Herschel Mission Planning Software

Jon Brumfitt, Pedro Gómez-Alvarez, Antonio Villacorta, Pedro García-Lario, Rosario Lorente, Laurence O'Rourke
Herschel Science Centre, European Space Astronomy Centre (ESAC),
European Space Agency (ESA), P.O. Box 78, Villanueva de la Cañada,
28691, Madrid, Spain

Abstract

The mission planning software developed for the Herschel Project is presented: The Herschel Inspector and mid/Long-term Scheduler (HILTS) and the short-term scientific Mission Planning system (SMPS).

Introduction

Herschel is an ESA cornerstone observatory mission launched on 14 May 2009. Herschel covers the wavelength range from 55 to 672 microns with three instruments: HIFI, PACS and SPIRE (Pilbratt et al. 2010 and references therein). Planning, visualization and inspection capabilities are important in any observatory. Cryogenic space observatories such as Herschel, which has an estimated lifetime of 3.5-4 years, call for additional efforts to maximize the observatory scientific return.

This paper starts with a brief description of those Herschel mission aspects relevant to mission planning, including proposals, instruments and constraints. It will then describe the two tools that comprise the Herschel Mission planning software: the Herschel Inspector and Long-Term Scheduler (HILTS) and the Scientific Mission Planning System (SMPS).

HILTS was initially conceived to assist Herschel medium and long-term planning. The tool is also useful to assess the mission's past, present and future status. Short-term mission planning for a given Operational Day[1] (OD) is executed using the Herschel Scientific Mission Planning System (SMPS) (Brumfitt 2005), which generates satellite telecommands that are uplinked to Herschel on a daily basis. Both HILTS and SMPS have been developed using a common Java object-oriented framework which implements basic astrometric, graphical, timing, pointing, etc functionality. This framework was initially developed for SMPS and then reused by HILTS.

The Mission

Herschel's operational database is populated by approximately 30,000 observation requests pertaining to 411 science proposals, from around 300 PIs (see figure 12 for their geographic distribution). There are several factors impacting Herschel scheduling: helium optimization, slews minimization, proposal completion, scientific grades, Targets of Opportunity (ToOs) and operational issues. Herschel has also thermal and communication constraints: the observatory attitude is constrained by the (anti)Sun, Earth, Moon and some planets; the observatory needs also to communicate with the ground station every 24 hours, during the so-called Daily Telecommunication Period (DTCP).

[1] The so-called operational day (OD) figure is the number of days elapsed from beginning of the Herschel mission

Instruments

The Herschel spacecraft has three instruments, HIFI, PACS and SPIRE. However, for mission planning purposes, each instrument is treated as a number of sub-instruments, as follows:

- HIFI bands [1A,1B,...,7A,7B]
- PACS photometry
- PACS spectrometry
- SPIRE photometry
- SPIRE spectrometry
- SPIRE/PACS parallel mode

Each OD is typically assigned to a single sub-instrument in order to improve efficiency. This reduces the overheads in switching between sub-instruments. In the case of HIFI, several bands are often scheduled in an OD. The largest overhead is recycling the liquid Helium cooler. The PACS and SPIRE instruments each have their own cooler system, which requires recycling separately, each taking approximately 3 hours. Once recycled, the instrument can be used for about two days. For PACS, recycling is only needed for photometry and not for spectrometry. For example, having spent three hours recycling the PACS cooler, it is most efficient to perform only PACS photometry observations for the following two days. Similarly, after recycling the SPIRE cooler, the following two days should be devoted to SPIRE. In parallel mode, the PACS and SPIRE coolers can be recycled in parallel, taking about three hours, after which parallel mode observations should be performed for two days.

Since the spacecraft attitude is severely constrained during the three-hour DTCP, this time is less available to be used for scientific observations. Consequently, it is a good time to recycle the cooler and perform any other instrument preparation.

The other instrument preparation times are less significant than cooler recycling, but nevertheless make it desirable to keep to one sub-instrument per day. For example, preparing PACS for either photometry or spectrometry takes about 30 minutes (each), in addition to the cooler recycling time needed for photometry.

Instrument preparation operations, such as cooler recycling and detector curing, are known as engineering observations, as they do not perform a scientific measurement. They are scheduled like scientific observations but do not require any particular spacecraft attitude.

Constraints

The Herschel spacecraft is shown in figure 1. The solar panel is nominally positioned to face the Sun so as to generate sufficient power. In this configuration, the Sun shade and solar panel shield the telescope and cryostat from the Sun. The spacecraft may be maneuvered by ± 30 degrees about the Y axis but by only ± 3 degree about the X axis, in order to satisfy power and thermal considerations. The telescope boresight points along the X axis and therefore has a view of a circular band of sky, 60 degrees wide, covering about 50% of the sky. The instruments impose small additional circular restrictions on the boresight around Mars, Jupiter and Saturn. Earth and Moon constraints normally lie within the Sun constraint. These constraints are illustrated in figure 2.

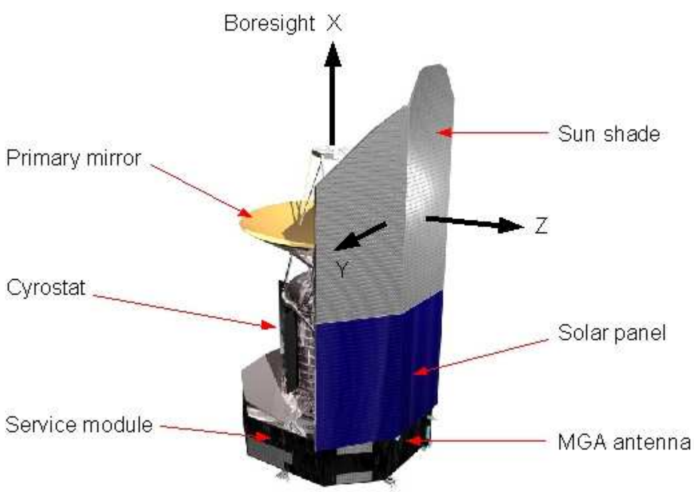


Figure 1: Herschel spacecraft showing axis directions

Communication with the ground station takes place in a 3-hour Daily Telecommunications Period (DTCP), during which the spacecraft is maneuvered to point its Medium Gain Antenna (MGA) at the Earth. This period is used to uplink telecommands and downlink the resulting telemetry from the previous day. In principle, scientific observations can be performed during DTCP, but only a restricted field of view.

The antenna constraint on the Z axis, during DTCP, results in an additional constraint on the boresight direction, when it is combined with the Sun constraint. When the Sun-spacecraft-Earth angle is greater than about 15 degrees, this takes the form of two roughly elliptical regions on the sky, one of which can be seen in figure 2.

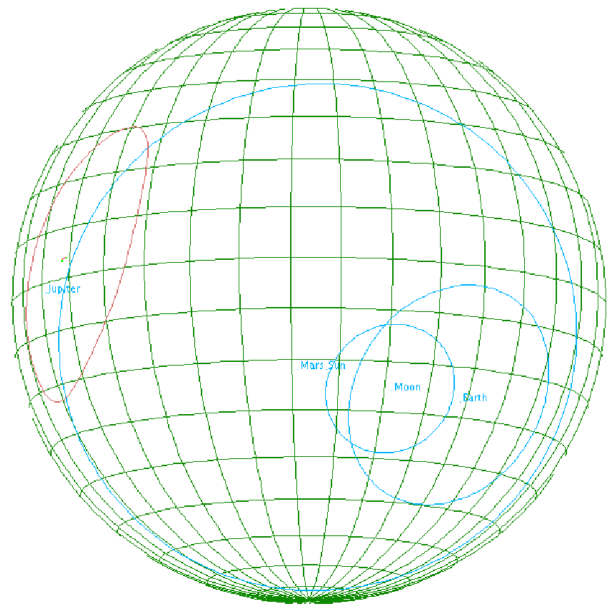


Figure 2: Herschel pointing constraints: See the big solar and the two smaller earth and moon constraints as well as the elliptical MGA constraint, which is in effect during the daily communication period (DTCP)

Herschel Inspector and mid/Long term Scheduler (HILTS)

Although initially intended as a Long-Term scheduler, it was soon realized that it could be also useful for other important purposes. Amongst the features currently present in the tool are:

- Automatic and manual medium/long-term scheduler
- Mission inspector: It gives a means to assess various aspects of the mission at any given time: visibility of sidereal and solar system objects (at a given time, within the antenna constraint, etc), status of observations, cone searches, pointing history, observation footprint, regions of the sky affected by stray light, etc.
- Query browser: it gives the means to perform arbitrary complex queries over more than 20 criteria.
- Statistical engine: it generates various types of statistics (see statistics section).
- Duplications: With each observing call it is required to identify potential duplications between new observations and the existing ones, helping to remove redundant science and thus maximizing scientific return.

- Catalog interface with IRAS, AKARI and user catalogs.
- VO-aware, to interoperate with other VO tools[2].

HILTS is a Java tool, whose main screen is divided into a set of panels (see figure 3):

- *Time panel:* It is in turn composed of a set of horizontal sub-panels: A simple Gregorian calendar; a time selector, where the current time is selected; the OD sub-panel, where the OD divisions and select observation visibility are represented; assigned observations sub-panel, where the scheduled and already executed observations are represented; current observing block restrictions (groups of ODs preallocated to a given instrument mode) and the available scheduling interval.
- *Sky panel:* Visible observations and current constraints are represented in this panel. The satellite pointing history for the current OD can also be plotted.
- *Query panel:* Composed of multiple tabs, allowing arbitrary complex selections using the available criteria: Observation programmes, instruments and instrument modes, request status, Solar System Objects (SSOs), duration, etc.
- *Proposal panel:* Current selected proposals are listed and can also be (de)selected.
- *Requests panel:* Where the current selected observations are listed
- *Catalogs panel:* By default IRAS and AKARI catalogs. User catalogs can also be loaded.
- *Status panel:* General status information

All panels are interconnected with each other by means of the adoption of the Model-View-Controller (MVC) software pattern. For instance, when a new time is selected in the time panel, constraints and visible observations are updated simultaneously in the sky panel, while visible proposals and catalog objects are also updated in their respective panels. Selecting objects visible at a given time, is the default visibility selection. Other alternatives are available: (in)visibility during a time interval, during the DTCP, always visible, etc.

Long-Term Scheduling

HILTS supports both manual and automatic scheduling. The former, by simple drag-and-drop from the observation panel to the scheduled observations sub-panel. The tool automatically places the observation at the earliest time within the dropped OD, taking into account observing blocks, observations duration, configuration and slews, amongst other factors. The latter (see figure 4) is attained by first selecting a suitable interval of typically several months and one of the set of pluggable strategies. For instance, if the *remaining visibility* strategy is selected, the tool will assign each of the visible observations by order of remaining visibility.

HILTS scheduling is typically an iterative process: starting with one of the available “filler” strategies and finishing with an optimization phase (a simulated annealing optimization is being developed). Once a satisfactory schedule is obtained, it can be exported to XML and loaded into the SMPS.

There are several factors impacting the quality of a schedule, amongst them: Helium and slew optimization, proposal and programme completion, scientific priorities, sky homogenization, operational issues, ToOs, etc. All these factors generally compete with each other, making it very difficult to generate the ”perfect” schedule (provided such a thing can be defined) in one go. Instead, HILTS allows the effect of a given strategy to be simulated, giving significant information and helping the human being in making decisions.

Statistics

HILTS can generate detailed statistics focused on several mission aspects, which help evaluate current mission status and thus retrofit observation strategies. Among the reports HILTS is capable of generating are:

- *Mission status reports:* The completion status of each programme, proposal, instrument and instrument mode is generated on a weekly basis. This information is useful for the science and mission planning teams to assess the overall mission status (see figure 11)
- *Duplication reports:* With each open call of proposals it is necessary to determine which of the new observations could be potentially duplicating other observations in already accepted proposals. This is performed by the tool using two criteria: spatial and spectral overlapping (see figure 10).
- *Pressure reports:* HILTS can estimate the amount of observing time that is available during each OD in a given period of time (see figure 5 and 6). This information is useful to adequate the observing block schema to the available time for a given period of time.
- *Scheduling reports:* When HILTS generates a long-term schedule it simultaneously generates statistical information of certain parameters such as: the efficiency of each scheduled OD, the available time to schedule each OD, taking into account the already scheduled observations (see figure 7 and 8)
- *Density reports:* In order to represent spatial densities of any magnitude, the tessellation of celestial sphere using the Hierarchical Triangular Mesh (HTM) has been used (Szalay et al. 2007). See figure 13 for the global distribution of unobserved time at the time of writing. Other plots (per instrument, programme, etc) are of course possible.
- *Competition reports:* Represents the amount of observing time each region of the sky has to ”compete” with, when it is visible (see figure 9). It is interesting to note that this is in general decoupled with the aforementioned time densities: a relatively shallowly-observed region can have a large competition figure, if has to share its visibility with densely-observed regions.

The AJAX Google presentation API[3] has been extensively used to implement this functionality.

[2] Virtual Observatory http://www.ivoa.net/

[3] http://code.google.com/apis/visualization/documentation/gallery.html

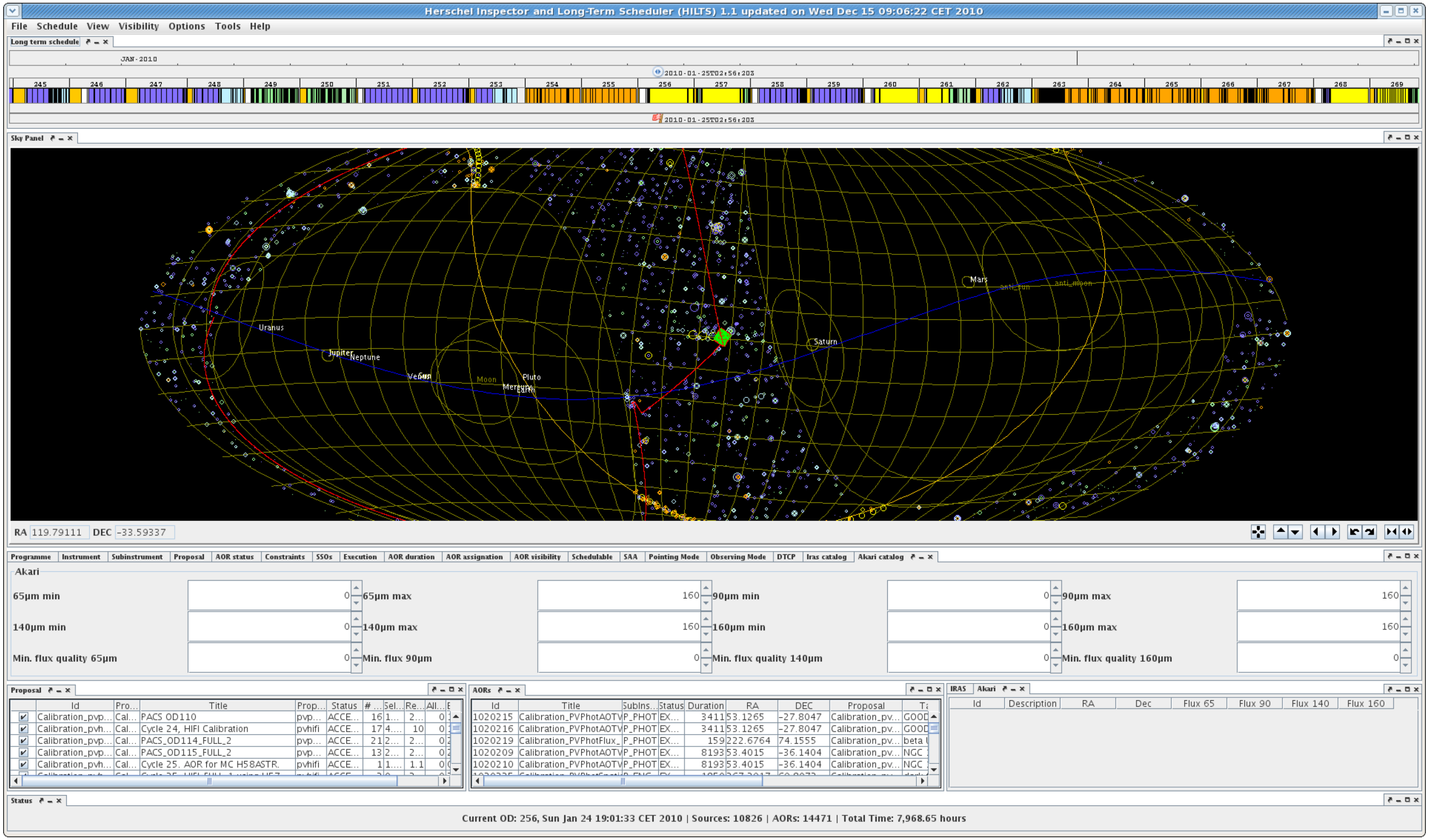


Figure 3: HILTS main screen. From top to bottom and from left to right: The time panel with its sub-panels, the sky panel, the query panel in which each tabbed panel represent a different query criterion, the proposal panel, the AOR panel, the catalog panel and the status panel

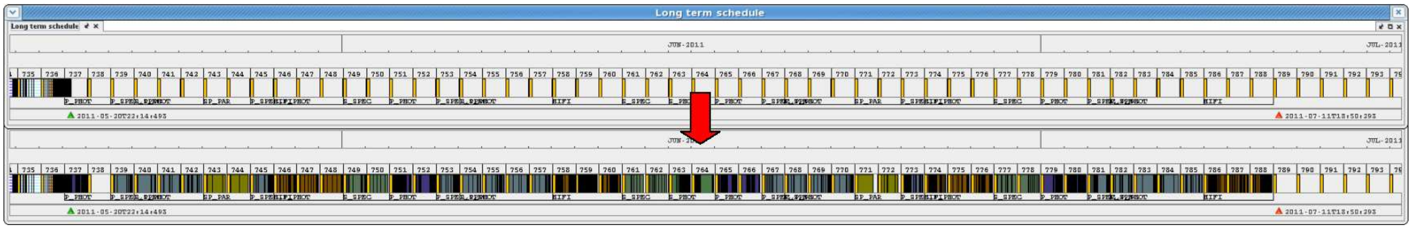


Figure 4: Before and after an automatic scheduling run

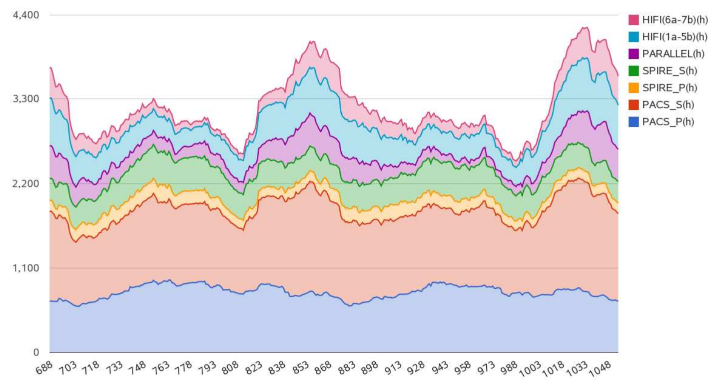


Figure 5: Available time (hours) per day and sub-instrument throughout a year. The X axis represents the operational day

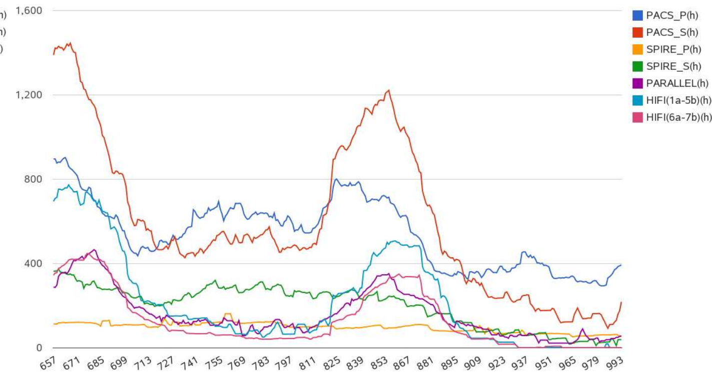


Figure 7: Available time as a long-term schedule is generated.

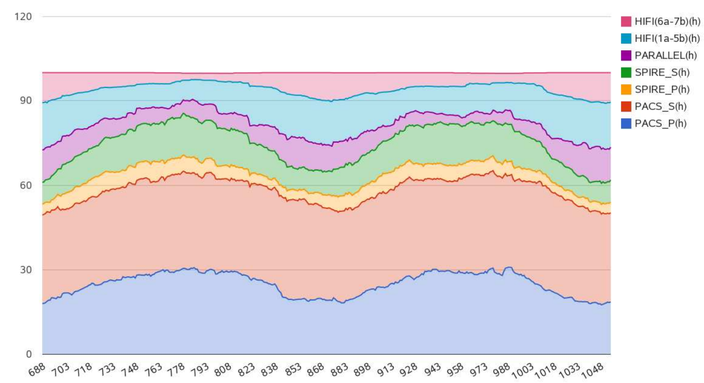


Figure 6: Fraction of available time per sub-instrument and OD for a year

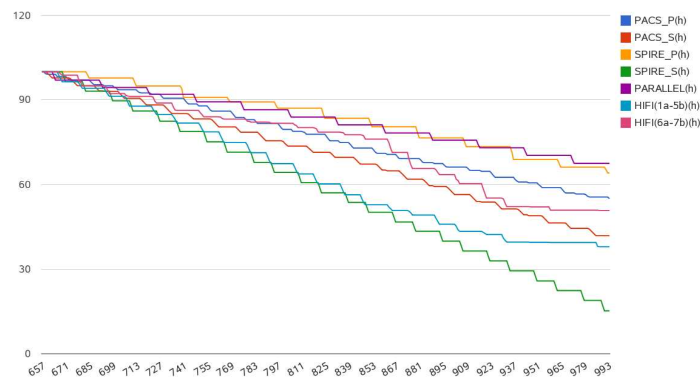


Figure 8: Unobserved time (fraction of the initial) as a long-term schedule is generated.

Catalogs and Virtual Observatory

HILTS is also able to interact with on-line catalogs from Vizier (Genova et al. 2006). Specially relevant catalogs such as IRAS and AKARI can be also filtered by flux in the query panel. A synthetic catalog of IR sources for the selection of candidate "filler observations" is also included.

HILTS can also inter-operate with VO tools such as Aladin (Boch, Thomas 2011) using the SAMP protocol (see figure 14): If an HILTS and Aladin session are running simultaneously the former can transmit its current position to the latter where we can analyze in deeper detail the region of interest.

The Scientific Mission Planning System (SMPS)

The purpose of the SMPS is to generate a daily schedule of telecommands that is uploaded to the spacecraft. This includes:

- commands to the Attitude Control and Monitoring System (ACMS) to maneuver the spacecraft, both to slew between observations and to perform raster and scan pat-

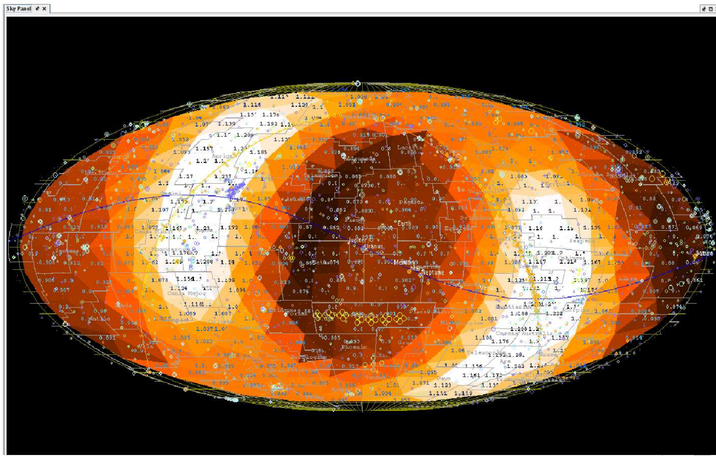


Figure 9: All-Sky competition plot using a HTM tessellation

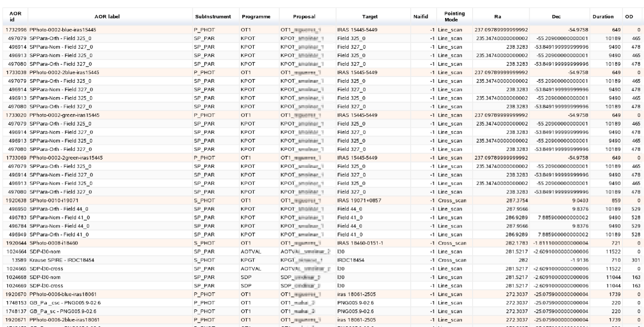


Figure 10: Duplication analysis: Each group represents a set of potentially colliding observations

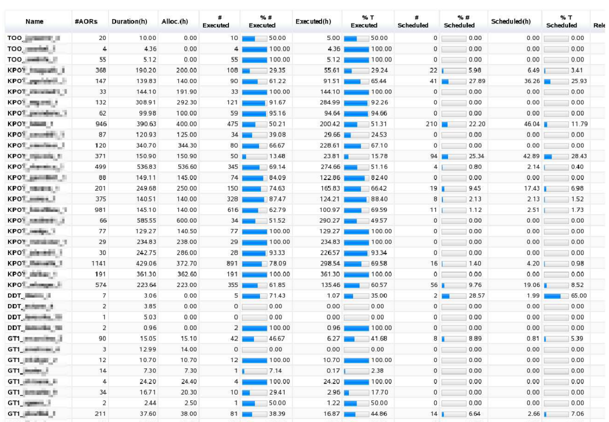
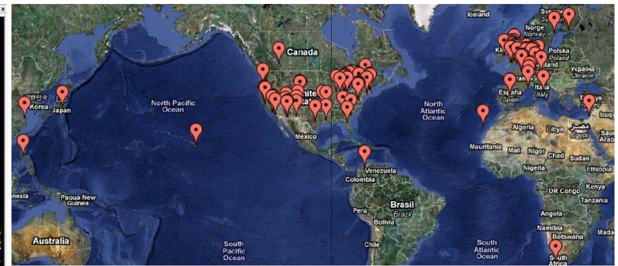


Figure 11: Proposal reports

terns

- commands to the scientific instruments to perform measurements
- commands to perform various engineering operations such as recycling the cryogenic cooler.



igure 12: Geographical distribution of Herschel's propos-ls

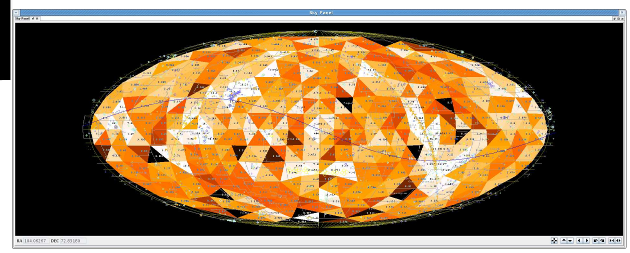


Figure 13: Observing time density using HTM tessellation

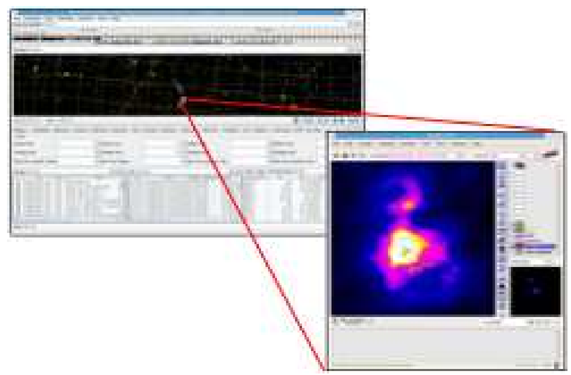


Figure 14: Joint HILTS-Aladin session centered at M42

For scheduling purposes, the mission is divided into operational days (ODs) that cover the period from the start of one DTCP to the start of the next. The duration of an operational day is nominally 24 hours, but may vary depending on the active ground station.

SMPS is a Java tool, whose main screen is divided into a set of views (see figure 16):

- *Time view:* displays the scheduled observations on a timeline, in addition to any temporal constraints on their placement.
- *Sky view:* displays the candidate observations that could be scheduled on that OD, plus any spatial constraints on their placement. In addition, it highlights the scheduled observations and draws the slew path that links them.
- *Requests table view:* displays the candidate observations as a multi-column table, giving details about each observation.

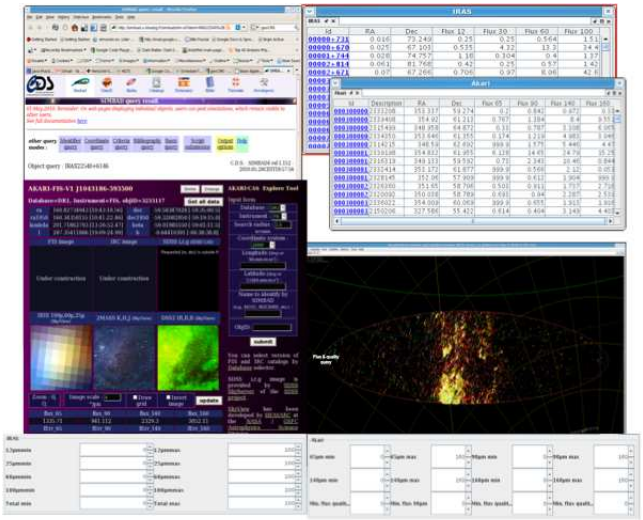


Figure 15: Catalog capabilities: IRAS and AKARI sources visible at the MGA Herschel constraint are displayed.

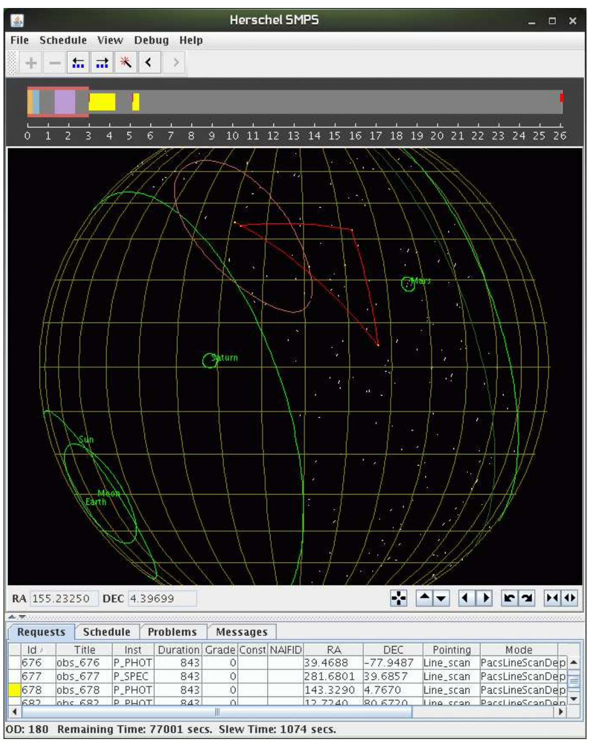


Figure 16: SMPS main screen

- *Schedule table view:* displays the scheduled observations as a time-ordered sequence.
- *Problems panel:* displays any validation problem detected when the user performs a validation or a simulation of the schedule.
- *Status panel:* displays general status information.

Short term mission planning

The short term mission planning process starts with the processing of an orbit file delivered by the Flight Dynamics team (FD) located at the Mission Operations Centre (MOC) in ESOC (European Space Operations Centre). An Orbit File is delivered to the HSC once a week, after trajectory optimizations, covering the remaining period to the end of the mission. Use of the ground station is shared with the Planck mission, which may in turn affect the scheduling of the Herschel DTCP.

The process continues with the loading of a Planning Skeleton File (PSF) delivered by the MOC (one PSF per OD). The PSF is effectively an empty schedule that defines time constraints on various operations, such as commanding the instruments and maneuvering the spacecraft. It also includes certain key events, such as Acquisition and Loss of signal (AOS/LOS) and the start/end of DTCP. Spacecraft Operations (SOPS) windows are included to reserve time for MOC to insert commands for orbit corrections, reaction wheel biasing, etc, when they receive the completed schedule from the HSC.

Scheduling observation of moving Solar System Objects (SSO), such as planets, comets and asteroids, makes use of ephemeris files that are obtained from the JPL Horizons system. The SMPS performs various corrections such as proper motion, stellar aberration and boresight alignment and in the case of SSO, light travel time.

The SMPS is used to add scientific observations and other activities to the schedule. When the Mission Planner is satisfied with the schedule, he generates a Planned Observation Sequence (POS) file that expands the observations down to the level of individual telecommands.

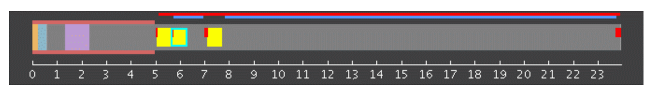
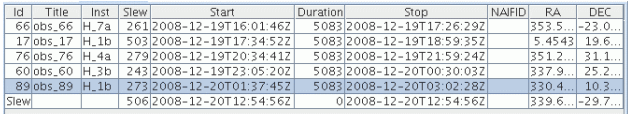


Figure 17: Operational Day time-line with 3 observations added. The observations are shown in yellow. The slews just before each observation and at the end of the OD are shown in red

The POS contains pointing commands that invoke basic ACMS pointing patterns, such as fine pointing, raster and line scan. More complex pointing modes are constructed using these basic modes as building blocks. While the spacecraft is executing a pointing pattern, such as a raster, the instrument is sent a sequence of telecommands, which must be carefully synchronized with the sequence of spacecraft maneuvers. This synchronization is achieved by defining the spacecraft and instrument commands for each observing mode in a special language which models the execution and timing of operations on the spacecraft.

The Mission Planner provides a summary of the schedule and gives it to the Project Scientist for approval. When it has been approved, the mission planner exports the schedule to MOC for further processing and uplink.

When MOC receives the schedule, they insert various commands such as orbit correction maneuvers, into the



Id	Title	Inst	Slew	Start	Duration	Stop	NAIFID	RA	DEC
66	obs_66	H_7a	261	2008-12-19T16:01:46Z	5083	2008-12-19T17:26:29Z		353.5...	-23.0...
17	obs_17	H_1b	503	2008-12-19T17:34:52Z	5083	2008-12-19T18:59:35Z		5.4543	19.6...
76	obs_76	H_4a	279	2008-12-19T20:34:41Z	5083	2008-12-19T21:59:24Z		351.2...	31.1...
60	obs_60	H_3b	243	2008-12-19T23:05:20Z	5083	2008-12-20T00:30:03Z		337.9...	25.2...
89	obs_89	H_1b	273	2008-12-20T01:37:45Z	5083	2008-12-20T03:02:28Z		330.4...	10.3...
Slew			506	2008-12-20T12:54:56Z	0	2008-12-20T12:54:56Z		339.6...	-29.7...

Figure 18: Example of an schedule with 4 HIFI observations and a final slew

SOPS windows reserved for them, and perform checks on spacecraft constraints and slew times. As a result of this expansion and checking, the POS becomes an Enhanced Planned Observation Sequence (EPOS) file. These form the the basis for uplink. If MOC encounter a problem, they may notify the HSC and request that the affected days are re-planned.

Each time the SMPS generates a POS file, it commits the changes in the database and marks the observations as 'scheduled' so that they are no longer available for scheduling in subsequent ODs. The SMPS does not allow further changes to the schedule unless it is first de-committed. This allows the OD to be re-planned and releases the observations so that they can be rescheduled. De-committing a schedule requires a procedural interaction with MOC to ensure that schedules are not changed once they have been uplinked to the spacecraft or executed. It also requires authorization from the Project Scientist.

The mission planning process is usually carried out on a weekly basis. MOC deliver a set of seven PSFs at least 15 working days prior to uplink. The HSC delivers the corresponding POS files back to MOC at least 10 days before uplink. This allows time for up to two iterations if problems are encountered. A shorter turn-around is possible in special cases, such as dealing with a Target of Opportunity (ToO). A ToO may require decommitting the affected schedule(s) and replanning.

Pointings

SMPS can display a schematic view of the observation pointing, which does not necessarily include all the complexities of the real observation, such as interrupted slews in line scans. The observation does not need to be scheduled, so the orientation is an approximate one for the OD. Once an observation is scheduled at a particular time, it is possible to generate a more accurate view using the ACMS simulator. In this case, the attitude evolution for the OD in a sky view is shown. It is possible to zoom in to inspect the details of an individual observation and it models subtle details of the ACMS behavior.

Figure 19 shows the simulation window zoomed-in to display the details of a line-scan observation. It can be seen that the scan slews back to the end of the scan line after deceleration because holds are inserted between the scan lines. The ACMS simulator also performs a final check of spacecraft commands and constraints.

Conclusions

The mission planning software used at Herschel Science Centre (HSC) has been presented. It covers the whole range

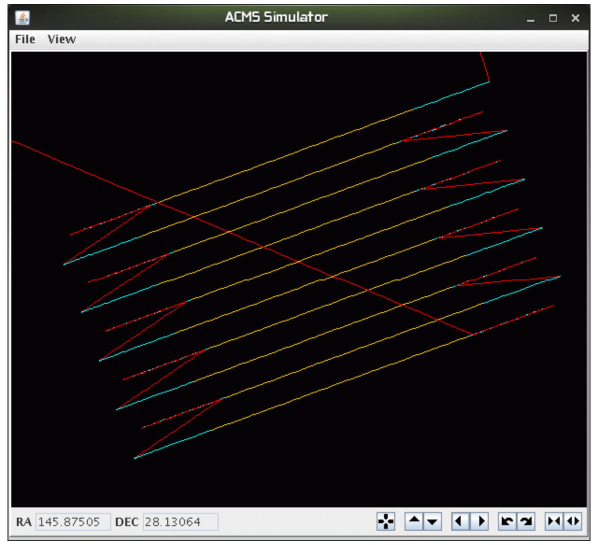


Figure 19: Detailed simulation of a line-scan

of needed functionality for dealing with the difficult task of mission planning and scheduling. HILTS deals with overall mission browsing, inspection, medium/long mission planning and statistical capabilities. The Scientific mission planning system (SMPS) with the detailed short-term scheduling producing the telecommand set to be uplinked to the Herschel satellite. Both tools have been developed using a common object-oriented framework. This framework has proven to be highly modular and potentially reusable for future applications.

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