CLUSTER SCIENCE PLANNING – LESSONS-LEARNED FOR FUTURE PLASMA MISSIONS

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ABSTRACT

This paper outlines the Cluster science planning work undertaken at the Joint Science Operations Centre (JSOC). It first summarises some of the key items in the evolution of JSOC over what is now 13 years of activity. It then outlines the current approach to generation of Cluster planning (the Master Science Plan). This is followed by a summary of the key lessons learned from Cluster and their application to future multi-spacecraft missions (including the continuing operations of Cluster through to 2009).

1. INTRODUCTION

The Cluster Joint Science Operations Centre is responsible for coordinating the planning and commanding of Cluster payload operations on behalf of the ESA Project Scientist. JSOC was established in 1993 and was ready for the first unsuccessful launch of Cluster in 1996. Following the approval of Cluster-II, JSOC was adapted to reflect key changes in mission operations. Cluster was successfully launched in the summer of 2000 and, following commissioning, JSOC commenced routine operations of the Cluster payload in January 2001. JSOC has operated successfully since that date and has built up extensive experience of multi-spacecraft science operations.

Cluster science planning has evolved considerably over the years and, in particular, during nearly five years of actual operations. Much of this evolution has been externally driven by changes in mission operations. For example, the addition of a second ESA ground station, in the summer of 2002, allowed expansion of orbit coverage from 50% to 100%; this required significant changes to JSOC software and procedures. At the time of writing further JSOC changes are underway to adapt from two ground stations with similar visibility (Vilspa and Maspalomas) to two with very different visibility (Maspalomas and Perth).

These changes have also been an opportunity for internal changes to implement lessons-learned. A consistent theme in the consequent improvements is the need for planning to be guided by realistic modelling of the Cluster science data flow. The mission started with planning guided by statistical rules for average data flow. These proved to be cumbersome to use and failed to detect some pathological cases where burst mode periods could have caused on-board storage to overflow. These rules were replaced in 2002 by an approximate modelling of data flow and in 2005 by an accurate modelling of data flow. These changes have made it much easier to plan Cluster operations. The growing reliability of the data flow model allows us to have confidence when scheduling burst mode in locations outside previous experience.

Another important theme in lessons-learned has been a gradual but consistent extension in the use of software tools for well-defined tasks. This allows human effort to focus on high-value tasks that call for judgement to maintain the high quality of Cluster science operations.

In the rest of this paper we first outline how Cluster planning is performed today. We then summarise key lessons learned along the route to the present JSOC planning approach. Finally we highlight how some of these lessons will be applied in the second Cluster extension covering 2006 to 2009.

2. CLUSTER MASTER SCIENCE PLAN

The generation of Cluster Master Science Plan (MSP) is outlined in Fig. 1. The key features are:

1. We generate a baseline plan giving 100% coverage in normal data rate mode using orbit and event data from ESOC [1], together with additional events obtained from models run at JSOC [2]. The baseline plan is identical on all four spacecraft.

2. We add any special operations required to maintain instrument safety and satisfy constraints advised by ESOC. These are typically periods when data-taking is stopped briefly: (a) while sensitive instruments are switched off around manoeuvres (residual gas from the thrusters could cause arcing of high-voltage systems); and (b) when payload operations are stopped to conserve battery power around long eclipses. These special switch-off periods may be specific to one particular or applied to all four spacecraft.

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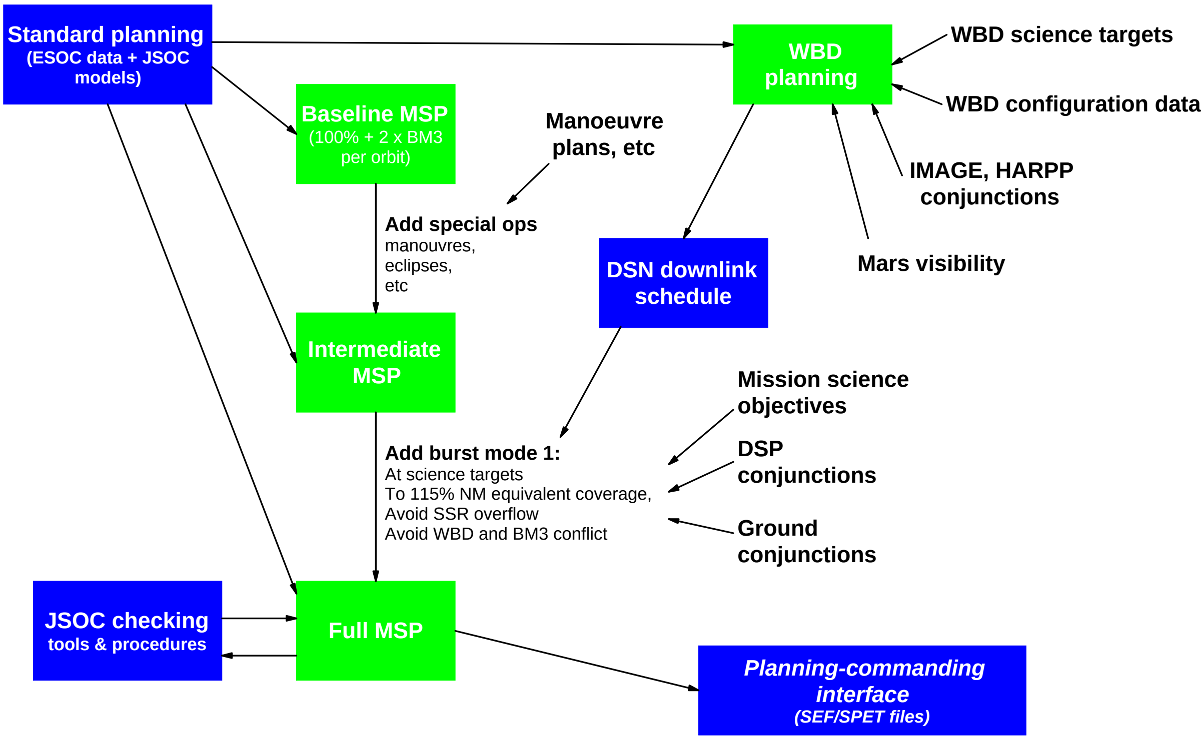

Fig 1. Generation of the Cluster Master Science Plan

3. We add burst mode periods in which data are collected at six times normal rate. These are inserted at suitable science targets (e.g. cusp, magnetopause, plasmasheet) – and especially where those targets are in conjunction with other missions (such as Double Star) or with ground-based systems (such as EISCAT). Given the highly dynamic nature of space plasma phenomena, these periods are simultaneous on all four spacecraft; we do not attempt to phase burst mode with respect to the spacecraft separations. The assignment of burst mode periods is subject to constraints on telemetry modes (e.g. the spacecraft cannot run burst mode while downlinking data to DSN, see below). Most importantly the use of burst mode is constrained by the overall data flow back to Earth (i.e. on-board storage and downlink capacities). Thus JSOC uses a simple model of this data flow to identify periods in the timeline when there is capacity to collect burst mode data. This model is also used to verify that scheduled burst mode does not risk overflow of on-board storage. In all cases the model separately calculates the data flow for each spacecraft, but then extracts the worst case, as this is the critical factor limiting simultaneous observations on all four spacecraft.

4. In parallel with the planning steps above we support planning of Cluster downlink to the NASA Deep Space Network to support operations of the Cluster WBD instrument. WBD data are downlinked in real-time, so this planning must find periods of opportunity when the spacecraft are in a position: (a) to take data to address WBD scientific objectives, (b) visible from DSN ground stations, and (c) not visible from the ESA ground stations used for Cluster (to eliminate conflict with ESA up/downlink). These periods of opportunity are passed to DSN, who select a sub-set of opportunities for implement. JSOC use only this sub-set to constrain the scheduling of Cluster burst mode data acquisition.

5. The validated Master Science Plan is made available on the JSOC web site [3] in both tabular and graphical formats. Fig. 2 shows an example of the graphical format. This is the Bryant plot format, first developed for AMPTE-UKS [4]. The horizontal axis represents time incrementing uniformly – here represented as a full orbit number inclusive of a fractional part. The vertical axis represents orbit phase, i.e. time since last perigee. Thus each orbit is represented by a line gradually sloping to the right, with the starting perigee at the bottom of the plot, apogee mid-way up the plot and the ending perigee at the top. The width of the line shows the type of data-taking at each point: dashed line = no data-taking, thin solid line = normal mode data-taking and thick solid line = burst mode data taking. Other symbols represent events such as radiation belt exit and entry, WBD data-taking periods and plasma boundary crossings. The example in Fig. 2 represents a period when Cluster apogee was in the tail, so the main boundary is the tail neutral sheet, shown by small squares. On dayside obits the magnetopause and bow shock crossings are shown. Note that the Bryant plot is generated for a specific spacecraft – in this case Cluster

spacecraft 1 (Rumba). The baseline operations of the other spacecraft are very similar and thus a single plot is considered adequate for the purpose.

6. The validated Master Science Plan is also used to generate internal data products that drive the JSOC commanding sub-system. The interface between planning and commanding [5] uses these products, together with rules provided by instrument teams, to (a) derive the required timeline of instrument modes and (b) construct a draft timeline of command sequences needed to command the instruments to execute those modes. This draft is made available for PI review and revision.

This approach has proved very effective in supporting the planning of Cluster multi-spacecraft operations within the limited resources available. The baseline plan of 100% coverage (Step 1) is very easily achieved. The cost driver for planning is the complexity brought by special operations such as manoeuvres and eclipses and by the need to plan special data acquisitions (burst mode, WBD), i.e. steps 2, 3 and 4.

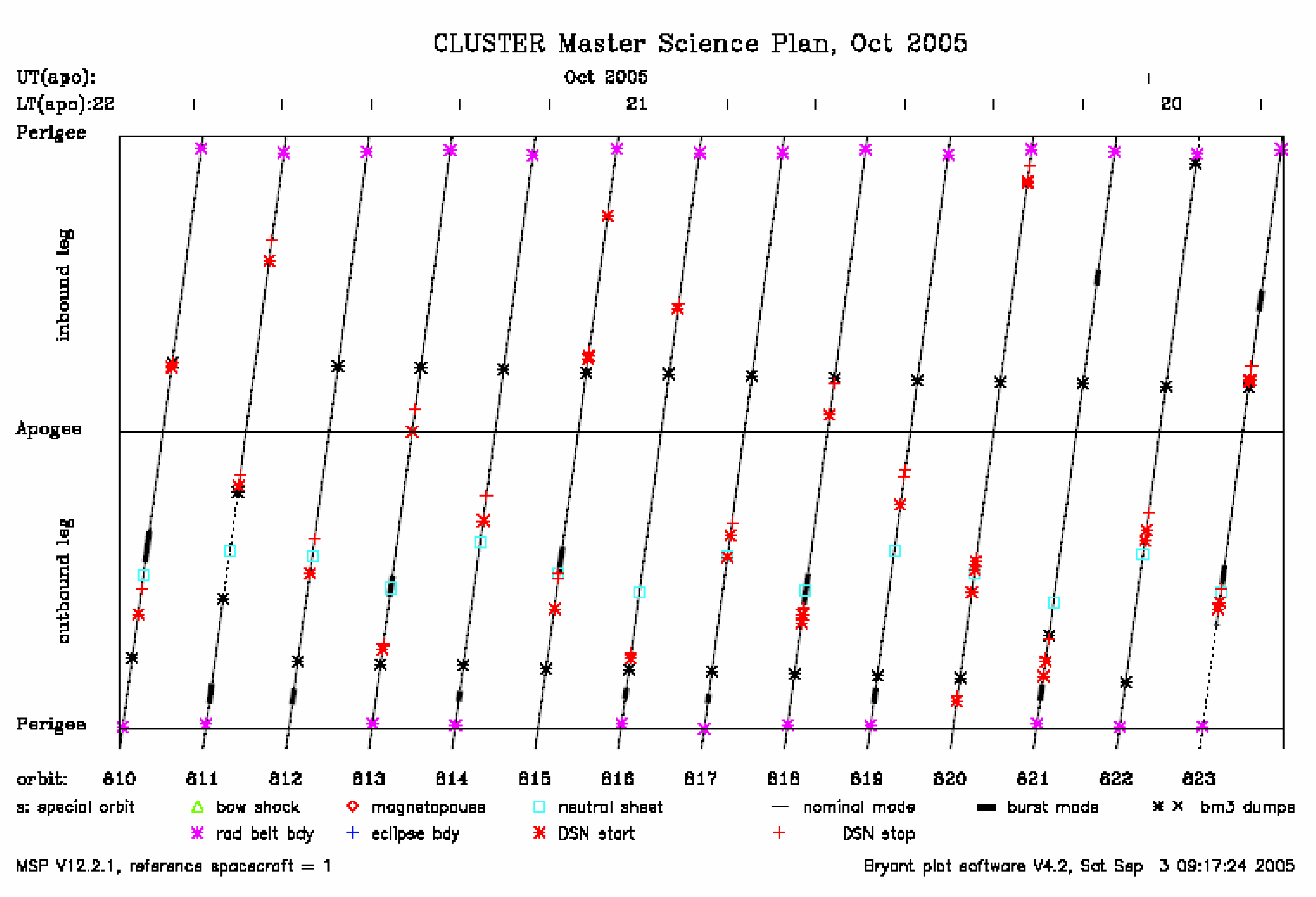

Fig. 2. Bryant plot for 14 Cluster orbits in October 2005

3. LESSONS LEARNED

3.1 Full orbit coverage is critical

The most important lesson from Cluster operations is to confirm an old lesson. This is that solar-terrestrial studies need continuous time series of observations. As noted in the introduction, Cluster had 50% orbit coverage up to the summer of 2002 and 100% coverage thereafter. It is widely recognised in the Cluster community that the change to 100% coverage has greatly improved the Cluster science return, e.g. by ensuring that important events are not missed or truncated. From a JSOC viewpoint, the introduction of 100% coverage brought a major operational advantage. It eliminated the need to plan where not to take data, which was a very difficult task. Its elimination allowed JSOC to make the transition from 50% to 100% coverage at no additional cost.

It is important to understand that 100% coverage ensures that we observe the fuzzy targets that exist in the space plasma environment (e.g. magnetopause, bow shock, plasmasheet). Their location is subject to considerable natural uncertainty as shown in Fig. 3.

below. This uses a Bryant plot format, as in Fig. 2, to compare observed and predicted crossings of the bow shock and magnetopause. The 1σ uncertainty of these crossings is 3 to 5 hours for the Cluster orbit (see below).

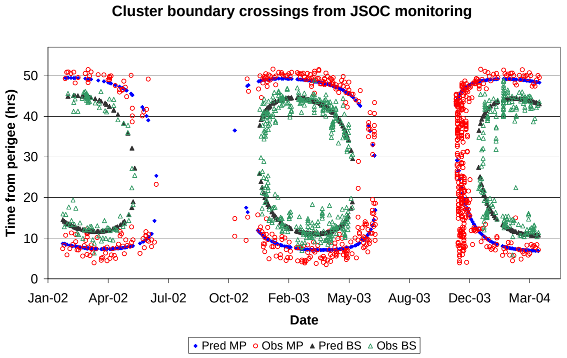

Fig. 3. Observed and predicted locations of Cluster magnetopause and bow shock crossings

The figure demonstrates how continuous time series ensure that we see response to events mediated by solar wind inputs. There are many early magnetopause crossing in November 2003; these appear as “tail” of points extending down towards the bottom of the plot. Such space plasma events are inherently unpredictable on timescale of Cluster planning. Successful observations require either 100% coverage or real-time control (to respond on the ≤ 30 minute timescale on which good predictions are feasible). Today that requires an unaffordable 24 by 7 ground control, but might be more feasible in long-term via autonomous operation.

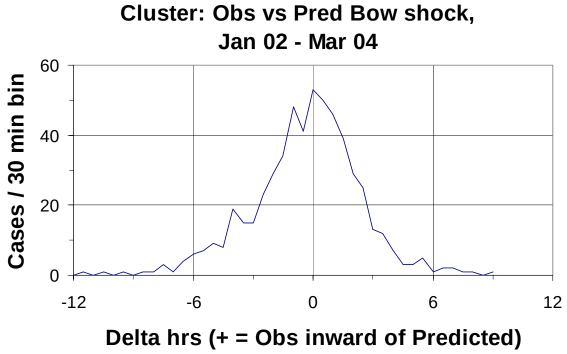

Fig. 4. Distribution of Cluster bow shock crossings

Fig. 4 above shows the distribution of time differences between observed and predicted bow shock crossings. For 560 cases, this distribution is symmetric with a mean of -0.6 hours and standard deviation of 2.7 hours.

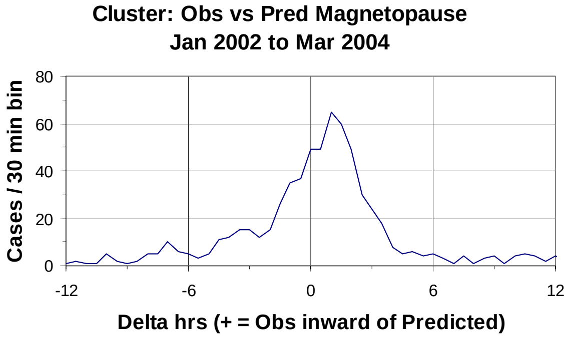

Fig . 5. Distribution of Cluster magnetopause crossings

Fig. 5 below shows a similar distribution of time differences for magnetopause crossings. For 669 cases, this distribution has a mean of +0.5 hours and a standard deviation of 5.0 hours. The marked asymmetry arises from the “tail” of early magnetopause crossings in November 2003 as shown in Fig. 3.

3.2 Keep it simple

As previously noted Cluster planning is dominated by scheduling occasional activities such as burst mode, DSN downlink and special operations – and also coordination with other missions. These all require careful planning to separate incompatible activities, to respect resource constraints, and to validate that all these issues are addressed in the final Master Science Plan. It is these occasional activities which drive operations costs, not the core science objective of 100% orbit coverage. Fig. 6 illustrates the problem. The planning of complex operations must balance many factors relating to individual spacecraft, to individual ground stations and other relevant missions.

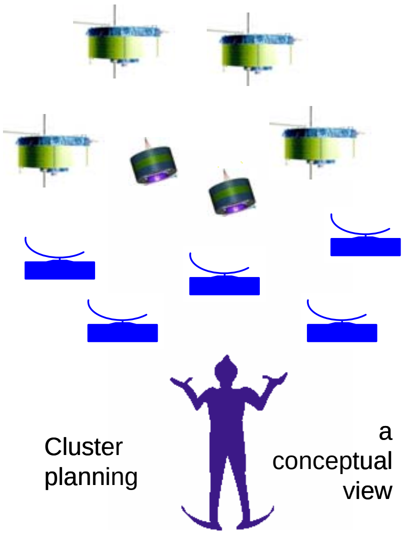

Fig. 6. Cartoon illustrating complex operations.

Future space plasma missions would benefit from focus on simple science operations that produce consistent data and, as far as possible, avoid complexity. It is vital to consider science operations from the start of mission design, if costs are to be controlled while delivering the high scientific return. It is important to have visibility of how the evolution of ideas during mission development will impact operations work and be clear that any cost impacts are acceptable.

3.3 Tools for multi-spacecraft planning

The planning and analysis of multi-spacecraft operations is vitally dependent on good software tools. The key functions are outlined in Fig. 7 below and then described in some detail.

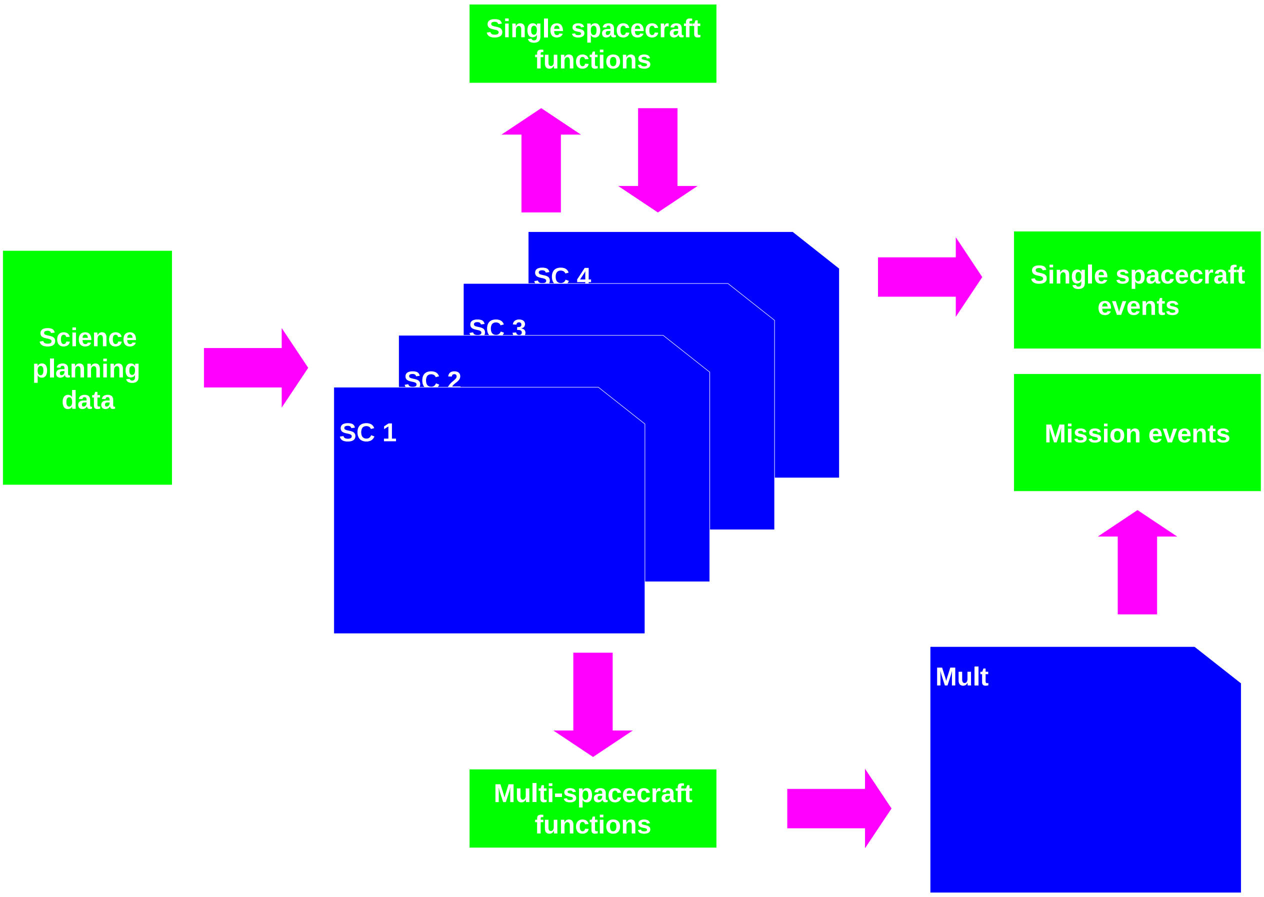

Fig. 7. Schematic of functions needed in a multi-spacecraft planning tool

The key planning functions are:

1. Ingestion of externally sourced time series of planning data for each spacecraft (e.g. its predicted position and velocity).

2. Internal generation of new time series fields via functions that apply to a single spacecraft (e.g. distance from key plasma boundaries, distance from a ground station)

3. Internal generation of new time series fields via functions that apply to an ensemble of spacecraft.

4. Derivation of single spacecraft and mission-wide events from these time series.

These tools must support flexible addition of new functions both at single and multi-spacecraft level. This flexibility is essential if the science planning is to respond to natural evolution of the mission. This evolution comprises (a) the evolution of science objectives in respond to results from the mission itself and from parallel scientific activities, (b) changes in spacecraft and instrument performance as they age through operational wear-and-tear and through exposure to the space environment, and (c) changes in the orbit due to manoeuvres and luni-solar perturbations leading to changes in the regions encountered along the orbit. An example of orbit change is Cluster's 2009 encounter with the auroral acceleration region.

Fig. 8 and Fig. 9 below show examples of single spacecraft functions used in Cluster planning. Fig 8 shows a recently-introduced function used to plan WBD observations of kilometric continuum. The scientific constraint on this planning is that the magnetic latitude must be greater than 30° (north or south) and the geocentric distance of the spacecraft must be greater than 8 Earth radii. Fig. 9 shows a long standing JSOC planning function which estimates the distance of the spacecraft from the tail neutral sheet (e.g. using a neutral sheet model such as that of Tsyganenko). This can be then used to schedule plasmasheet observations.

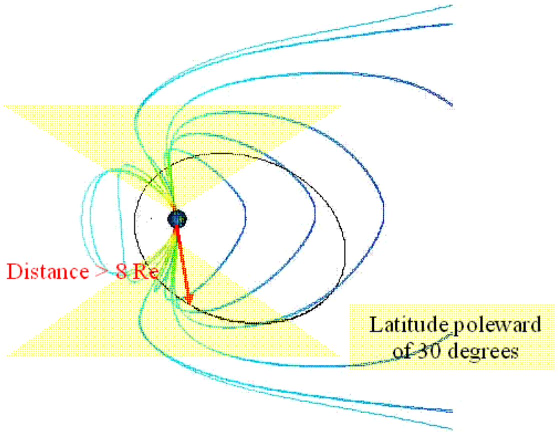

Fig. 8. Cluster planning function: Use GSE position (X, Y, Z) to derive magnetic latitude & geocentric distance.

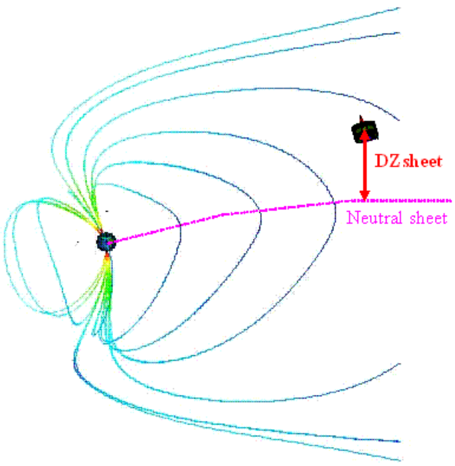

Fig. 9. Use GSE position (X, Y and Z) to derive spacecraft distance from the tail neutral sheet.

4. SUMMARY

The history and current status of the Cluster planning work has been outlined. Three key lessons-learned are presented:

- The critical importance of 100% orbit coverage
- The great value of keeping operations simple
- The need for good software tools for multi-spacecraft planning

It is intended that these lessons-learned will be applied to main the quality of science operations during the now-agreed extension of Cluster operations to 2009. It is also hoped that they can be passed to other missions.

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6. REFERENCES

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