of the on-ground filtered attitude determination algorithm, which processes the raw attitude quaternion[4] provided by the ASTR[2] (See [RD.16] and [RD.18]). The time resolution for AHF entries will be 0.125 seconds Attitude data for post slew and stable pointings is also provided containing information averaged over a spin cycle (nominally 60 seconds) and over an observation (dwell) period. This phase covers the period up to the start of operations to conduct the manoeuvre to the next planned attitude.
III	Orbit Control	For orbit control manoeuvres, attitude entries in the AHF will be an average of two 8 Hz samples of the attitude quaternion provided by the ASTR[2] during the manoeuvre. This data is provided in the Planck ACC OCM mode HK telemetry (See [RD.11]). The time resolution of AHF entries generated will be 0.25 seconds.

1. This phase also includes the period of settling from the time when the spin axis reorientation manoeuvre is completed up until to the entry into SCM.
2. This assumes nominal ASTR function in autonomous tracking and fine attitude determination submode (ATFAD). See [RD.12] and [RD.13].
3. From the time when the spin axis reorientation manoeuvre is completed + margin (seconds)
4. Science mode TM for Planck contains the raw ASTR attitude quaternion at 8 Hz. A quality index computed based on catalogued and measured star positions will be used to check the ‘quality’ of the ASTR measurements and is also provided at 8 Hz.

There are, in addition, several important points listed as follows:-

1. The cutoff frequency of the filter will be fixed for the mission. Currently this is set to one decade above maximum body nutation frequency.
2. A batch of data that requires filtering shall comprise an integer multiple of half nutation periods.
3. For dwell periods longer than scanning law pointing durations (max. 70 mins), data will be filtered in batches. Batch durations will be selected such that they contain an integer multiple of half nutation periods.
4. In the case of data gaps, a single data gap will define 2 batches that need to be filtered. These batches will comprise an integer multiple of half nutation periods.

7.3.2. High frequency data record structure

The data contained in this record is the raw attitude data from the ASTR when the spacecraft is in HCM or OCM, provided at 4 Hz. In SCM, the ASTR raw attitude data is provided at a frequency of 8 Hz, which is further filtered on-ground (See ref. [RD.16]). Detailed contents of this record are shown in Table 3. The idea is to transfer information from the following sources in a single record:-

1. Mission planning information
2. Reconstituted attitude and spin rate information
3. Useful ASTR housekeeping data
4. Other Derived information

7.3.3. Spin period frequency data record structure

The data contained in this record is derived from high frequency records when the spacecraft is in SCM. This data is averaged over a complete spin period[1], where the spin period is computed from the average spin rate over the complete observation duration. The validity time for these records corresponds to the mid-point time stamp of the high frequency data records used to compute the spin averaged record. Detailed contents of this record are shown in Table 4. The idea is to transfer information from the following sources in a single record:-

1. Mission planning information
2. Reconstituted attitute and spin rate information averaged over a spin period
3. Other Derived information

7.3.4. Observation frequency data record structure

The data contained in this record is averaged over a complete observation period, which is nominally 30 to 70[2] minutes. The validity time for these records corresponds to the mid-point time stamp of the high frequency data records used to compute the observation averaged record. Detailed contents of this record are shown in Table 5. The idea is to transfer information from the following sources in a single record:-

1. Mission planning information
2. Reconstituted attitute and spin rate information averaged over an oberserva-tion period

Other derived information regarding the dynamical properties of the spacecraft. (See Annex A.3 for handling of these data)

1. Nominally 60 seconds, which may change during the performance verification phase
2. This duration is the time between the start of 2 subsequent HCM manoeuvres

Table 3: AHF Data Record Structure (high frequency entries)

Item	Offset	Note	Type	Description
1	0	[1]	A1,1X	Data structure type identifer
2	2	[2]	A8,1X	Pointing-request-identifier for the data in this record
3	11	[3],[12]	A12,1X	Start time of the stable-pointing period
4	24	[3]	A12,1X	Time for which the data in this record are valid
5	37	[4]	A1,1X	Spacecraft ACMS mode identifier
6	39	[5]	F10.7,1X	Quaternion vector X component
7	50	[5]	F10.7,1X	Quaternion vector Y component
8	61	[5]	F10.7,1X	Quaternion vector Z component
9	72	[5]	F10.7,1X	Quaternion vector S component
10	83	[6]	F8.4,1X	Ecliptic longitude of angular momentum vector
11	92	[7]	F8.4,1X	Ecliptic latitude of angular momentum vector
12	101	[8]	F8.4,1X	Spin phase angle
13	110	[9]	F10.6,1X	Spin rate
14	121	[10]	F5.1,1X	Solar aspect angle
15	127	[11]	F8.4,1X	Difference between reconstituted and commanded angular momentum vector ecliptic longitude
16	136	[11]	F8.4,1X	Difference between reconstituted and commanded angular momentum vector ecliptic latitude
17	145	[18]	F8.4,1X	Principal axis tilt (Wobble) angle ψ_1
18	154	[18]	F8.4,1X	Principal axis tilt (Wobble) angle ψ_2
19	163	[20]	F8.4,1X	Nutation angle θ
20	172	[21]	F8.4,1X	Body nutation phase angle ϕ_n
21	181	[21]	F8.4,1X	Inertial nutation phase angle ψ_n
22	190	[3],[13]	A12,1X	Time of first thruster actuation following mode transition into HCM
23	203	[14]	A1,1X	ASTR or propagated attitude flag
24	205	[15]	F7.2,1X	ASTR Quality index
25	213	[16]	A2	Attitude data filtering batch number

Table 4: AHF Data Record Structure (spin period frequency entries)

Item	Offset	Note	Type	Description
1	0	[1]	A1,1X	Data structure type identifer
2	2	[2]	A8,1X	Pointing-request-identifier for the data in this record
3	11	[3],[12]	A12,1X	Start time of the stable-pointing period
4	24	[3]	A12,1X	Time for which the data in this record are valid
5	37	[6]	F8.4,1X	Ecliptic longitude of angular momentum vector
6	46	[7]	F8.4,1X	Ecliptic latitude of angular momentum vector
7	55	[8]	F8.4,1X	Spin phase angle
8	64	[9]	F10.6,1X	Spin rate
9	75	[10]	F5.1,1X	Solar aspect angle
10	81	[11]	F8.4,1X	Difference between reconstituted and commanded angular momentum vector ecliptic longitude
11	90	[11]	F8.4,1X	Difference between reconstituted and commanded angular momentum vector ecliptic latitude
12	99	[18]	F8.4,1X	Principal axis tilt (Wobble) angle ψ_1
13	108	[18]	F8.4,1X	Principal axis tilt (Wobble) angle ψ_2
14	117	[20]	F8.4,1X	Nutation angle θ
15	126	[21]	F8.4,1X	Body nutation phase angle ϕ_n
16	135	[21]	F8.4,1X	Inertial nutation phase angle ψ_n
17	144		A71	Blank record

Table 5: AHF Data Record Structure (observation frequency entries)

Item	Offset	Note	Type	Description
1	0	[1]	A1,1X	Data structure type identifer
2	2	[2]	A8,1X	Pointing-request-identifier for the data in this record
3	11	[3],[12]	A12,1X	Start time of the stable-pointing period
4	24	[3]	A12,1X	Time for which the data in this record are valid
5	37	[6]	F8.4,1X	Ecliptic longitude of angular momentum vector
6	46	[7]	F8.4,1X	Ecliptic latitude of angular momentum vector
7	55	[8]	F8.4,1X	Spin phase angle
8	64	[9]	F10.6,1X	Spin rate
9	75	[10]	F5.1,1X	Solar aspect angle
10	81	[11]	F8.4,1X	Difference between reconstituted and commanded angular momentum vector ecliptic longitude
11	90	[11]	F8.4,1X	Difference between reconstituted and commanded angular momentum vector ecliptic latitude
12	99	[18]	F8.4,1X	Principal axis tilt (Wobble) angle ψ_1
13	108	[18]	F8.4,1X	Principal axis tilt (Wobble) angle ψ_2
14	117	[20]	F8.4,1X	Nutation angle θ
15	126	[21]	F8.4,1X	Body nutation phase angle ϕ_n
16	135	[21]	F8.4,1X	Inertial nutation phase angle ψ_n
17	144	[17]	F8.1,1X	Observation duration
18	153	[22]	F10.6,1X	Nutation to spin rate ratio (ω_n/ω_s)
19	164	[22]	F10.6,1X	Imbalance (Δ)
20	175	[19]	F8.4,1X	Principal axis Azimuth angle ψ_3
21	184	[20]	F10.2,1X	Nutation damping time constant τ_n
22	195	[23]	F10.4,1X	X-axis principal moment of inertia, I_X
23	206		A9	Blank record

7.3.5. Notes

Refer also to §7.3.1, regarding the sequence of events.

[1] Data Structure Type identifier
This is intended as a means for the user to identify which record structure to apply in order to extract the data;

H for high frequency data[1]
M spin frequency data (nominally 60 seconds)
L observation frequency data (between 30 and 60 minutes)

[2] Pointing-request identifier
This is intended as a flexible means of associating several records within the AHF with each other - it has the form NNNNNNNN. It is conceived as a means of keeping the AHF as generic as reasonably possible and it is used as follows:
This identifier will be an echo of the pointing ID to be found in the APPL ICD ([RD.8]).

The reconstructed attitude data during a slew will be associated with each other by having the same unique pointing-request identifier as that given in the PPL.

MOC created pointings shall have a unique pointing ID with the format 9NNNNNNN which is a number created by MOC associated with the particular observation.

[3] See §7.1 regarding the time format

[4] Current ACMS mode identifier. Format (A1).

H for angular momentum control mode : HCM
S for science mode : SCM
O for orbit control mode : OCM

[5] The quaternion describes at a given time (expressed as a 6 byte OBT), the orientation of the PLANCK body reference frame (This reference system is defined in Annex A.1.4) with respect to the Ecliptic inertial reference system. The components of the quaternion are in the range [-1,+1]. In order to have an angular resolution of 0.00001°, the format needs to be at least (F10.7). The quaternion will be filtered using the ground processing algorithm described in [RD.16]. Note that the quaternion must be renormalised prior to use by the user in any coordinate transformation work.

[6] Ecliptic longitudes in the AHF are expressed in decimal degrees. Format (F8.4) range is [0°, 360°[.

[7] Ecliptic latitudes in the AHF are expressed in decimal degrees. Format (F8.4) range is [-90°, 90°].

1. Data interval for SCM is 0.125 seconds and 0.25 seconds for HCM/OCM

[8] Spin Phase in the AHF are expressed in decimal degrees. See Annexes A.1.2, A.2.2 and A.3.8 for definition of the zero point and method to compute the spin phase. Format (F8.4) range is [0°, 360°[.

[9] Spin rate in the AHF is expressed in decimal degrees/second. Format (F10.6).

[10] Angle between the angular momentum vector and the sun direction is expressed in decimal degrees. Format (F5.1) range is [0°, 180°[.

[11] Angular differences between target and estimated attitude are expressed in decimal degrees. Format (F8.4) range is]-100°,+100°[.

[12] Start time of observation as per the start time of the entry into SCM. This entry is constant for all entries in the AHF corresponding to the initial slew, post-slew and stable pointing periods after a slew (see 7.3.1.).

[13] Time of first thruster actuation after mode transition into HCM. This entry is constant for all entries in the AHF corresponding to the initial slew, post-slew and stable pointing periods after a slew (see 7.3.1.).

[14] In the case where the ASTR has temporarily lost it's inertial reference, the attitude will be propagated based on a model of the spacecraft dynamics within the ACC software. The attitude data source flag is set to 1 when the attitude is derived via the ASTR quaternion and 0 when the attitude is propagated using a model of the spacecraft dynamics. Format (A1).

[15] The measured and identified catalogued star positions are used to derive, within the on-board software of the ASTR a 'quality index' related to the attitude solution provided by the ASTR. This represents a weighted sum of the on-diagonal elements of the covariance matrix also computed with the ASTR software (See pp182-183 of [RD.14]). The quality index will be used to derive this weighted sum expressed in arcsec. Format (F7.2).

[16] Batch number associated to a set of sampled quaternions that are filtered. For OCM and HCM records this is set to zero. For SCM records this is incremented by 1 and starts at 01. Format (A2) range is [00,99].

[17] The observation duration is defined as the amount of stable pointing data processed in order to produce this AHF entry. It will be the dwell duration after completion of a slew manoeuvre using the HCM mode. Format (F8.1) and expressed in seconds.

[18] For the observation period record, the Principal axis tilt angles[1] represent the average value over the observation period. For the spin averaged records it refers to the average value over the spin period and for the high frequency records, it corresponds to the batch filtered instantaneous values. See also Annexes A.1 and A.3. Format (F8.4) range is]-100, 100[arcmin.

1. ψ_1 is the rotation around the body z-axis and ψ_2 is the rotation around the new body y-axis. For small rotations the order of the rotations ψ_1 and ψ_2 is interchangeable.

[19] Principal axis azimuth angle[1] is expected to remain constant over an observation period. See also Annexes A.1 and A.3. Format (F8.4) range is [0°, 360°[.

[20] For the observation period record, the nutation angle refers to the maximum nutation at the start of the stable pointing period. Due to energy dissipation, this will decay throughout the period of the observation according to the nutation damping time constant[2]. For the spin averaged records it refers to the nutation level at the record validity time and for the high frequency records, it corresponds to the batch filtered instantaneous values. See also Annexes A.1 and A.3. Format (F8.4) range is [0, 1000[arcmin.

[21] The inertial and body nutation phase angles are only valid in the presence of nutation. In the case of zero nutation, the sum of these quantities without a 2π radian wrap around or identically the spin phase should be used in the construction of the coordinate transformations. See also Annexes A.1 and A.3. Format (F8.4) range is [0°, 360°[.

[22] The nutation to spin rate ratio and dynamic imbalance are derived where possible from independant ACMS calibration phases. These records will remain constant in between these ACMS calibration phases. Format (F10.6).

[23] Principal moment of inertia about the X-axis. Format (F10.4).

7.4. *File Example*

The example shows parts of an attitude history file that is representative from an orbit and attitude point of view and has been derived from SOVT-1 OD 126. The file contains data processed from the execution of all slews and stable pointings.

1. ψ_3 is the rotation around the new body x-axis, after the successive rotations ψ_1 about the body z-axis and ψ_2 about the new body y axis.
2. This is defined to be the rate of change of the nutation amplitude during one observation period.

```
2008-12-03T12:30:49Z 2008-12-04T11:59:54Z 2008-12-03T12:00:00Z 2008-12-04T12:00:00Z 2008-12-17T11:56:49Z 0126 645360 0005    1.0
H 09170180 5FC8E00DA142 5FC8DA79712F H  0.5671104  0.4140755 -0.4216767 -0.5736863  72.5045  -0.1839 183.8416   6.036842 179.2   5.1769  -4.2890  -5.6556  -0.5634   3.3362 184.7593 359.0823 5FC8DAACE14F 1    0.74 00
H 09170180 5FC8E00DA142 5FC8DA79B130 H  0.5594939  0.4084854 -0.4271157 -0.5811010  72.5921  -0.1908 185.3527   6.042546 179.2   5.0893  -4.2821  -5.6556  -0.5634   1.8431  20.0026 165.3501 5FC8DAACE14F 1    0.52 00
H 09170180 5FC8E00DA142 5FC8DA79F12D H  0.5517852  0.4028344 -0.4324733 -0.5884083  72.5757  -0.1800 186.8618   6.038038 179.2   5.1057  -4.2929  -5.6556  -0.5634   0.6555   3.1549 183.7069 5FC8DAACE14F 1    0.74 00
H 09170180 5FC8E00DA142 5FC8DA7A312F H  0.5439761  0.3971121 -0.4377578 -0.5956174  72.5720  -0.1753 188.3718   6.039119 179.2   5.1094  -4.2976  -5.6556  -0.5634   0.3323 337.6978 210.6740 5FC8DAACE14F 1    0.68 00
H 09170180 5FC8E00DA142 5FC8DA7A712F H  0.5360677  0.3913276 -0.4429592 -0.6027282  72.5310  -0.1750 189.8816   6.039710 179.2   5.1504  -4.2979  -5.6556  -0.5634   2.3121 188.5250   1.3566 5FC8DAACE14F 1    0.50 00
H 09170180 5FC8E00DA142 5FC8DA7AB130 H  0.5280724  0.3854669 -0.4480911 -0.6097287  72.5830  -0.1725 191.3916   6.038959 179.2   5.0984  -4.3004  -5.6556  -0.5634   0.6842  16.0205 175.3712 5FC8DAACE14F 1    0.79 00
H 09170180 5FC8E00DA142 5FC8DA7AF12F H  0.5199892  0.3795359 -0.4531489 -0.6166197  72.6111  -0.1672 192.9015   6.039583 179.2   5.0703  -4.3057  -5.6556  -0.5634   2.2383   8.7200 184.1815 5FC8DAACE14F 1    0.74 00
H 09170180 5FC8E00DA142 5FC8DA7B312F H  0.5118029  0.3735575 -0.4581073 -0.6234182  72.4921  -0.1810 194.4108   6.038682 179.2   5.1893  -4.2919  -5.6556  -0.5634   5.0987 183.0626  11.3482 5FC8DAACE14F 1    0.92 00
H 09170180 5FC8E00DA142 5FC8DA7B712F H  0.5035466  0.3674818 -0.4630230 -0.6300854  72.6973  -0.1439 195.9216   6.040954 179.2   4.9841  -4.3290  -5.6556  -0.5634   7.2714   5.8755 190.0461 5FC8DAACE14F 1    1.01 00
H 09170180 5FC8E00DA142 5FC8DA7BB130 H  0.4951875  0.3613673 -0.4678292 -0.6366623  72.5387  -0.1721 197.4311   6.039007 179.2   5.1427  -4.3008  -5.6556  -0.5634   2.5457 181.8091  15.6220 5FC8DAACE14F 1    1.08 00
H 09170180 5FC8E00DA142 5FC8DA7BF12F H  0.4867508  0.3551763 -0.4725705 -0.6431178  72.6292  -0.1495 198.9414   6.040921 179.2   5.0522  -4.3234  -5.6556  -0.5634   2.9082   7.6434 191.2981 5FC8DAACE14F 1    1.18 00
H 09170180 5FC8E00DA142 5FC8DA7C312F H  0.4782274  0.3489337 -0.4772174 -0.6494670  72.5755  -0.1632 200.4508   6.037998 179.2   5.1059  -4.3097  -5.6556  -0.5634   0.6466 155.7206  44.7302 5FC8DAACE14F 1    1.15 00
H 09170180 5FC8E00DA142 5FC8DA7C712F H  0.4696124  0.3426414 -0.4817698 -0.6557125  72.5053  -0.1725 201.9602   6.038333 179.2   5.1761  -4.3004  -5.6556  -0.5634   4.9184 185.9385  16.0217 5FC8DAACE14F 1    0.46 00
H 09170180 5FC8E00DA142 5FC8DA7CB130 H  0.4609223  0.3362695 -0.4862670 -0.6618292  72.6323  -0.1186 203.4710   6.041427 179.2   5.0491  -4.3543  -5.6556  -0.5634   3.2658 350.6480 212.8231 5FC8DAACE14F 1    0.68 00
H 09170180 5FC8E00DA142 5FC8DA7CF12D H  0.4521580  0.3298469 -0.4906647 -0.6678340  72.5967  -0.1510 204.9802   6.038121 179.2   5.0847  -4.3219  -5.6556  -0.5634   0.6453  58.7169 146.2632 5FC8DAACE14F 1    0.62 00
H 09170180 5FC8E00DA142 5FC8DA7D312F H  0.4433089  0.3233630 -0.4949828 -0.6737252  72.6035  -0.1375 206.4905   6.040431 179.2   5.0779  -4.3354  -5.6556  -0.5634   0.8933   8.3356 198.1549 5FC8DAACE14F 1    0.68 00
H 09170180 5FC8E00DA142 5FC8DA7D712F H  0.4343857  0.3168279 -0.4992132 -0.6794964  72.5984  -0.1282 208.0000   6.038147 179.2   5.0830  -4.3447  -5.6556  -0.5634   0.7855 332.4988 235.5012 5FC8DAACE14F 1    0.98 00
H 09170180 5FC8E00DA142 5FC8DA7DB130 H  0.4253852  0.3102310 -0.5033622 -0.6851501  72.6205  -0.1214 209.5103   6.040573 179.2   5.0609  -4.3515  -5.6556  -0.5634   1.9018   1.1503 208.3600 5FC8DAACE14F 1    0.97 00
H 09170180 5FC8E00DA142 5FC8DA7DF12D H  0.4163034  0.3036110 -0.5073793 -0.6907084  72.4369  -0.2147 211.0185   6.035939 179.2   5.2445  -4.2582  -5.6556  -0.5634  10.6088 181.6995  29.3190 5FC8DAACE14F 1    0.78 00
H 09170180 5FC8E00DA142 5FC8DA7E312F H  0.4071609  0.2968993 -0.5113653 -0.6961152  72.6770  -0.0828 212.5296   6.041323 179.2   5.0044  -4.3901  -5.6556  -0.5634   5.6816   4.4641 208.0655 5FC8DAACE14F 1    0.70 00
.
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H 09170180 5FC8E00DA142 5FC8E02EA142 S -0.5523761 -0.4782676 -0.4061470 -0.5488035  77.6841  -4.4681   6.9416   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0697  10.6675 356.2741 5FC8DAACE14F 1    0.71 01
H 09170180 5FC8E00DA142 5FC8E02EC142 S -0.5559669 -0.4809130 -0.4029979 -0.5451753  77.6841  -4.4681   7.6928   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0692   9.4361 358.2567 5FC8DAACE14F 1    0.60 01
H 09170180 5FC8E00DA142 5FC8E02EE142 S -0.5595338 -0.4835378 -0.3998315 -0.5415237  77.6841  -4.4681   8.4440   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0687   8.1747   0.2693 5FC8DAACE14F 1    0.81 01
H 09170180 5FC8E00DA142 5FC8E02F0142 S -0.5630766 -0.4861417 -0.3966479 -0.5378489  77.6841  -4.4681   9.1951   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0682   6.8857   2.3095 5FC8DAACE14F 1    0.78 01
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H 09170180 5FC8E00DA142 5FC8E02F4142 S -0.5700896 -0.4912868 -0.3902297 -0.5304299  77.6841  -4.4681  10.6975   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0674   4.2348   6.4627 5FC8DAACE14F 1    0.72 01
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H 09170180 5FC8E00DA142 5FC8E02FA142 S -0.5804249 -0.4988459 -0.3804770 -0.5191310  77.6841  -4.4681  12.9511   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0664   0.1210  12.8301 5FC8DAACE14F 1    0.78 01
H 09170180 5FC8E00DA142 5FC8E02FC142 S -0.5838203 -0.5013228 -0.3771932 -0.5153199  77.6841  -4.4681  13.7023   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0661 358.7260  14.9763 5FC8DAACE14F 1    0.95 01
M 09170180 5FC8E00DA142 5FC8E02FD142  77.6841  -4.4681  14.0769    6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634    0.1052 352.7100  21.3669
H 09170180 5FC8E00DA142 5FC8E02FE142 S -0.5871906 -0.5037783 -0.3738932 -0.5114866  77.6841  -4.4681  14.4534   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0659 357.3249  17.1285 5FC8DAACE14F 1    0.65 01
H 09170180 5FC8E00DA142 5FC8E0300142 S -0.5905357 -0.5062120 -0.3705771 -0.5076314  77.6841  -4.4681  15.2046   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0657 355.9214  19.2833 5FC8DAACE14F 1    0.83 01
H 09170180 5FC8E00DA142 5FC8E0302142 S -0.5938554 -0.5086240 -0.3672451 -0.5037543  77.6841  -4.4681  15.9558   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0656 354.5190  21.4369 5FC8DAACE14F 1    0.99 01
H 09170180 5FC8E00DA142 5FC8E0304142 S -0.5971496 -0.5110142 -0.3638973 -0.4998556  77.6841  -4.4681  16.7070   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0655 353.1213  23.5857 5FC8DAACE14F 1    0.60 01
H 09170180 5FC8E00DA142 5FC8E0306142 S -0.6004181 -0.5133823 -0.3605339 -0.4959354  77.6841  -4.4681  17.4582   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0654 351.7319  25.7263 5FC8DAACE14F 1    0.65 01
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H 09170180 5FC8E00DA142 5FC8E030A142 S -0.6068776 -0.5180524 -0.3537607 -0.4880313  77.6841  -4.4681  18.9606   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0654 348.9917  29.9689 5FC8DAACE14F 1    0.63 01
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H 09170180 5FC8E00DA142 5FC8E030E142 S -0.6132328 -0.5226335 -0.3469267 -0.4800434  77.6841  -4.4681  20.4629   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0655 346.3244  34.1385 5FC8DAACE14F 1    1.01 01
H 09170180 5FC8E00DA142 5FC8E0310142 S -0.6163710 -0.5248903 -0.3434873 -0.4760183  77.6841  -4.4681  21.2141   6.008880 172.6  -0.0027  -0.0048  -5.6557  -0.5634   0.0656 345.0254  36.1887 5FC8DAACE14F 1    0.76 01
.
.
H 09170180 5FC8E00DA142 5FC8E3158142 S -0.6937459 -0.5334631  0.3295528  0.3543002  77.6836  -4.4684 150.8160   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1089 225.4940 285.3220 5FC8DAACE14F 1    0.62 01
H 09170180 5FC8E00DA142 5FC8E315A146 S -0.6914058 -0.5312949  0.3330500  0.3588334  77.6836  -4.4684 151.5671   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1089 225.4306 286.1365 5FC8DAACE14F 1    0.87 01
H 09170180 5FC8E00DA142 5FC8E315C142 S -0.6890359 -0.5291039  0.3365329  0.3633512  77.6836  -4.4684 152.3181   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1089 225.3692 286.9489 5FC8DAACE14F 1    0.76 01
H 09170180 5FC8E00DA142 5FC8E315E142 S -0.6866365 -0.5268902  0.3400014  0.3678533  77.6836  -4.4684 153.0692   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1089 225.3101 287.7591 5FC8DAACE14F 1    0.59 01
H 09170180 5FC8E00DA142 5FC8E3160142 S -0.6842075 -0.5246539  0.3434552  0.3723396  77.6836  -4.4684 153.8202   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1089 225.2534 288.5669 5FC8DAACE14F 1    0.86 01
H 09170180 5FC8E00DA142 5FC8E3162142 S -0.6817492 -0.5223950  0.3468943  0.3768100  77.6836  -4.4684 154.5713   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1088 225.1993 289.3719 5FC8DAACE14F 1    1.01 01
H 09170180 5FC8E00DA142 5FC8E3164142 S -0.6792616 -0.5201137  0.3503185  0.3812641  77.6836  -4.4684 155.3223   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1088 225.1481 290.1742 5FC8DAACE14F 1    0.73 01
H 09170180 5FC8E00DA142 5FC8E3166142 S -0.6767448 -0.5178101  0.3537277  0.3857019  77.6836  -4.4684 156.0734   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1088 225.0998 290.9736 5FC8DAACE14F 1    0.88 01
H 09170180 5FC8E00DA142 5FC8E3168142 S -0.6741989 -0.5154842  0.3571216  0.3901231  77.6836  -4.4684 156.8244   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1087 225.0547 291.7698 5FC8DAACE14F 1    1.00 01
H 09170180 5FC8E00DA142 5FC8E316A146 S -0.6716241 -0.5131361  0.3605002  0.3945275  77.6836  -4.4684 157.5755   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1087 225.0127 292.5628 5FC8DAACE14F 1    0.96 01
L 09170180 5FC8E00DA142 5FC8E316B142  77.6836  -4.4684 157.9532    6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642    0.0999 220.4553 297.4978  1545.8    0.191411    0.025739    3.0476    63563.93  2827.0866
H 09170180 5FC8E00DA142 5FC8E316C142 S -0.6690204 -0.5107661  0.3638633  0.3989150  77.6836  -4.4684 158.3266   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1087 224.9740 293.3525 5FC8DAACE14F 1    1.05 01
H 09170180 5FC8E00DA142 5FC8E316E146 S -0.6663880 -0.5083740  0.3672108  0.4032854  77.6836  -4.4684 159.0776   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1086 224.9388 294.1388 5FC8DAACE14F 1    0.99 01
H 09170180 5FC8E00DA142 5FC8E3170142 S -0.6637270 -0.5059602  0.3705425  0.4076384  77.6836  -4.4684 159.8287   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1086 224.9069 294.9217 5FC8DAACE14F 1    1.01 01
H 09170180 5FC8E00DA142 5FC8E3172142 S -0.6610374 -0.5035246  0.3738582  0.4119739  77.6836  -4.4684 160.5797   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1086 224.8786 295.7011 5FC8DAACE14F 1    0.97 01
H 09170180 5FC8E00DA142 5FC8E3174142 S -0.6583195 -0.5010674  0.3771579  0.4162917  77.6836  -4.4684 161.3308   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1085 224.8538 296.4770 5FC8DAACE14F 1    1.00 01
H 09170180 5FC8E00DA142 5FC8E3176146 S -0.6555733 -0.4985886  0.3804414  0.4205916  77.6836  -4.4684 162.0818   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1085 224.8324 297.2494 5FC8DAACE14F 1    0.95 01
H 09170180 5FC8E00DA142 5FC8E3178142 S -0.6527989 -0.4960885  0.3837086  0.4248735  77.6836  -4.4684 162.8329   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1085 224.8145 298.0183 5FC8DAACE14F 1    1.04 01
H 09170180 5FC8E00DA142 5FC8E317A142 S -0.6499965 -0.4935670  0.3869593  0.4291371  77.6836  -4.4684 163.5839   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1085 224.8001 298.7838 5FC8DAACE14F 1    0.88 01
H 09170180 5FC8E00DA142 5FC8E317C142 S -0.6471662 -0.4910243  0.3901933  0.4333822  77.6836  -4.4684 164.3349   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1084 224.7889 299.5460 5FC8DAACE14F 1    0.99 01
H 09170180 5FC8E00DA142 5FC8E317E146 S -0.6443081 -0.4884606  0.3934106  0.4376088  77.6836  -4.4684 165.0860   6.008935 172.6  -0.0022  -0.0045  -5.6570  -0.5642   0.1084 224.7810 300.3050 5FC8DAACE14F 1    0.89 01
```

Example : AHF containing HCM manoeuvre and stable pointing phases

8. Data Definition (Software Routines)

8.1. Routine Name and Description

N/A

8.2. Calling Sequence

N/A

8.3. Input Parameters

N/A

8.4. Output Parameters

N/A

8.5. Return Codes

N/A

8.6. Restrictions on use

N/A

8.7. Running environment

N/A

Annex A: Definitions

The conventions and nomenclature used in this appendix follow [RD.1] and [RD.15].

Annex A.1: Reference Systems

The reference frames that are of interest for purposes of spacecraft 3-axes attitude reconstruction are listed as follows:-

Annex A.1.1: Ecliptic inertial reference system

- Origin at solar system barycentre
- X_I parallel to mean equinox of J2000.0
- Z_I parallel to ecliptic north pole at J2000.0
- Y_I completes the right handed set

Annex A.1.2: Angular momentum reference system

- Origin at spacecraft centre of mass
- X_H aligned with the angular momentum vector
- Y_H lies in the same plane as the angular momentum vector and the ecliptic north pole Z_I. It is also normal to the angular momentum vector
- Z_H completes the right handed set

Annex A.1.3: Planck principal axis reference system

- Origin at spacecraft centre of mass
- X_P aligned with the maximum principal axis
- Y_P aligned with the intermediate principal axis
- Z_P aligned with the minor principal axis

Annex A.1.4: Planck body reference system

The origin of the Planck body reference system and the principal axis reference system are coincident. It is also noted that the nominal orientation of the Attitude Control Axis (ACA) and Satellite Coordinate Axis (SCA) reference systems[1], are the same as the Planck body reference system, with different positions of the reference frame origins. They are equivalent for attitude reconstruction purposes.

- Origin at spacecraft centre of mass
- X_B aligned with a fixed mechanical direction in the spacecraft. Nominally coincident with X_{SCA} and X_{ACA} axes
- Z_B perpendicular to X_B and contained in the plane defined by X_B and the telescope line-of-sight. Nominally coincident with Z_{SCA} and Z_{ACA} axes.
- Y_B completes the right handed set

1. Defined by the operational star tracker reference system

Annex A.2: Coordinate Transformations

Annex A.2.1: Ecliptic inertial reference to angular momentum reference

The transformation from the ecliptic inertial reference system to the angular momentum reference system can be represented as a 3-2-1 Euler rotation sequence [α, -δ, π/2], where α and δ are computed from the angular momentum vector expressed in the ecliptic inertial reference system as follows:-

$$\alpha = mod(\mathrm{atan2}(hI(2), hI(1)), 2\pi)$$
$$\delta = \mathrm{asin}(hI(3)) \qquad Eq(A.2.1.1)$$

- α is the ecliptic longitude of the angular momentum vector in the ecliptic inertial reference system of J2000.
- δ is the ecliptic latitude of the angular momentum vector in the ecliptic inertial reference system of J2000.

The angular momentum vector, expressed in the ecliptic inertial reference system, is provided by the Planck ground attitude detemination algorithms described in [RD.16]. The ecliptic longitude and ecliptic latitude computed above, can be used to construct the following transformation matrix.

$$DCM_{H-I} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} \cos\delta & 0 & \sin\delta \\ 0 & 1 & 0 \\ -\sin\delta & 0 & \cos\delta \end{bmatrix} \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad Eq(A.2.1.2)$$

Annex A.2.2: Angular momentum reference to the Principal axis reference

The transformation from the angular momentum reference system to the Planck principal axis reference system can be represented as a 1-2-1 Euler rotation sequence [ψ, θ, φ], where:-

- ψ is the inertial nutation phase
- θ is the nutation angle
- φ is the body nutation phase

In the absence of nutation there is only one phase angle, namely the spin phase given as follows:-

$$\Phi = mod((\phi + \psi), 2\pi) \qquad Eq(A.2.2.1)$$

This is defined to be zero when the principal axis Y_P coincides with the angular momentum reference axis Y_H

The transformation from the angular momentum reference system to the principal axis reference system is performed using the following transformation matrix:-

$$DCM_{P-H} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{bmatrix} \qquad Eq(A.2.2.2)$$

In the Planck ground attitude determination algorithms (see Ref. [RD.16]), the nutation angle and nutation phase angles are determined from the above transformation matrix as follows:-

$$\theta = \mathrm{acos}(DCM_{P-H}(1,1))$$
$$\phi = mod(\mathrm{atan}2(DCM_{P-H}(2,1), DCM_{P-H}(3,1)), 2\pi) \qquad Eq(A.2.2.3)$$
$$\psi = mod(\mathrm{atan}2(DCM_{P-H}(1,2), -DCM_{P-H}(1,3)), 2\pi)$$

If the nutation angle is below a certain threshold, it is not possible to extract the nutation phase angles. In this case, the above transformation matrix reduces to:-

$$DCM_{P-H} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\Phi & \sin\Phi \\ 0 & -\sin\Phi & \cos\Phi \end{bmatrix} \qquad Eq(A.2.2.4)$$

Where Φ is the spin phase angle (See also Annex A.3.8).

In the absence of nutation, the user of the AHF should use the nutation phase angles as follows:-

$$\Phi = mod((unwrap(\phi) + unwrap(\psi)), 2\pi) \qquad Eq(A.2.2.5)$$

Alternatively, the nutation phase angles are not used and the spin phase angle is used directly to compute the desired coordinate transformation matrix.

Annex A.2.3: Planck body reference to Principal axis reference

The transformation from the Planck body reference system to the Planck principal axis reference system can be represented as a 3-2-1 Euler rotation sequence [ψ_1, ψ_2, ψ_3], where:-

- ψ_1, ψ_2 are the tilt angles of the spin axis w.r.t. the nominal spin axis (X_B)
- ψ_3 is the azimuth angle

The transformation from the Planck body reference system to the principal axis reference system can be performed using the following transformation matrix:-

$$DCM_{P-B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi_3 & \sin\psi_3 \\ 0 & -\sin\psi_3 & \cos\psi_3 \end{bmatrix} \begin{bmatrix} \cos\psi_2 & 0 & -\sin\psi_2 \\ 0 & 1 & 0 \\ \sin\psi_2 & 0 & \cos\psi_2 \end{bmatrix} \begin{bmatrix} \cos\psi_1 & \sin\psi_1 & 0 \\ -\sin\psi_1 & \cos\psi_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Eq(A.2.3.1)

The principal axis tilt angles are derived based on the constant + derivative terms in the following model for the spacecraft transverse axis angular rates.

$$\omega_{y_i} = \omega_{y_0} + t_{STR_i}\left(\frac{d\omega_y}{dt}\right) + A_y \cos\nu_N\varphi_{x_i} + B_y \sin\nu_N\varphi_{x_i}$$

$$\omega_{z_i} = \omega_{z_0} + t_{STR_i}\left(\frac{d\omega_z}{dt}\right) + A_z \cos\nu_N\varphi_{x_i} + B_z \sin\nu_N\varphi_{x_i} \qquad Eq(A.2.3.2)$$

These constants, derivative terms and coefficients are obtained from the Planck ground attitude determination algorithms (see Ref. [RD.16]).

The quantity φ_x is a pseudo-spin phase angle[1] (see Step 6.2 of Ref. [RD.16]) and ν_N is the nutation to spin rate ratio[2] is estimated in the presence of nutation by performing a frequency analysis on telemetred STR attitude quaternion data.

Theoretically, the nutation to spin rate ratio is given as a function of the principal axis moments of inertia as follows:-

$$\nu_N = -\sqrt{\frac{(I_1 - I_2)(I_1 - I_3)}{I_2 I_3}} \qquad Eq(A.2.3.3)$$

Also, the principal axis tilt angles are computed as:-

$$\psi_{1_i} = \left[\frac{\omega_{y_0} + t_{STR_i}\left(\frac{d\omega_y}{dt}\right)}{\omega_{1_i}}\right]$$

$$\psi_{2_i} = -\left[\frac{\omega_{z_0} + t_{STR_i}\left(\frac{d\omega_z}{dt}\right)}{\omega_{1_i}}\right] \qquad Eq(A.2.3.4)$$

and ω_{1_i} is the angular velocity about the principal axis closest to the Planck body reference system X-axis.

1. This is not to be confused with the actual spin phase angle.
2. This quantity is estimated by performing a frequency analysis on a batch of processed STR data collected during periods where nutation is present.

Annex A.3: Observation Record Data Conversion Algorithms

This appendix contains the necessary algorithms required to reconstruct the spacecraft 3 axes attitude at any time during a particular observation period, given the contents of the Attitude History File observation frequency data record, described in Section

Annex A.3.1: Principal Axis Tilt

The direction of the spin axis (principal X-axis with the absence of nutation) in the Planck body reference system is therefore given by:-

$$\overrightarrow{X_P} = \begin{bmatrix} \cos\psi_2 \cos\psi_1 \\ \cos\psi_2 \sin\psi_1 \\ -\sin\psi_2 \end{bmatrix} \qquad Eq(A.3.1.1)$$

in the absence of nutation, this is aligned with the angular momentum vector.

Annex A.3.2: Principal Axis Inertia Ratios

We define the inertia ratios α_y and α_z as follows:-

$$\alpha_y = \frac{I_x}{I_y} - 1 \qquad \alpha_z = \frac{I_x}{I_z} - 1 \qquad Eq(A.3.2.1)$$

where (I_x, I_y, I_z) are the principal axis moments of inertia.

The estimated parameters in the observation frequency data record will be related to these basic parameters.

Annex A.3.3: Nutation to Spin Rate Ratio

The nutation to spin rate ratio, in the AHF observation frequency data record, is given by:-

$$\frac{\omega_n}{\omega_s} = \sqrt{\left(\frac{I_x}{I_y} - 1\right)\left(\frac{I_x}{I_z} - 1\right)} = \sqrt{\alpha_y \alpha_z} \qquad Eq(A.3.3.1)$$

In the general case of a nutating asymmetric spacecraft, the spin rate will not be constant, whereby, ω_s, is the maximum spin rate. In the absence of nutation, the spin rate is constant.

Annex A.3.4: Axial Dynamic Imbalance

The axial dynamic imbalance, Δ, is a measure of the degree of asymmetry between the 2 spacecraft transverse principal moments of inertia. It is defined to be a positive quantity as follows:-

$$\Delta = \frac{I_x}{I_z} - \frac{I_x}{I_y} = \alpha_z - \alpha_y \qquad Eq(A.3.4.1)$$

Annex A.3.5: Moments of inertia

From Eq(A.3.3.1) and Eq(A.3.4.1), we have the following quadratic equation:

$$\alpha_y^2 + \Delta\alpha_y - \left(\frac{\omega_n}{\omega_s}\right)^2 = 0$$

Eq(A.3.5.1)

which can be solved for α_y. The root ensuring that α_y is positive will be taken.

Rearranging Eq(A.3.4.1), it follows that α_z can be obtained from:

$$\alpha_z = \Delta + \alpha_y$$

Eq(A.3.5.2)

Rearranging Eq(A.3.2.1) and knowing the spin axis principal moment of inertia[1] I_x, we can therefore solve for the transverse principal moments of inertia as follows:

$$I_y = \frac{I_x}{1 + \alpha_y} \qquad I_z = \frac{I_x}{1 + \alpha_z}$$

Eq(A.3.5.3)

The axial dynamic imbalance is zero for an axial symmetric spacecraft, since the transverse principal moments of inertia are equal.

Annex A.3.6: Body inertia tensor

The principal axis moments of inertia and the principal axis reference system to the PLANCK body reference system transformation can be used to construct the full inertia tensor as follows:

$$I_B = (DCM_{P-B}^T) I_P (DCM_{P-B})$$

Eq(A.3.6.1)

where $I_P = \text{diag}\{I_x, I_y, I_z\}$

Annex A.3.7: Nutation Angles for an Asymmetric Spacecraft

For an asymmetric spacecraft, the trace of the transverse components of the angular momentum vector describes an ellipse. The minimum and maximum nutation angles are related to the sizes of the minor and major axes of this ellipse as follows:-

$$\sin\theta_{min} = \sqrt{\frac{\alpha_y}{\alpha_z}} \sin\theta_{max}$$

Eq(A.3.7.1)

For an axial symmetric spacecraft, the inertia ratios are equal and therefore the nutation angle is constant.

1. The actual I_x can be derived from the PLANCK mass properties file provided routinely by FD to PSO and DPCs. The free nutation motion is invariant against a scaling of I_x; it depends only on the inertia ratios I_x/I_y and I_x/I_z..

Annex A.3.8: Nutation Angle and Phases

Also, the direction of the angular momentum vector in the principal axis reference system is given by:-

$$\overrightarrow{H_P} = \begin{bmatrix} I_x\omega_x \\ I_y\omega_y \\ I_z\omega_z \end{bmatrix} = H\begin{bmatrix} \cos\theta \\ \sin\theta\sin\varphi \\ \sin\theta\cos\varphi \end{bmatrix} \quad \textit{Eq(A.3.8.1)}$$

where in the absence of external disturbance torques, the angular momentum, *H*, is constant in magnitude (*H*) and direction, with respect to the ecliptic inertial reference system and the angular momentum reference system.

The time, t_0, in the following development is defined as the validity time for the data in the observation frequency data records.

<u>Body Nutation Phase</u>

The body nutation phase, ϕ, determines the phase of the angular momentum vector in the principal axis reference system.

From the kinematic relationships between the spacecraft angular rates and the Euler rates, the rate of change of the body nutation phase is given by:-

$$\phi(t) = \phi(t_0) + \int_{t_0}^{t}\left(\omega_x - H\left(\frac{I_y\omega_y^2 + I_z\omega_z^2}{I_y^2\omega_y^2 + I_z^2\omega_z^2}\right)\cos\theta\right)dt \quad \textit{Eq(A.3.8.2)}$$

For an axial symmetric spacecraft, the body nutation phase is obtained from the previous expression as the following linear function of time:-

$$\phi(t) = \phi(t_0) - \omega_n(t - t_0) \quad \textit{Eq(A.3.8.3)}$$

For an asymmetric spacecraft, the body nutation phase will also contain additional periodic terms, with coefficients that are a function of the axial dynamic imbalance, Δ.

<u>Nutation Angle</u>

The nutation angle represents the instantaneous angle between the angular momentum vector and the major principal axis of inertia. It is expressed mathematically by the following:-

$$\tan\theta = \frac{\sqrt{I_y^2\omega_y^2 + I_z^2\omega_z^2}}{I_x\omega_x} \quad \textit{Eq(A.3.8.4)}$$

For an axial symmetric spacecraft and in the absence of external torques and internal energy dissipation, the nutation angle remains constant.

<u>Inertial Nutation Phase</u>

The inertial nutation phase, ψ, determines the phase of the major principal axis in the angular momentum reference system.

From the kinematic relationships between the spacecraft angular rates and the Euler rates, the rate of change of the inertial nutation phase is given by:-

$$\psi(t) = \psi(t_0) + H\int_{t_0}^{t}\left(\frac{I_y\omega_y^2 + I_z\omega_z^2}{I_y^2\omega_y^2 + I_z^2\omega_z^2}\right)dt$$

Eq(A.3.8.5)

For an axial symmetric spacecraft, the inertial nutation phase is obtained from the previous expression as the following linear function of time:-

$$\psi(t) = \psi(t_0) + \frac{(\omega_n + \omega_s)}{\cos\theta}(t - t_0)$$

Eq(A.3.8.6)

For an asymmetric spacecraft, the inertial nutation phase will also contain additional periodic terms, with coefficients that are a function of the axial dynamic imbalance, Δ.

<u>Spin Phase</u>

The spin phase angle, Φ, can be determined by projecting the ecliptic Z-axis into the spacecraft principal axis reference system Y-Z plane. This is done by constructing the transformation from the ecliptic inertial reference system of J2000 to the principal axis reference system and then performing the following transformation.

$$u_{pole} = DCM_{P-I}\begin{bmatrix}0\\0\\1\end{bmatrix}$$

Eq(A.3.8.7)

The spin phase angle is then computed as:-

$$\Phi = \operatorname{atan}2(-u_{pole}(3), u_{pole}(2))$$

Eq(A.3.8.8)

Annex A.3.9: Nutation damping time constant

The Planck spacecraft spins about it’s major principal axis of inertia. Due to internal energy dissipation mechanisms (e.g. fuel slosh excitation by reorientation manoeuvres), the spacecraft is stable in that, it will tend to a minimum energy state whereby the nutation is completely damped. In this state, the spacecraft will be spinning about it’s major principal axis of inertia which will be aligned with the angular momentum vector.

The nutation damping is modelled as an exponential decay in the nutation angle to zero, the rate of which, is defined by the nutation damping time constant, τ.

Eq(A.3.9.1)

$$\theta(t) = e^{-(t - t_0)/\tau}\theta(t_0)$$

Annex A.3.10: Spacecraft Phase Angle

The spacecraft phase angle is defined as follows:-

$$\sigma(t) = \phi(t) + \psi(t) \qquad \textit{Eq(A.3.10.1)}$$

which is the same quantity as the spin phase angle Φ, defined in Annex A.3.8.

For an axial symmetric spacecraft, without nutation, this expression reduces to the following linear function of time:-

$$\sigma(t) = \phi(t_0) + \psi(t_0) + \omega_s(t - t_0) \qquad \textit{Eq(A.3.10.2)}$$

Annex A.3.11: Coordinate Transformation Construction

The requirement is to provide an estimate of the parameters within the observation frequency data record at a specified Epoch and to provide a means to reconstruct the spacecraft 3-axes attitude using this data. The Planck on-ground attitude data filtering algorithms, which form part of the AHF generation software, are described in [RD.16]. All entries in the observation frequency record are derived from outputs of this attitude data filtering, apart from the parameters that are estimated as part of dedicated calibration campaigns[1].

The outputs of the Planck on-ground attitude data filtering are listed as follows:-

- Angular momentum vector in ecliptic inertial reference system, h_I
- Principal axis tilt angle estimates [ψ_1, ψ_2]
- The filtered ecliptic inertial to Planck body frame transformation, DCM_{B-I}

From which the following transformations can be derived:-

- Ecliptic inertial to angular momentum reference transformation, DCM_{H-I}
- Planck body to principal axis reference transformation, DCM_{P-B}

These transformation matrices can be combined to compute the transformation from the angular momentum reference system to principal axis reference system as follows:

$$DCM_{P-H} = DCM_{P-B} \cdot DCM_{B-I} \cdot DCM_{H-I}^T \qquad \textit{Eq(A.3.11.1)}$$

From which the angles [ψ, θ, ϕ] are extracted as a 1-2-1 Euler rotation sequence, where:-

- ψ is the inertial nutation phase
- θ is the nutation angle
- ϕ is the body nutation phase

1. The nutation to spin rate ratio (ω_n/ω_s), the dynamic imbalance (Δ) and the principal axis azimuth angle (ψ_3)

The reverse operations could be performed based on the data taken from the observation frequency record, so that the 3-axis attitude required to transform from ecliptic inertial to Planck body reference as follows:-

$$DCM_{B-I} = DCM_{P-B}^{T} \cdot DCM_{P-H} \cdot DCM_{H-I}$$

Eq(A.3.11.2)

where the transformation matrices are computed by substituting data extracted from the observation frequency records, into the formulas given in:-

- Annex A.2.1 - Ecliptic longitude and latitude, DCM_{H-I}
- Annex A.2.2 - nutation amplitude and phase angles, DCM_{P-H}
- Annex A.2.3 - principal axis tilt angles and azimuth angle, DCM_{P-B}