TITLE:	**Planck LFI – On Moving Objects Solar System Calculations**
DOC. TYPE:	**TECHNICAL NOTE**
PROJECT REF.:	**PL-LFI-OAT-TN–034**
PAGE:	**I of IV, 00**
ISSUE/REV.:	**1.0**
DATE:	**28 Mar 2006**

Issued by	**Michele Maris** **Carlo Burigana**	**Date:** **Signature:**	**28 Mar 06**
Agreed by	**A. ZACCHEI** **LFI DPC Manager**	**Date:** **Signature:**	**28 Oct 2006**
Approved by	**R.C. BUTLER** **LFI Program Manager**	**Date:** **Signature:**	**Xxx**
Approved by	**N. MANDOLESI** **LFI Principal Investigator**	**Date:** **Signature:**	**Xxx**

DISTRIBUTION LIST

Recipient	Company / Institute	E-mail address	Sent
A.Zacchei	INAF-OAT	zacchei@oats.inaf.it	
A.Gregorio	Trieste University	Anna.gregorio@ts.infn.it	
R.C.Butler	INAF-IASF-Bologna	butler@iasfbo.inaf.it	
N.Mandolesi	INAF-IASF-Bologna	mandolesi@iasfbo.inaf.it	

CHANGE RECORD

Issue	Date	Sheet	Description of Change	Release
0	2006 Mar 03		Starting of the document	0
1	2006 Mar 28		First Issue	0

TABLE OF CONTENTS

1 SCOPE

This document describes methods and tools to computes ephemerids of moving objects of the Solar System in the framework of the Planck mission.

1.1 LIMITS OF APPLICABILITY

In what regard the existing Flight Simulator this document referrers only to the DM.

2 APPLICABLE/REFERENCE DOCUMENTS

2.1 APPLICABLE DOCUMENTS

2.2 REFERENCE DOCUMENTS

[RD-1] Asteroid detection at millimetric wavelengths with the Planck survey,
G. Cremonese, F. Marzari, C. Burigana, M. Maris, New Astronomy, Volume 7, Issue 8, p. 483-494, 2002

[RD-2] Description of the DE405 ephemerid file can be recovered from
http://www.cv.nrao.edu/~rfisher/Ephemerides/ephem_descr.html

[RD-3] Description of the use and corrections to astrometric coordinates
http://www.cv.nrao.edu/~rfisher/Ephemerides/ephem_use.html

[RD-4] The IMCCE documentation and data can be accessed at
ftp://ftp.imcce.fr/pub/ephem

[RD-5] In Flight Main Beam Reconstruction for Planck/LFI
C. Burigana, P. Natoli, N. Vittorio, N. Mandolesi, M. Bersanelli,
Experimental Astronomy, 12 (2), p. 87 - 106, 2001

2.3 ACRONYMS LIST

FD	Flight Dynamics
FS	Flight Simulator
L2	Second Lagrangian Point of the Sun-Earth System
LS	Level S
SS	Solar System
SSB	Solar System Barycentre
TOD	Time Ordered Data
TOI	Time Ordered Information

3 INTRODUCTION

3.1 THE GEOMETRICAL PROBLEM

Fig. 1 resumes the main problem in locating an object within the Solar System from Planck.

It is evident that to know whether an object is observed and when, we have to determine the location of the object relative to Planck. This means that we have to know at that time WHERE Planck is located as well as WHERE the object is.

In addition to these geometrical considerations it has to be considered the delay due to light propagation and the relative velocity of the two bodies inducing light aberration. Those effects cause the body to be seen by an observer in a different position respect to the position expected on pure geometrical considerations.

A software dedicated to determine the conditions of observability of a SS object would have to accomplish the following tasks:

1. compute the position of Planck respect to the SS Barycentre (SSB) at a given epoch,
2. compute the position of a body at the same epoch (geometrical position) respect to the SS Barycentre,
3. the geometrical position of the object respect to Planck,
4. correct for delay in propagation of light, light aberration and (if required) relativistic corrections in order to obtain the body position as seen by Planck at the given epoch (apparent position),
5. compares the apparent position with the pointing direction of each beam of Planck in order to determine whether, when and where (within the beam reference frame) the body has been observed,
6. using a model of the radiometric emission of the body and apparent body distance from the spacecraft at the epoch of the observation, to compute the antenna temperature of the body at the epoch of observation for the given frequency,
7. using the beam pattern and the apparent location of the boy with respect to the beam reference frame, to compute the expected signal in Planck at the given frequency.

This report is centred on tasks from 1 to 5.

No general formula exists for any of these tasks, a set of tools are needed in place.

The position of a body within the Solar System may be calculated using celestial mechanics subroutines or may be computed from tables as those produced by the JPL HORIZON 2000 web service.

For the Planck position within the Solar System, it is required to have an accurate Planck orbit.

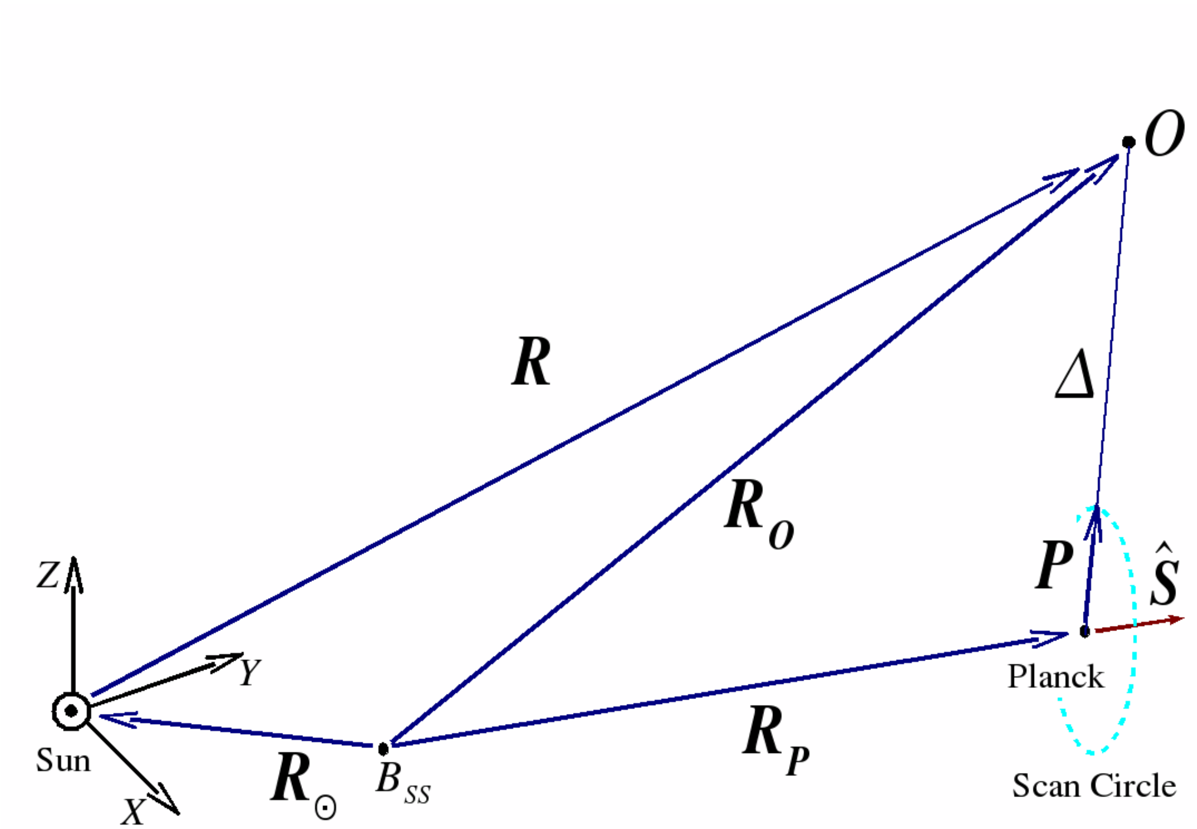

Fig.1 Geometry of detection of a Solar System body by Planck. Here *O* is the object, $\boldsymbol{R}_O$ its position in the Solar System respect to the SSB (B_{ss}), $\boldsymbol{R}_P$ is the Planck position respect to (B_{ss}), $\boldsymbol{R}_{\odot}$ is the position of the Sun respect to B_{ss}, ***R*** is the position of the body respect to the Sun, ***P*** is the instantaneous pointing direction, Δ is the distance of the body respect to Planck, ***S*** is the Planck spin axis.

At last flux prediction depends on the istantaneous distance of the body from the Sun and from Planck. Simple geometrical effects govern the Flux observed by Planck. A convenient representation is:

$$\text{Flux\_Observed} = \text{Flux\_0} / (\text{Delta}^2 \, \text{R}^2)$$

where Delta is the Planck – Body distance in Astronomical Units

R is the Sun – Body distance in Astronomical Units

Flux_0 is the expected flux at Delta = 1 AU and R = 1 AU.

Flux_0 must be inferred from observations, but the assumption of Flux_0 as a time independent quantity will allow an accuracy in the flux prediction between some 1% and 10% depending on the object and the frequency.

3.2 THE PROBLEM OF PLANET SCANNING

Planets are used as calibrators to reconstruct the beam pattern of each Feed Horn [RD-5].

Usually, only the brighter external planets are considered (Mars, Jupiter, Saturn and in some cases Uranus).

Accurate reconstruction requires to consider not only the planet when crossing the main beam but also when crossing regions just outside the centre of the main beam.

The accuracy by which the apparent position of planets in the sky has to be known has to exceed the pointing accuracy, i.e. better than few arcsecs.

3.3 THE PROBLEM OF OBJECT IDENTIFICATION

The ERSC and the QDS needs to know whether an unexpected bright object detected in TODs or maps is a SS moving object or not.

The algorithm for this determination would be:
1. to determine whether there is a point source within a beam
2. to determine the UT at which the point source have been detected
3. to compute the position of all the possible bright enough SS moving objects at the UT of interest
4. to check whether one or more of them cross the beam (pixel) at the epoch of detection

Having pointing accuracies better of few arcsecs the calculations of apparent positions will have to be better than this level.

3.4 THE PROBLEM OF ASTEROIDS

In [RD-1] it has been discussed the possibility for Planck to observe asteroids. The paper concluded that up to some hundred of asteroids would be able to be observed by Planck with a S/N greater than 1.

A simple extrapolation shows that the number of asteroids able to generate a signal with a S/N > 0.1 is of some thousands.

A tool to flag those samples in TOD or in MAPS flagged by the present of a potentially bright asteroid is needed.

4 LEVELS OF ACCURACY

Accuracy on ephemerids is connected to

1. Dynamical modelling
2. Geometrical modelling
3. Reference frame modelling

4.1 DYNAMICAL MODELLING

We may identify two levels of dynamical accuracy

Osculating

It is assumed that orbital elements are constant in time

Perturbative

Perturbations on orbital elements are considered

4.2 GEOMETRICAL MODELLING

We may identify basically three levels of geometrical accuracy

Geometrical

In this case just the geometrical position of objects is computed at a given time *t*

Astrometrical

Time delay due to finite velocity of propagation of light is taken in account, positions are computed at time *t-c/d* where *d* is the distance between the observer and the object, *c* speed of light

Apparent

The aberration of light due to the relative motions of object and observer is taken in account

Refer to [RD-3] for a more detailed explanation.

4.3 REFERENCE FRAME MODELLING

We may identify at least four levels of geometrical accuracy

Solar System Barycentre

Neglecting at all the position of the spacecraft in the Solar System i.e. assuming the spacecraft is in the barycentre

Geocentric

Assuming the spacecraft is located at the Earth center

L2

Assuming the spacecraft is located in the L2 point

Simple orbit about L2

Assuming a simple description of spacecraft orbit around L2

Flight dynamics orbit about L2

Assuming a rigorously computed orbit about L2

Effective orbit about L2

Assuming the effective orbit followed by the satellite during the mission

5 APPLICATIONS AND REQUIREMENTS

Depending on the kind of application different levels of accuracy (as defined in section 4) can be exploited.

5.1 SIMPLE MISSION PLANNING

In this case the scopes are testing of :
1. scanning strategy evaluation for cosmological purposes (map making, etc.)
2. scanning strategy evaluation for mission planning
3. straight-light evaluation impact
4. planet transit data flagging
5. evaluation of main beam reconstruction procedures from planet transit
6. evaluation of procedures for moving objects identification in TODs

For cases 1 a simplistic simulator with the satellite in SSB is sufficient.

For the other cases a simulator based on Osculating elements and Geometrical positions reference frame cantered on the Sun or L2 and a simple orbit about L2 is sufficient.

The current version of SIMMISS in the LS implements all of these approximations.

The current version of SIMMISS does not include minor bodies as asteroids or comets.

5.2 REALISTIC DATA ANALYSIS

In this case the scopes are
1. scanning strategy optimization
2. straight-light assessment and removal
3. planet transit data flagging
4. main beam reconstruction from planet transit
5. moving objects identification in TOIs
6. science studies of Solar System bodies
7. removal of systematic from Solar System bodies

In this case we need a full precision (perturbative orbit of the Solar System bodies, apparent positions and flight dynamics orbit).

5.3 IN – FLIGHT AND POST-FLIGHT DATA ANALYSIS

As in Sect. 5.2 but replacing spacecraft flight dynamics orbit with the effective orbit.

6 TOOLS

In this section we will describe

1. existing tools on-the-shelf outside Planck
2. existing tools on-the-shelf already used in Planck
3. status of the flight simulator

6.1 TOOLS OUTSIDE PLANCK

Outside the Planck collaboration a number of tools exist.

6.1.1 JPL HORIZON 2000

It is the most accurate and flexible tool in the network. It allows calculation for planets and +170000 minor bodies (asteroids and comets) and even the L2 libration point. It allows calculations for geocentric observers, barycentre observes, and some pre-selected space missions. However the WEB interface does not allows to introduce the orbit of other missions. It can be accessed by the network with tree interfaces: web based, telnet (interactive) and email. The first is good to query one object at a time, the other allows multiple queries. Email allows automated queries.

6.1.2 JPL DE405 EPHEMERID TABLES

They are at the core of the JPL HORIZON 2000 code. Planetary tables are available to the public. The availability of these tables for minor bodies would have to be assessed after a recent (early 2006) rearrangement of the JPL HORIZON 2000 site.

6.1.3 LIBRARIES BASED ON JPL DE405

A number of libraries in C, C++, F90, F77, JAVA, IDL with different levels of quality exists to handle JPL DE405 files. Sometimes they allows only to compute geometric positions or they are specialized for geocentric reference frames. Before to choose one, quality, correctness and the proper application of corrections to obtain the apparent coordinates shall be assessed. The most complete libraries seem those provided by the NRAO.

6.1.4 EPHEM AND OTHER OPEN-SOURCE EPHEMERIDS COMPUTING ENGINES

Based on the aforementioned libraries or other libraries those codes are used in the professional and non professional astronomical community for observation planning. Their quality should be assessed before to adopt them.

6.1.5 OTHER SOURCES OF EPHEMERID TABLES

A good centre is the IMCCE [RD-4] especially for tables of asteroids.

6.2 TOOLS INSIDE PLANCK

6.2.1 ESOC – FLIGHT DYNAMICS CALCULATOR

This tool is provided and maintained by ESOC.

It incorporates DE405 tables for planets to compute planetary perturbations, as the code to simulate the spacecraft flight dynamics. An asset of this code is that it is written in MatLab, a language not supported at the DPC with some core routines in C or F77. It is likely that the MatLab interface would be easily ported into the (LINUX) OCTAVE language which may be easily incorporated in the LevelS pipeline.

6.3 STATUS OF THE FLIGHT SIMULATOR

The current release (DM model) of the flight simulator includes just a very simple model based on Keplerian osculating orbits.

7 IMPLEMENTATION OPTIONS

1. Replace the SS model in the Flight Simulator with a newly designed module including a more accurate SS dynamics.
2. Replace the SS model in the Flight Simulator with tabulated positions from the JPL HORIZON 2000 system and a simple interpolator.
3. Replace the Solar System model in the Flight Simulator with interpolation of DE405 tables.
4. As 3 but replacing the Flight Dynamics model with the ESOC/FD code
5. Minor bodies would have to be added by using tables of yearly osculating elements. JPL would be able to provide these tables, but the current interface allows to download tables in SPICE format and at a rate of no more than 20 objects per query. A reasonable data base would contain some thousand of objects. Osculating elements would have to be updated regularly. A better mechanics to provide these tables would have to be defined. Alternatively minor bodies tables may be provided as data bases from IAU minor bodies centre for a well defined epoch. A code able to evolve these elements to the epoch of interest will have to be provided, like to the prototype code of F.Marzari.

Option 1 can be safely excluded, there is plenty of on-the-shelf software able to cope with our requirements.

Option 2 is a reasonable solution for Planets. We will need to generate: 20 tables (planets, Moon and Sun positions and velocities plus L2 position and velocities) and define an interpolation code as an Orbit table for Planck. This solution is bad for asteroids and comets due to the large number of objects to be tabulated.

Option 3 is the most flexible solution but libraries and codes for interpolation shall be imported from outside. In addition it is likely that we will have to worry for conversions of coordinate systems and other corrections already included by the JPL tables.

Option 4 would be even more flexible, but it would be good to allow the orbit to be introduced in tabular mode to allow processing of the effective orbit.

Option 5 has to be explored and discussed in details in the near future.