Report from the Forum held at ISSI on Near-Earth electromagnetic environment monitoring with the Swarm-Cluster combination

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Kirsti Kauristie and Hermann Opgenoorth

0. Preamble

The Forum's main aim is to bring together international experts to discuss and review new science opportunities offered by the simultaneous availability of Swarm and Cluster observations. These opportunities may go beyond the objectives of each of the missions. Data from other relevant satellites or ground based facilities can also be included in the discussion and the proposed activities. It is expected that new ideas will emerge for studying the impact of the solar wind and interplanetary magnetic field on the near Earth environment but also ideas for improving our knowledge of the Earth interior deserve attention. To stimulate the discussion a small study team (under an ESA contract) will prepare important background information about the Swarm and Cluster constellation and data and bring along some first ideas. It is anticipated that the opportunities proposed and reviewed during the meeting need to be further elaborated in terms science benefits, methodology and feasibility. All consolidated opportunities will be collected and summarized by the study.

1. Introduction

The ESA Swarm mission will comprise of three satellites on polar orbits. Two satellites (A and B) will orbit side-by-side at an initial altitude of 460 km and the third satellite (C) will orbit at 530 km altitude. The orbital planes of A&B and C will gradually drift away from each other during the mission time. The prime objective of the Swarm mission is to provide the best ever survey of the geomagnetic field and its long-term temporal evolution, and to gain new insights into improving the knowledge of the Earth's interior. Another primary target of Swarm is the study of the near-Earth electromagnetic environment, especially the ionospheric-magnetospheric current systems and their effect on the magnetic field at the Swarm orbit altitudes. It is well known that the magnetic fields created by these currents constitute the biggest noise factor for studying the Earth interior components and they need to be monitored (and eventually eliminated from the Swarm data) as accurately as possible.

The ESA Cluster mission was launched in 2000. The constellation of four satellites with identical instrumentation was originally dedicated to the research of various boundary regions in the magnetosphere. Cluster is now into its 13th year of operations, with over 80% of the payload in good working order. As the mission has evolved, the orbit and operations have also, facilitating new science opportunities. For example, Cluster observations at the magnetopause and in the magnetotail have revealed regions of field-aligned currents with a transverse scale size around an ion inertial length (hundreds of kilometres) associated with magnetic reconnection. These narrow regions extend over large distances along the field lines. Data from low altitude satellites and ground-based radars have confirmed that currents with a transverse scale size as small as a few hundreds of meters to a few kilometres do exist.

Having both Swarm and Cluster satellite constellations in simultaneous operation during 2013-2014 (and potentially also during 2015-2016) offers a unique opportunity to make joint observations to facilitate science that is unobtainable from the missions alone. However, some fine-tuning of the constellations maybe required (within certain boundary conditions) to provide optimal scientific

return related to the new objectives. The advantage of the combined constellation is that the satellites from Swarm in Low Earth Orbit (LEO) and Cluster in a more distant orbit in the magnetosphere (4-20 Earth radii) will have relatively close encounters on the same magnetic field line. In addition there will also be occasions, when they are not magnetically connected, but in relative positions of strategic value for the studied subject, like e.g. dynamic processes in the magnetosphere and ionosphere. Both situations open new opportunities to learn about the energy exchange, particle acceleration and detailed current flow between the ionosphere and the magnetosphere. The experience gained from the combination of the two missions will be useful in proposing future mission concepts for Earth science, space science and potentially future space weather missions.

2. The ISSI Forum

The Forum was arranged as a sequence of six sessions. The first, introductory session, provided the participants with some background information about the Swarm and Cluster missions, about the ESA project "Exploiting Synergies between Swarm and Cluster" (ESSC), and about other novel ground-based and satellite instrumentation that are supposed to provide useful support to future operations that we refer to as Swarm Cluster Virtual Mission or SCVM. The four next sessions addressed different science topics:

Session II: Dynamics and structure of currents flowing between the magnetosphere and ionosphere along the geomagnetic field lines (hereafter called field-aligned currents, FACs). Impact of FACs in the ionosphere (energy input, heating and coupling with the neutral atmospheric conditions).

Session III: Appearance of boundary layers between different magnetospheric domains and dynamic events in the magnetospheric conditions. How boundaries and events can be observed in the ionosphere? Opportunities for statistical studies and multi-instrumental case studies (SCVM and other supporting instrumentation).

Session IV: Latest innovations in the modelling of three dimensional (3D) ionospheric electrodynamics and the consequent impact in the research of magnetosphere-ionosphere coupling processes (c.f. topics of Sessions II and III).

Session V: Plasma waves appearing in the magnetosphere and associated pulsations observed by ground-based and satellite instruments. The benefits of wavelet analysis and advantages of multi-satellite approaches to achieve a global view on the wave generation, propagation and decay mechanisms.

The Forum was finalized with a session for concluding remarks. The science opportunities presented in the above described sessions were discussed and advice for the future work of the ESSC project was given. The Forum even gave some direct recommendations for ESA and other space agencies. Suggestions for future ISSI activities in the form of Workshops and Working Groups were the final outcome of the discussion section. The following sections of this document review these recommendations.

3. Forum discussions

The ESSC project presented first results from the Ionospheric Conductance study and some other highlights from the latest activities of the ESSC work which is split into two parts. The main objective of Part 1 is to perform a detailed study for obtaining ionospheric currents, conductances

and plasma convection maps from Swarm magnetic and electric field recordings. Furthermore, a scheme to estimate the coupling factor between ionosphere and magnetosphere with combined Swarm and Cluster data is presented. The objective of Part 2 is to perform a more general survey about the new science opportunities for SCVM, keeping in mind the predicted orbit information and instrument specifications of the two missions.

The Forum members acknowledged the work of Part 1 as an important new opening in the research of magnetosphere-ionosphere coupling processes. In particular, achieving systematic and recurrent information about the ionospheric conductances below the Swarm spacecraft was seen as a valuable step forward as it enables improved studies on ionospheric energy dissipation and feedback processes (e.g. magnetospheric plasma wave reflection in the ionosphere).

The Forum encouraged the study team to address the following topics in the final study report:

- *Ring current (RC):* Azimuthal and radial variations of RC and its linkage with ionospheric currents; Discrepancy in the in-situ and LEO observations;
- *Field aligned currents (FAC):* FAC linkage with auroral precipitation, conductances and plasma waves; Interaction between large and meso-scale structures;
- *Auroral structures:* Physics of auroral arcs when both longitudinal gradients and tangential electric field are present. Magnetospheric source region of auroral structures.
- *Plasma waves (especially Ultra Low Frequency Domain (ULF), 1 mHz – 5 Hz*): Generation, decay and propagation in the magnetosphere. Linkage between solar wind parameters. Interaction between wave activity and radiation belt dynamics.
- *Ionosphere as a load and as an active feedback provider:* Quantitative assessment of the ionospheric energy budget and its linkage with energy input from the magnetosphere. Refilling of the plasmasphere from the ionosphere after geomagnetic storms
- *3D ionospheric electrodynamics:* Advancements from the current standard approach where the ionosphere is modelled as a thin layer. How currents closing inside the ionosphere affect magnetosphere-ionosphere coupling in different geophysical conditions? How exact can the 3D ionosphere be modelled with magnetohydrodynamic simulations?

A key item that came out of the Forum discussions was the question of magnetic conjugacy events. As magnetospheric plasma can flow much easier along the geomagnetic field lines than across them, the field lines can often be considered as equipotential lines in magnetosphere-ionosphere coupling processes. Consequently, so called magnetic conjugacy cases where a LEO satellite is traversing the same magnetic field lines as Cluster are exceptionally useful for multi-spacecraft analysis. As the topology of the geomagnetic field is continuously varying according to solar wind conditions, finding the conjugacy cases accurately is extremely challenging. There exist, however, statistical models for the magnetic field topology, which in favourable conditions can help scientists to estimate when and where two satellites (or satellite groups) will most probably be in magnetic conjugacy. The same approach is used also when satellite observations are compared with ground-based data. In such cases the ionospheric footpoint of the satellite is determined by tracing the satellite location along the statistical field line to the ionosphere and the ground-based data in the surroundings of this footpoint are used to support the interpretation of satellite data.

The most widely used statistical models in magnetospheric research have been created by Prof. Nikolai Tsyganenko (University of St. Petersburg). The family of Tsyganenko field models provides several mapping options which can be selected according to different research topics. All

models use as input variables a set of parameters which describe the prevailing solar wind conditions and global geomagnetic activity level.

Prior to the Forum the ESA study team had conducted a statistical survey on the occurrence rates of events where Swarm and Cluster will be magnetically conjugated. The Tsyganenko model published in 1989 was used in the study. The survey suggested that during a four year period roughly 500 cases of high-level conjugacy events would be available. A high level conjugacy event was determined to be a case where the mutual distance between Cluster and Swarm (A&B) ionospheric footpoints were separated by less than 0.5° in latitude and 0.25° in longitude. **The Forum noted that the number high level conjugacy events is relatively small and therefore it is important give emphasis also to those opportunities provided by SCVM which do not require magnetic conjugacy.**

When considering the feasibility of new science opportunities it is important to remember the limitations in the forthcoming Cluster and Swarm operations, which were also discussed in the Forum. For example, changing the Cluster orbit perigee is not anymore possible with the remaining fuel. No observations are made during long eclipse seasons (a few weeks a year during summer). On the other hand, Cluster inter-spacecraft distances along the orbit can be adjusted to optimise observations of specific phenomena e.g. improved FAC estimation with magnetometer data. The Swarm satellite orbits, inter-spacecraft distances and the longitudinal drift of the orbit planes have been fixed to support the research of internal magnetic field structures. However, during the early parts of the mission the gradually increasing longitudinal difference of Swarm-C and Swarm-A&B will be exceptionally favourable also for external field studies.

4. Recommendations for the future ISSI activities

The combined usage of Swarm and Cluster observations will bring together the research communities of the ESA Earth Observations and Science programs. Therefore SCVM has potential to initiate interesting cross-disciplinary research projects. ISSI can support these opportunities with dedicated workshops and working groups. The Forum recommends establishing three pairs of inherently coupled workshop and working group activities in order to ensure efficient utilization of the preparatory work conducted in the ESA Swarm-Cluster synergy study. Below we list the themes of the suggested activities and their main objectives:

- ISSI Workshop 1: "Coupling between the external and internal parts of the geomagnetic field"
    - Identifying overlapping areas in the external and internal field research
    - Evaluating the potential impact of using different internal field models when determining the external field from total magnetic field for magnetosphere-ionosphere research
    - Investigating the distribution and intensity of quiet time magnetospheric and ionospheric currents.

- ISSI Working Group1: "Magnetic field modeling in the near-Earth space environment"
    - Studying the opportunities to link magnetospheric magnetic field models (Tsyganenko models) with accurate internal field models (better than IGRF)
    - Identifying the observational and modeling efforts needed to gain better understanding about the Ring Current and other external current systems
    - Search of improved parameters for modeling efforts

- ISSI Workshop 2: "Coordinated event analysis efforts in near- Earth space research"
    - Conducting coordinated research projects with the help of versatile ground-based and satellite observations. Examples for research topics are listed in the Section 2 of this document.
    - Analyzing Swarm-Cluster constellation data in the wider context provided by the other supporting instrumentation (c.f. the next section).

- ISSI Working Group2: "Multisatellite data-analysis tools for Swarm-Cluster"
    - Investigating how the multisatellite data-analysis tools developed for Cluster can be modified to support SCVM
    - Developing new algorithms for SCVM data analysis

- ISSI Working Group3: "3D ionosphere modeling"
    - Investigating how SCVM observations can support the latest advancements in the theoretical work towards 3D modeling of ionospheric conditions

- ISSI Workshop3: "Review of the new science from Swarm-Cluster"
    - Arranged at the end of the nominal SCVM operation period in order to review the work conducted in the previous workshops and working groups
    - Discussions about the future prospects in multi-point probing of near-Earth space and its interaction with the atmosphere.

5. Recommendations for ESA and other space agencies

The occurrence survey of Swarm-Cluster magnetic conjunction events conducted by the study team demonstrated that good cases are relatively rare: Roughly in 500 cases during four years the Swarm and Cluster magnetic footpoints in the ionosphere were close enough for studying mesoscale structures (<100 km) along the same magnetic flux tube (i.e. the high level conjugacy cases introduced in Section 4 of this document). This number includes all MLT-sectors, satellite positions and magnetic activity levels. If the 500 cases are binned to different categories according to the needs of the research topics (e.g. midnight sector conjugacy in the auroral oval during magnetic activity for substorm current wedge studies) the occurrence rates may easily drop down to ~100. Consequently, it is important i) to use also other strategic constellations in addition to the conjugacy events and ii) to include supporting instrumentation in event search and analysis. Besides ESA also other space agencies (e.g. NASA, CSA and JAXA) and some multi-national consortia have made recent investments to other space-based and ground-based instrumentation that would be very valuable in support of SCVM research. In particular, the following assets were highlighted in the discussions:

The THEMIS (Time History of Events and Macroscale Interactions during Substorms) Mission and the THEMIS ground-based network(GB), CGSM-GO

- The AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) Project (FAC products, also raw magnetic field data) and SuperMAG
- MMS, e-POP, VanAllen Probes(+Balloon), DMSP, NOAA/POES, MIT, Resonance, ERG
- Other GB networks (MIRACLE, MAGDAS, SuperDARN, EISCAT, quasi-definitive data from Intermagnet)

Maintaining especially GB instrument networks is often based on national funding with uncertain continuity. A letter of endorsement from ESA to support the GB instrument maintenance work to augment the SCVM effort would therefore be highly appreciated.

The Forum recommends ESA to conduct the following actions in order to ensure that the best constellations are identified and analysed efficiently:

- Swarm orbit information should be provided to planning tools like CEF (JAXA), Tipsod (NASA) and OVT (Orbit Visualization Tool).
- Swarm Quicklook data (L1B and L2) should be available for researchers with a simple browsing service (user defined zooming in property, c.f. Cluster CSDS). Further discussion e.g. about wavelet interface and other necessary properties could be given as a task for a ESA working group.
- For pulsation studies it would be necessary to get high time resolution Swarm A and B data (16 Hz and 50 Hz) in North-East-Center coordinates
- During the early phase of Swarm mission the gradually apart drifting orbital planes of C and A&B will provide unique opportunities to study local time gradients. Special attention should be paid to the Cluster performance during this period.

6. Concluding remarks: recommendations to ESA for Swarm data product verification projects

As final point Forum discussed about potential new Swarm data products that would push forward near-Earth space research essentially. Big expectations were associated especially to the ionospheric conductance strips that can be derived from Swarm A&B data with the method presented in the Part 1 work of the ESA study. Poynting flux and plasma convection maps were mentioned as other interesting examples in the discussions. Additional candidates could be identified by the Working Group 2, which was introduced earlier in this document. After careful verification of these data products their inclusion to the systematic Swarm data processing chain would be a welcome upgrading to the mission.

Finally, the Forum participants would like to express their gratitude to ISSI for arranging the gathering which was considered as a very fruitful opportunity to discuss about new openings in the research of geomagnetic field modelling and magnetosphere-ionosphere coupling processes. For themselves the Forum participants took the challenge to apply in the near future for an ISSI Team initiative in order to prepare a review article about the science opportunities discussed in the meeting.

APPENDIX I: List of participants

Amm, Olaf, FMI, Finland
Balasis, Georgios, National Observatory of Athens
Dandouras, Iannis, IRAP, Toulouse, France
Dunlop, Malcolm, RAL/STFC
Floberghagen, Rune, ESA/ESRIN, Frascati, Italy
Gjerlov, Jesper, University of Bergen, Norway
Haagmans, Roger, ESA/ESTEC, The Netherlands
Kauristie, Kirsti FMI, Finland
Knudsen, David, University of Calgary
Lühr, Hermann, GFZ, Potsdam, Germany
Nakamura, Rumi, Austrian Academy of Science, Space Science Institute

Olsen, Nils, Danish Technical University
Opgenoorth, Hermann, IRF Uppsala, Sweden /ISSI, Bern, Switzerland
Pitout, Frederic, IRAP, Toulouse, France
Plank, Gernot, ESA/ESTEC, The Netherlands
Stolle, Claudia, DTU Space, Denmark
Taylor, Matt, ESA/ESTEC, The Netherlands
Vogt, Joachim, Jacobs University, Bremen, Germany
Yoshikawa, Akimasa, Department of Earth and Planetary Sciences, Kyushu University, Japan

Marco Callisto, ISSI, Bern, Switzerland
Lennart Bengtsson, ISSI, Bern, Switzerland

APPENDIX II: Web links providing additional information about supporting instrumentation and coordination tools listed in Section 6.

Themis: http://www.nasa.gov/mission_pages/themis/main/index.html
CGSM-GO: http://www.cgsm.ca/
Ampere: http://multivu.prnewswire.com/mnr/iridium/45153/
SuperMAG: http://supermag.jhuapl.edu/
MMS: http://mms.gsfc.nasa.gov/
e-POP: http://mertensiana.phys.ucalgary.ca/
Van Allen Probes: http://www.nasa.gov/mission_pages/rbsp/main/index.html
DMSP particle data: http://sd-www.jhuapl.edu/Aurora/dataset_list.html
NOAA/POES: http://www.swpc.noaa.gov/pmap/
ERG: http://gemsissc.stelab.nagoya-u.ac.jp/erg/
MIRACLE: http://www.space.fmi.fi/MIRACLE/
MAGDAS: http://www.serc.kyushu-u.ac.jp/magdas/
SuperDARN: http://superdarn.jhuapl.edu/
EISCAT: http://www.eiscat.se/
Intermagnet: http://www.intermagnet.org/

CEF (JAXA): http://darts.jaxa.jp/stp/cef/cef.cgi
Tipsod (NASA): http://opensource.gsfc.nasa.gov/projects/tipsod/
OVT (Orbit Visualization Tool): http://ovt.irfu.se/
Cluster CSDS: http://sci2.estec.esa.nl/cluster/csds/csds.html