USE OF ON-BOARD AUTONOMY FOR FUTURE SPACE PLASMA STUDIES

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ABSTRACT

This paper seeks to stimulate debate on autonomous operation for future space plasma studies. We outline some possibilities for such operations: (a) transfer on-board of payload planning based on the sequence in which the spacecraft cross different scientific regions (e.g. as now done on the ground for Cluster and Double Star), and (b) options for a responsive approach in which real-time measurements are used to control payload operations. We propose ideas for future work that could promote debate on what autonomy can do (in particular, to improve scientific return) - and thereby to establish whether and when autonomous operations will become a real possibility for space plasma studies.

1. INTRODUCTION

It is frequently stated that future space plasma missions, such as CrossScale, should consider autonomous operations, but with little discussion of what autonomy means in this context. It is very timely to start such discussion so that the high-level requirements and design of future missions can capture the potential for autonomous operations to improve the scientific return. To promote that discussion we present two potential approaches to on-board autonomy for plasma studies and discuss their implications for high-level mission requirements. The two approaches are:

Predictive autonomy. This involves the on-board planning of observations using knowledge of spacecraft position to predict the crossing of different plasma regions and thus select the appropriate observing modes. This is essentially the transfer on-board of the planning processes currently performed by ground-based science operations centres such as the Cluster Joint Science Operations Centre (JSOC) [1,2].

Responsive autonomy. This involves the on-board assessment of current plasma conditions and their interpretation to set appropriate observing modes. This is the automation of the manual control used at ground-based science operations centres where and when real-time spacecraft access was available (e.g. AMPTE-UKS in the 1980s [3]). If such processes can be automated, their transfer on-board will allow autonomous operations outside ground station contact.

We note that these two approaches are not exclusive nor can we be sure that they represent the only options. They are presented here as a convenient way to stimulate much-needed debate. To promote that debate the rest of this paper discusses the two approaches in some detail and identifies some key questions for further debate.

2. PREDICTIVE AUTONOMY

As noted above predictive autonomy requires on-board knowledge of spacecraft position. There are a number of strategies to achieve this. The obvious modern approach for Earth-orbiting missions will be to use one of the global navigation satellite systems (GNSS) such as GPS or Gallileo. But this will work only when the spacecraft is inside the GNSS constellations, i.e. at geocentric distances less than 4 Earth radii. In general Earth-orbiting space plasma missions have only a part of their orbit period in this region (2% for Cluster, 13% and 27% for Double Star 1 and 2 respectively).

Furthermore, space plasma studies are a key element in planetary missions and these cannot use GNSS. Thus predictions of spacecraft positions for most space missions are likely to remain based on the determination of orbit elements and their use to calculate position at any time of interest. The orbit elements may be determined on-board from the available GPS position data or on the ground through classical tracking procedures. The uplink of ground–derived elements requires only a tiny uplink capacity, e.g. a daily set of Kepler elements will require <100 bytes/day.

However, the use of elements in on-board planning implies the need for an on-board clock that can provide accurate time values on a timescale suitable for use in orbit ephmerides. Existing spacecraft clocks (such as on Cluster) typically provide a relative time that needs frequent calibration for conversion to a fixed timescale. Advances in micro- & nano-technology (MNT) support chip-size atomic clocks and thus offer the prospect of an accurate on-board clock that can easily be accommodated on a nanosat.

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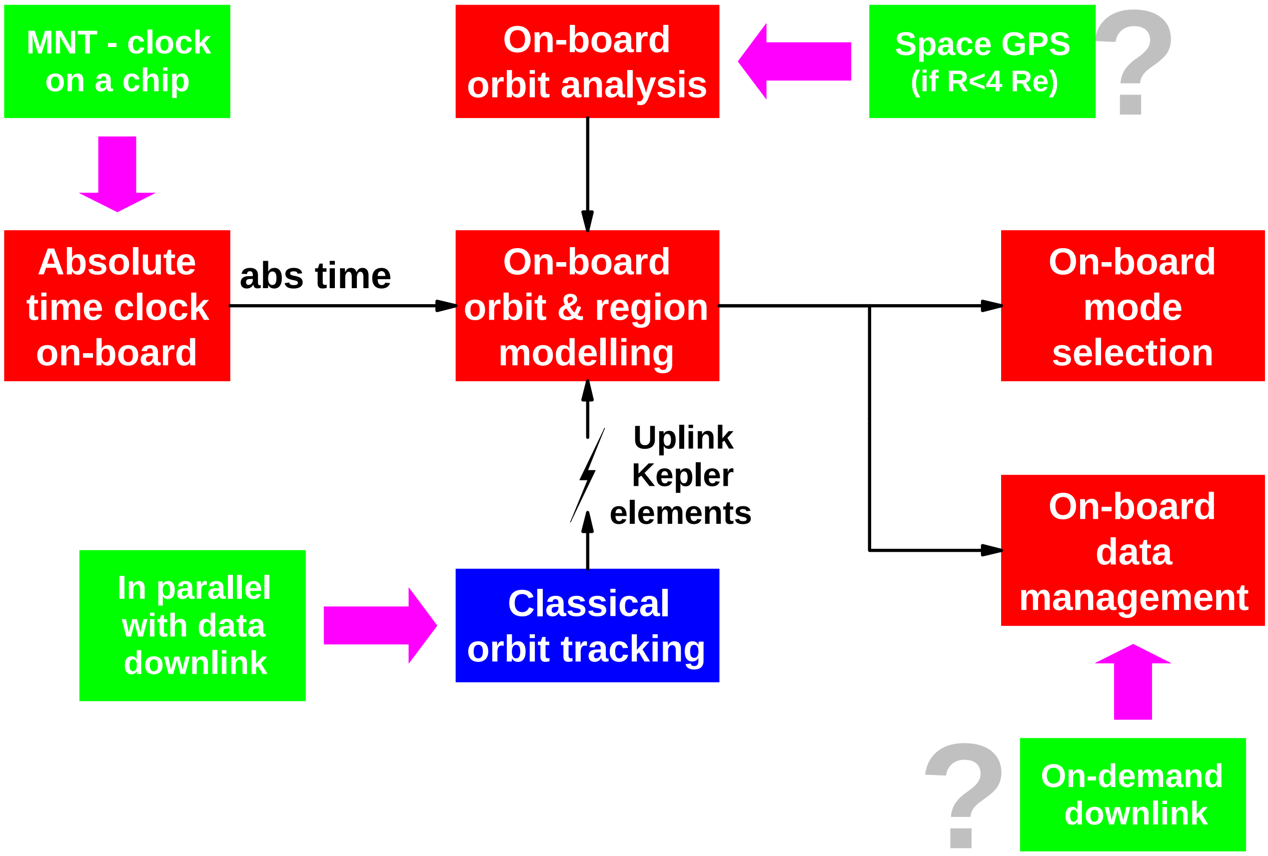

Fig 1. Key elements of predictive autonomy

Given this knowledge of spacecraft position, on-board software can then replicate current ground-based planning [1,2] and predict the time and location of crossings of plasma regions and boundaries (such as such as the radiation belts, cusp, plasmasheet, magnetopause, bow shock, etc.). These predictions can then be used to set appropriate instrument modes as the spacecraft approach important boundaries, e.g. switching off sensitive instruments prior to radiation belt entry. The key elements of predictive autonomy are shown in Fig. 1 above.

Note that these predictions are subject to considerable uncertainty due to the natural variability of the space plasma environment. For example, the observed times of Cluster magnetopause and bow shock crossings are distributed around the predicted times with a mean deviation close to zero but a standard deviation of 3 hours [4]. Thus, when approaching these boundaries, it is important to set appropriate modes well in advance of the boundary, and that these modes can handle the very different plasma conditions either side of the boundary. Fig. 2 shows an example of such variations during a two-hour crossing of the magnetopause region by the AMPTE-UKS spacecraft. The electron number density (Ne) and temperature (Te) of the plasma change abruptly at the magnetopause as indicated by the sharp rises and falls. The magnetopause location is highly variable on a timescale of minutes and thus we see repeated crossings over an extended period and not a single well-defined crossing. The conditions either side of the magnetopause are very different – with anti-correlated changes by a factor of ten in Ne and Te. It is important to set instrument modes that handle these variations.

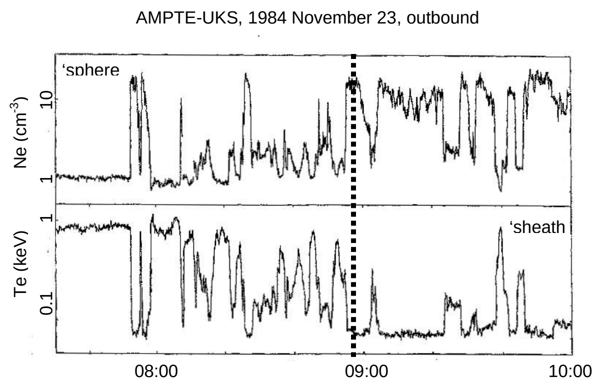

Fig 2. Typical plasma variations at the magnetopause, vertical line shows nominal crossing time (08:56)

Fig. 3 shows a possible scheme for achieving this on plasma mission with a low pericentre and apocentre in the solar wind orbiting a magnetised planet. On exit from the radiation belts (1), instruments can be switched into a mode for observing the magnetosphere. Some time before crossing the magnetopause outbound (2), instruments are set into a mode that can handle both magnetosphere and magnetosheath conditions. Similarly, before the outbound bow shock crossings (3), the instruments are set to a mode that can handle both magnetosheath and solar wind conditions. On the inbound leg the magnetosphere-magnetosheath mode is set before the magnetopause crossing (2') and the magnetosphere mode is set after the magnetopause crossing (3'). Finally a radiation belt mode (possibly instrument off) may be set before entry into the belts (0).

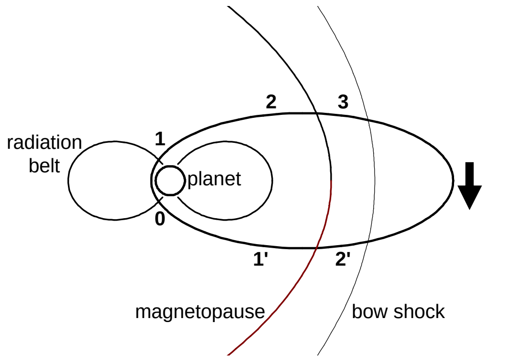

Fig 3. Schematic of a typical plasma mission orbit crossing radiation belts, magnetopause and bow shock

This approach follows that used in ground-based planning for Cluster and Double Star. But in those cases the mode switch times are set several weeks ahead of execution on the basis of the orbit predictions then available – and thus must include some margin for the uncertainty of those predictions. The margins must be large if there is significant atmospheric drag around pericentre. On-board automation of this scheme would allow the mode switch times to be established only a few hours ahead of execution using the accurate orbit predictions that will then be available. No margin will be needed and thus it will be much easier to schedule observations of phenomena just outside regions where instruments must be switched into safe modes. A key example is auroral and cusp phenomena just outside the radiation belts.

Knowledge of position can also be used to predict ground station visibility and schedule downlink. This may be implemented within a classic scheme where ground station time is allocated well in advance, but could also support schemes where downlink is scheduled on demand (as may arise in future through use of wider use of internet techniques and relays for space communications).

3. RESPONSIVE AUTONOMY

The key elements of responsive autonomy are shown in Fig. 4 below. It requires on-board analysis of instrument data to assess the ambient plasma environment and uses that to adjust instrument modes as appropriate. It can operate at any of three levels:

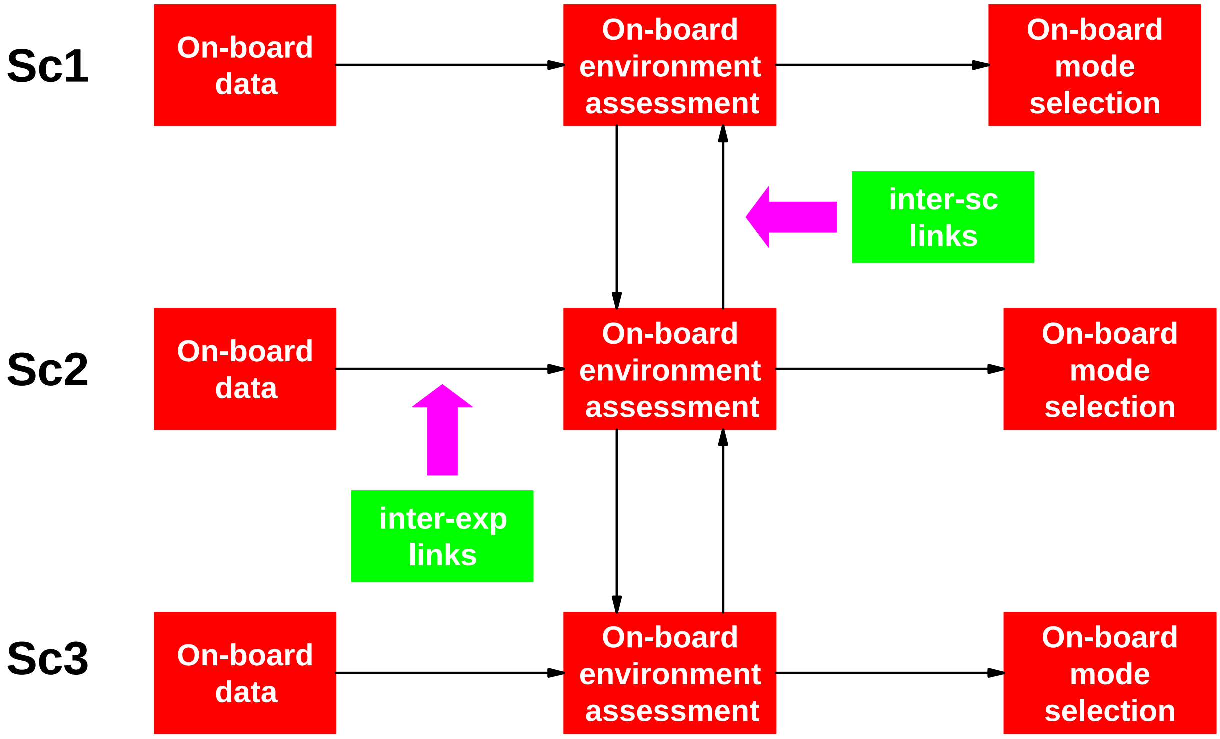

Fig 4. Key elements of responsive autonomy

1. Each instrument assesses its own data and adjusts itself as appropriate. It requires on-board data processing to a level that supports such assessment, e.g. generation of physical parameters such as particle fluxes and magnetic field strength. These should be calibrated, but not necessarily to the high level needed for later science analysis.

2. The instruments on each spacecraft deliver data for a coordinated assessment on-board the spacecraft. This then can adjust the instrument modes to match the current plasma conditions. It requires not only generation of calibrated physical products, but also facilities to deliver data to the on-board assessment system and to allow that system to command instrument adjustments.

3. Spacecraft within a constellation exchange data and adjust modes in response to this broader ensemble of data. It requires all the facilities of level 1 and 2 and also inter-spacecraft links to exchange data. For robustness, the assessment of the ensemble of data should be distributed across the constellation and not focussed on any one spacecraft. The assessment will also require good knowledge of the spacecraft separation vectors so that it can interpret differences between data at different spacecraft.

Level 3 can usefully be extended to include assessment of data from sources external to the constellation, e.g. from STP monitoring on other spacecraft and on the ground. Low bandwidth uplink of a few key parameters, such as the solar wind speed and magnetic field at the L1 point, could improve the overall operation of the constellation. Of course, the uplink of external parameters removes the true autonomy of the constellation, but that is just a semantic issue. The adoption of hybrid solutions should be considered if it improves the scientific return.

The critical issue for responsive autonomy is the balance between local and central decision making. The space plasma environment shows huge time variations whose impact propagates across the magnetosphere in minutes. Thus, for a close-spaced constellation mission such as Cluster, it is highly desirable to synchronise mode changes (consistent with instrument safety). This greatly facilitates analysis of multi-spacecraft data. Autonomy introduces a tension against this as it naturally favours local decisions. Thus effective implementation of autonomy will require development of strategies to handle this tension.

As we have noted, responsive autonomy will require good communications within a payload and across the constellation. The former is a well-established technology, e.g. inter-experiment links on Cluster. Inter-spacecraft links are a growing area of technology that will be important for autonomous operations of space plasma missions.

4. THE WAY FORWARD

There is a need for a broader review of what autonomy means in the context of space plasma missions – and, in particular, to see how space plasma science requirements for autonomy differ from other areas, such as Earth Observation, where studies of autonomy are more advanced [5]. For example:

1. How can autonomy improve the scientific return compared to traditional operations? For example, the space plasma environment is highly dynamic as already discussed. Given the critical importance of continuous observations for space plasmas [4], a manual response to these dynamics would require 24 by 7 real-time control, which is unaffordable. Thus most space plasma missions today cannot respond optimally to such dynamics – they just make a robust long-term planning and accept what happens. Autonomy could enable a near-real-term response that would be more optimal in responding to solar-terrestrial events (e.g. solar activity, solar wind state, geomagnetic storm, radiation belt injections). We note that such autonomy could be of value even for Earth-orbiting missions, but may be even more valuable in some planetary plasma environments. For example, the dynamical timescale of Mercury's magnetosphere is believed of order of a minute (compared to an hour for the Earth's magnetosphere). Autonomy could therefore improve the scientific return by enabling return of higher time resolution data for periods of interest (either by switching instrument modes or prioritising data periods for return to Earth).

2. How to ensure instrument safety and good performance in an autonomous environment? For example, the modes of particle instruments are frequently adjusted to match expected changes in the plasma environment such those shown in Fig. 2. Especial care is needed in high flux regions: (a) the high fluxes of energetic particles in radiation belts can be very damaging to low energy particle detectors if the latter are left switched on in the belts; (b) the high fluxes of thermal particles in the magnetosheath can degrade detectors designed to observe them and thus there is a need to trade-off between observations and detector life. Schemes for autonomous operation need to address these issues.

3. How to coordinate multi-spacecraft operations in an autonomous environment? It is clear that future advances in understanding the space plasma environment require consistent multi-point measurements. But naive implementations of autonomy will undermine consistency by causing each spacecraft to operate in different modes and thus making it harder to analyse multi-point measurements. Thus the

development of autonomy must address the need for constellation-level autonomy to ensure a reasonable degree of consistency in operational modes. In practice total consistency is unattainable since the spacecraft may be spread across different plasma regions such that no single mode can monitor all regions. Thus the aim must be to optimise the mode selection, e.g. by minimising diversity, but not eliminating it where needed.

We note that these issues are specific to space plasma studies and are applicable to plasma environments throughout the solar system. Thus planetary plasma studies have autonomy requirements that are distinct from those of surface studies. The latter have some commonality with Earth observation (e.g. both include requirements for observations of specific ground targets).

Thus planetary surface studies can benefit from studies of autonomy for EO missions. But planetary plasma studies have different requirements due to the highly dynamic nature of the phenomena to be observed. The targets of plasma studies are moving targets whose location is subject to significant natural uncertainty, often on time scales of minutes or less. These targets are much less specific than those considered in surface studies and thus plasma observations are made over long periods in order to capture these moving targets. These targets are usually identified post-facto by a low resolution survey of the data. Priority may then be given to processing and analysis of high resolution data taken around the target. Given this context it may be that a key objective of on-board autonomy for plasma studies is not to plan and control instrument operations but rather to survey the data stored on-board in order to identify science targets. The on-board survey results could then be used to set priorities for return of high resolution data to Earth. If this can be made to work successfully, it could significantly increase the scientific return by making best use of limited downlink capacity.

In general, plasma instruments can generate far more data than can be returned to Earth. This conflict is traditionally resolved by reducing the time resolution of the plasma data so that data generation matches downlink capacity. Autonomous identification of periods of interest would enable us to improve time resolution and would thus lead to new scientific insights. However, we must recognise that autonomous identification is a major technical challenge. Some work on this has been done at the level of individual instruments and has not yet proved very successful. Further studies are needed, especially looking at the problem at payload and constellation levels.

5. SUMMARY

We have outlined ideas on the development of on-board autonomy for space plasma studies and offer these as a stimulus to debate.

In particular we have discussed two distinct approaches to the planning and commanding of plasma instruments – one involving an on-board capability to predict the expected conditions and the other using on-board assessment of instrument data to determine current conditions. However, we anticipate that, in practice, a mix of these approaches will be needed. We have raised a number of issues that should be addressed in further studies of autonomy: (a) how autonomy increases the scientific return, (b) how to ensure instrument safety during autonomous operations, and (c) how autonomy should operate in a multi-spacecraft context.

We have also contrasted the autonomy requirements for plasma studies with those of surface studies (including Earth Observation) and show that plasma studies have distinct needs.

6. REFERENCES

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