Report on the meeting held in Toulouse (Nov. 2014) on tools for the scientific exploitation of Solar Orbiter data.

Frédéric Baudin[1], Eric Buchlin[1], Vincent Génot[2], Alexis Rouillard[2]

1. Institut d'Astrophysique Spatiale, Orsay, France
2. Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

1. Introduction

Solar Orbiter will provide unprecedented observations of the Sun and in-situ measurements of the inner heliosphere from heliocentric radial distances as close as 0.28AU. It is therefore a great opportunity for the solar and heliospheric communities to work together at studying the solar-heliosphere coupled system. **Tools for operation planning, data browsing and analysis have to be designed to facilitate comparisons of in-situ measurements and remote-sensing observations to optimise the scientific return of the mission.**That is why the two French data centers built around space remote sensing observations of the Sun (MEDOC - Multiple Experiment Data and Operation Center, http://medoc.ias.u-psud.fr/) and around in-situ measurements in the heliosphere (CDPP - Plasma Physics Data Center, http://cdpp.eu/) have decided to organize a **workshop on the tools for the scientific exploitation of Solar Orbiter** (focused on simple and fast tools rather than on complex analysis methods), in the frame of the national initiative for solar-terrestrial relations (PNST - Programme National Soleil-Terre, http://www.ias.u-psud.fr/pnst/). This workshop took place in Toulouse on November 4th to 6th (see http://www.ias.u-psud.fr/pnst/atelier_2014/, where the program and the presentations are available). We thank the scientists and engineers who attended this lively and constructive 3-day meeting. We also thank the PNST who have made this workshop possible and the CNES for continual financial support of our data centers.We report here the final thoughts resulting from this workshop related to tools for planning, data selection and analysis. We propose to strengthen ongoing tool developments and propose new actions. These actions are organized in different sections corresponding to the sessions of the meeting: planning and low-latency data, in-situ measurements, remote sensing observations, and their connections.

The references and acronyms used in the following can be found in the appendix.

2. Tools for planning, and Low-Latency data

Preliminary plans at ESA for operational planning tools, including low-latency (LL) data visualization, were shown (SOLab, eFinder, EPS, MAPPS). The present plans did not raise particular comments, but a clear interest for LL data has been expressed. Indeed, for some instruments such as EUI, some of these LL data will have a quality similar to regular data (they will just be much less frequent) and could then be very useful, first for planning (especially when SO will aim at the far-side of the Sun), and second for public outreach allowing a more or less continuous coverage of SO observations.

3DView (http://3dview.cdpp.eu/) is another tool developed at CDPP, that could prove useful for the planning of coordinated observations campaigns. 3DView provides visualizations of orbits of different celestial objects and spacecraft, including SO, Solar Probe Plus (SPP), STEREO…, and the Earth for ground-based observations. 3DView also offers the possibility of plotting the field-of-view of remote-sensing instruments, as well as in-situ data along the orbit, which can be also useful for scientific exploitation (see Figure below).

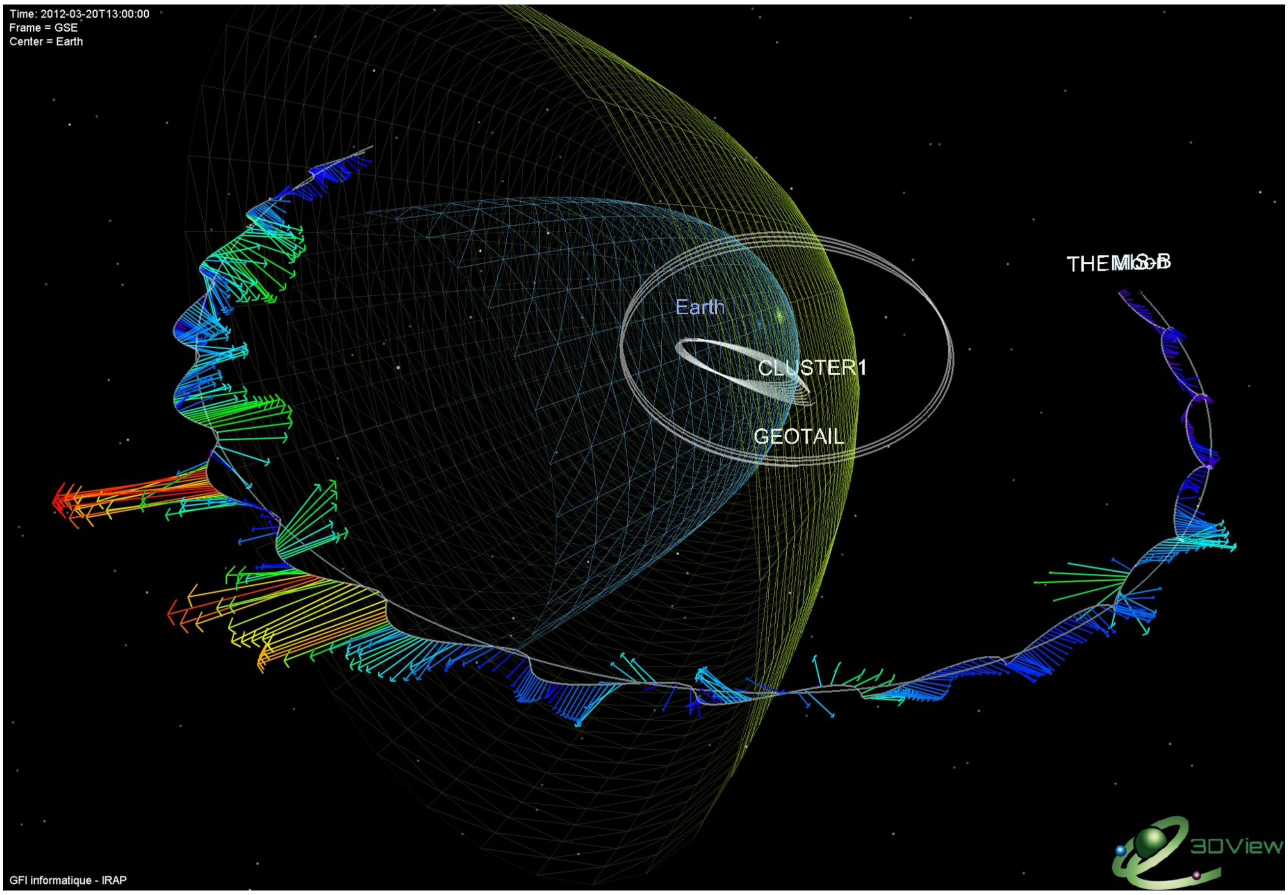

Figure 1 - 3DView illustration : Earth magnetosphere viewed from the tail dawn side with Cluster 1, Geotail, Themis B & C trajectories for several days. Themis B & C are in orbit around the Moon (hence the cycloids). The arrows represent the magnetic field as measured by Themis B. Magnetopause and bow shock models are also shown.

For the long-term planning (at mission-level, or for several orbits), the choice of the main scientific objectives will depend on the phase of the solar activity cycle during each SO orbit and on the activity expected then. But more precise activity forecasts (for example from data assimilation methods) now exist, and they could be used for further optimizations of the long-term planning.

3. Tools for in-situ measurements

Simple methods/tools to connect events at the Sun to SO clearly appeared as a need for the in-situ community. This can be thought of at different levels of complexity. Ideally propagation delays between solar images and in-situ data should be computed and readily available through data-browsing and data-mining tools. This may be done from simple ballistic consideration or by taking into account more complex magnetic geometry based on PFSS+solar wind models. **In any case the aim is to have methods that the user easily understands (no black box) and which are robust enough to have them embedded in automatic tools.** Further model sophistications are relevant for research activities and thus outside the initial scope of "simple tools" aimed at facilitating in-situ remote-sensing comparison. Further discussions on this central aspect are reported below.

AMDA (CDPP) is a robust tool that, for years, proved useful for many studies and in different mission contexts. The recent example of providing quicklooks for Rosetta plasma data (to a restricted group of users, RPC) shows that it could be adapted to SO needs. It should be pointed out that the interest of the tool lies into its ability to ease cross-comparison between instruments (or missions). **Therefore, if RPW and SWA teams are willing to have their data integrated into AMDA, it is highly desirable that MAG and EPD follow the same route.**

On the data representation, the need appeared for "status bars" exposing particular modes of operations (ex: burst for IS data, 'on/off' for remote-sensing data).

Another tool for in-situ data was presented: CL (IRAP). All kinds of data can be plotted, but the strength of CL is its ability to deliver fast and versatile representations of particle distribution functions. **AMDA and CLWeb have been encouraged to collaborate and develop bridges (in particular for the analysis of distribution functions).**

Whatever the display tool, an important requirement emerged concerning the "trust in data". This can be achieved by always tracing the source, version number, calibration files, spice kernels … which must readily be accessible to the user. This could be discussed within the ESA MADAWG team during the METADATA definition phase.

Different "automatic" methods to detect features such as CIR, shocks, … have been developed. Some of them will even be used to routinely trigger mode changes onboard instruments (ex: shock detection for RPW, see Kruparova et al., 2013). **Data mining tools could then similarly be tuned to offer the "automatic" computation of catalogues of event as new data flow in.**

4. Tools for remote sensing observations

Combining data from different SO remote-sensing instruments

An obvious aspect of SO data exploitation is the ability to easily superpose remote-sensing observations. When combining images from different instruments for scientific analysis, possible **misalignments** between them can be a serious issue. The misalignments measured on ground before launch will be taken into account, but misalignments due to thermo-elastic variations once in orbit may remain an issue. Few possibilities seem to allow the correction of this effect. The use of images taken at the limb could be a solution but since the different instruments have no common wavelength of observation, this correction may remain inaccurate (as different structures are seen, even at the limb). An anticipated important misalignment between SPICE and the high-resolution fields-of-view of EUI and PHI might also reduce the possibilities of using both SPICE imaging windows at the ends of the narrow "dumbbell" slits for alignment of SPICE data.

Several map projections could be used, and projection tools already exist in SolarSoft, but the code developed by C. DeForest could be also very useful. The translation of this code from PDL (module Transform::Cartography) to languages like IDL and Python should be considered.

For browsing purposes, HelioViewer (see Fig. 2), and in particular the new HelioViewer 3D version being developed at FHNW, seems to be a nice tool to view the combination of data from different instruments.

Then, in addition to taking the misalignments into account, a remote-sensing visualization tool should allow the user to choose between **different vantage points**: Solar Orbiter, Earth, Solar Probe+ (e.g. WISPR)… Several points of view or map projections could be displayed simultaneously in different windows. The superposition of a grid of coordinates would be useful. The instrument SoloHI presents a special case due to its very large angular field-of-view: when combined with other instruments, SoloHI images could optionally be displayed using a logarithmic scale in distance to make them viewable at the same time as disk images.

When visualizing **time sequences** of data sets including ones with low cadences compared to the others, the display of the latter should take the solar differential rotation into account.

For planning purposes, to prepare future observations, the visualization should possibly include some forecast of the evolution of structures (for example by an advection-diffusion model), in addition to differential rotation and to the other requirements for browsing purposes.

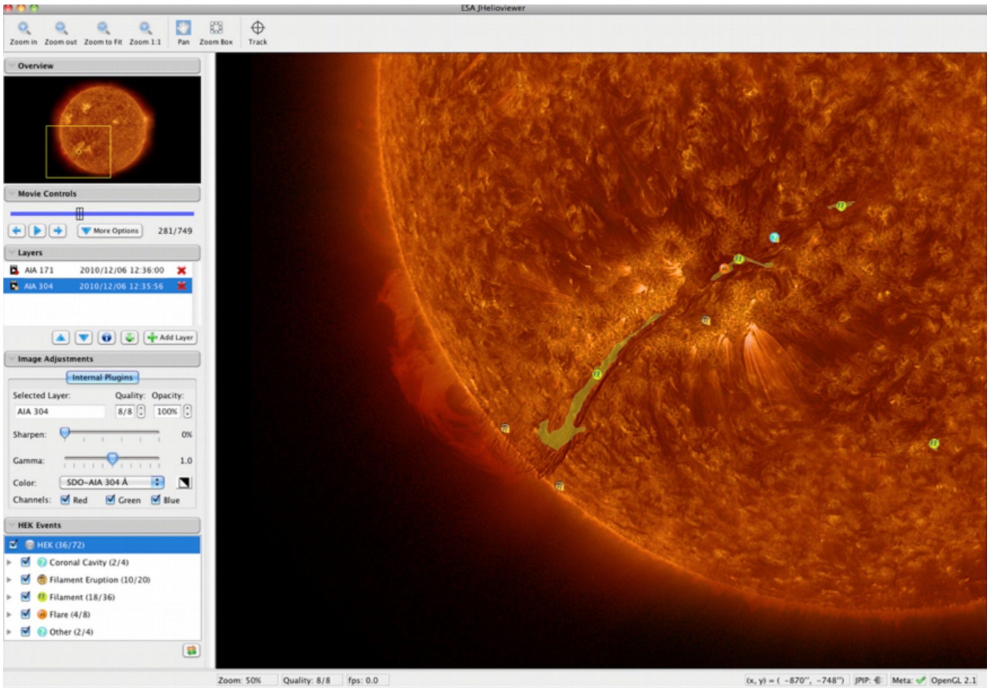

Figure 2: Illustration of JHelioViewer

Complementary data

The need of complementary data is obvious, first to plan observations and then to interpret them. Thus, some of these complementary data should be usable with Solar Orbiter data, for scientific analysis or in the chosen viewer. However, since any new data in JHelioViewer represents data storage and work to be done (for data ingestion, and, in the current version, for adapting the clients), new data can be included only if there is a sufficient interest.

Other space data would be very useful and many are already included in JHelioViewer and the upcoming 3-D version of JHelioviewer. Ground-based data is interesting too, but priority would go to data with a good continuity in time. **This includes on the one hand radio observations (which are not dependent on weather), and on the other hand the data provided by networks such as GONG.** GONG provides several potentially useful data products: vector magnetograms (for magnetic field extrapolations and the connection to in-situ measurements), Hα disk images (for identification of solar filaments), and seismic far-side imaging of magnetic structures (for SO observations planning when SO is observing on the far side of the Sun).

5. About the in-situ/remote sensing connection

Linking Solar Orbiter to the Sun

Solar Orbiter will provide detailed tracking and measurements (among others) of coronal mass ejections, the background solar wind and solar energetic particles. These features propagate differently to 1 AU: on average, CMEs and CIRs propagate radially outward to 1AU but with often very different kinematic properties whilst energetic particles follow the coronal and interplanetary magnetic field lines. Tools that aim to connect solar structures to in-situ measurements need to address these different propagation mechanisms.

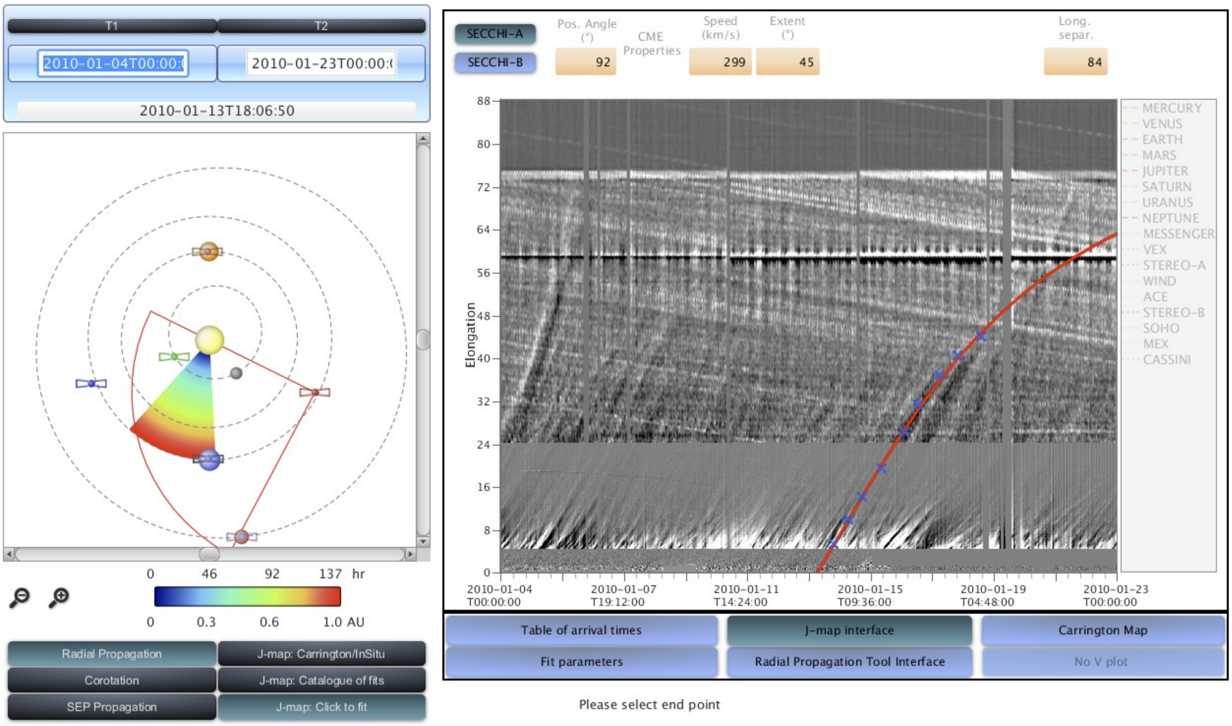

Figure 3: Propagation Tool illustrating here access to STEREO HI J-maps and superposed CME trajectories.

The Propagation Tool (http://propagationtool.cdpp.eu/) developed by the Solar-Terrestrial Observation and Relations Service (STORMS) and the CDPP and MEDOC data centers provides easy access to simple estimates of CME, solar wind and energetic particle propagation. The Propagation Tool provides links to the CDPP and MEDOC data centers thereby allowing users to start with in situ data stored at CDPP and find the relevant solar images in the MEDOC archive at the estimated release time or vice versa. This tool could also be interfaced with SiTools, a software developed by CNES and widely used at MEDOC for the distribution of present solar space misions (SoHO, STEREO, SDO): the Propagation Tool functionalities could be developed as web services thus allowing requests made from SiTools or other software to integrate lag time due to propagation. **To work with Solar Orbiter data, an out-of-ecliptic mission, a 3-D version of the Propagation Tool will need to be implemented.**

The 3-D aspect is of particular importance in the lower corona where magnetic field lines do not follow the Parker spiral model. In order to determine the origin in the lower corona of the particles detected in-situ, coronal magnetic field line reconstruction techniques need to be used. These techniques are typically based on photospheric magnetograms. The magnetic field measured by PHI or other instruments will be an important input for such reconstruction techniques. **Since the aim is not an ultra high-resolution determination of the magnetic structure in the low corona, an extrapolation based on Potential Field Source Surface (PFSS) could be considered as sufficient for the simple tools considered here.** The new 3-D version of JHelioviewer provides access to such reconstruction techniques. It is based on the archive of pre-calculated field line coordinates derived from PFSS and maintained by the Lockheed-Martin and Astrophysics Laboratory accessible via SolarSoft. The use of PFSS calculations requires some care about the determination of the lower boundary condition for the magnetic field in the hidden parts of the Sun (which can be obtained by modeling where observations from suitable other viewpoints are not available). Beyond the source surface, the upper boundary of PFSS extrapolations usually placed around 2.5 solar radii, the structure of the magnetic field has to be connected to larger distances, including the SO orbit. **Some work is under progress in Toulouse at the CDPP and STORMS for a reconstruction of the coronal/solar wind magnetic field based on a physical description of the acceleration of the solar wind using simple hydrodynamic codes.**

More advanced magnetic field reconstruction techniques that go beyond the PFSS model were also briefly discussed during the workshop, they included Non-Linear Force-Free Extrapolations (NLFF) like the family of XTRAPOL models (potential, linear and non-linear) developed at Ecole Polytechnique in Paris. These models will be discussed at the MADAWG meeting on more advanced numerical models for Solar Orbiter in February 2015.

Advanced data search

Due to its particular profile, the SO mission will provide remote-sensing observations only for given and relatively short time windows (in-situ measurements will be continuously performed). Thus, when making the data available for the scientific community, a particular tool for data searching would be needed. While data search based on observing or measurement time is common, this is not enough to find events interesting for scientific analysis. The list of results should not be excessively long; searching would be made easier by allowing the user of a data archive to search for data related to CME, filament/prominence, active region, etc. Such catalogs have already been developed in the frame of the HELIO European project (see for example the Heliophysics Feature Catalog at http://helio-hfc.ias.u-psud.fr/), or with the Heliophysics Event Knowledgebase, already plugged into HelioViewer (see Fig.2). This is also the main goal of the FP7 HELCATS project currently under way, which aims at providing detailed catalogues of CMEs and CIRs imaged by the new generation of heliospheric imagers on STEREO as well as ICMEs and CIRs measured in situ. The expertise developed at building these catalogues will prove useful for Solar Orbiter catalogues as well.

When searching data, the tool used should also show the observation coverage or data availability of each instrument in a simple and graphical manner.

The above general remarks on “propagation” should also guide studies/developments of adequate methods aiming at more easily interfacing in-situ data with remote-sensing imagery. The methods integrated in the Propagation Tool could be exposed as independent services (typically as web-services).

6. Conclusion

The partners involved in this workshop (CDPP, MEDOC, PNST) make proposals for some contributions to Solar Orbiter exploitation through this document sent to ESA, CNES, the Solar Orbiter MADAWG (Modelling And Data Analysis Working Group), and the PIs of the Solar Orbiter instruments. The CDPP and MEDOC are open to discussion in the aim of coordinating the future developments at the ESA level in coordination with CNES. The foreseen developments/studies may be summarized as follows:

- enhancement of Helioviewer to take into account SO specificities (point of view, need for planning well before observations) and to include SO data, useful complementary data, and magnetic extrapolation,
- enhancement of 3DView to take into account proper SO imager FOV and models of heliospheric magnetic field,
- development of solar wind models (also to be used in the above tools),
- development and coordination of AMDA/CL for 1/ visualization functionalities displaying observation contexts (modes, imagery, …) and 2/
- displaying all IS data in advance or simultaneously to the ESA archive,
- development of a Propagation service (based on the propagation models of the Propagation Tool),
- to study the possibility to implement automatic feature (shocks, CIR, …) detection in order to produce up to date catalogues of events.

Annex: references and acronyms

AMDA: Automatic Multi-Dataset Analysis
CDPP: Centre de Données de Physique des Plasmas
CIR: co-rotating interaction region
HFC: Heliophysics Feature Catalog
IHP: InterHelioProbe
LL: low-latency
MADAWG: Modeling and Data Analysis Working Group of Solar Orbiter
MEDOC: Multi-Experiment Data and Operation Center
PNST: Programme National Soleil-Terre (Solar-Terrestrial Relations Initiative)
PFSS: Potental Field Source Surface magnetic extrapolation
PropTool: Propagation Tool
SO: Solar Orbiter
SPP: Solar Probe Plus
STORMS: Solar and Terrestrial ObseRvations and Modelling Service.