On the role of advanced data routing protocols in enhancing the characterization and understanding of magnetospheric processes

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Abstract— **Magnetospheric processes play an important role in the Sun-Earth connection and space weather in general. The availability of multi-spacecraft observations can lead to the comprehensive characterization of magnetospheric processes and set the foundations for a deeper understanding and eventual forecasting of them. However, multi-spacecraft distributed observation methods and adaptive mission architectures require computationally intensive analysis methods. Moreover, accurate space weather forecasting and future space exploration far from Earth will be in need of real-time data assimilation technologies. Here we present the architecture and basic functionality of a Delay Tolerant Networking (DTN)-based application specifically designed in the framework of the "Space-Data Routers" (SDR) project, for data query, retrieval and administration that will enable the addressing of outstanding science questions related to space weather, by providing simultaneous real-time sampling of space plasmas from multiple points with cost-effective means and measuring of phenomena with higher resolution and better coverage.**

Keywords: space science, space data dissemination, cross missions, multiple missions, space weather

I. Introduction

The term "space weather" refers to conditions on the Sun and in the solar wind, Earth's magnetosphere, ionosphere, and thermosphere that can influence the performance, efficiency, and reliability of space- and ground-based infrastructure and can endanger unprotected humans in space conditions or above the Earth's poles [1, 2]. Nowadays, information is no longer gathered merely from a single spacecraft vantage point but also by multispacecraft distributed observatory methods and adaptive mission architectures that require computationally intensive analysis methods. Future explorers far from Earth will be in need of real-time data assimilation technologies to predict space weather at different solar system locations.

The most important capability requirements in enabling space weather prediction are:

- Simultaneous sampling of space plasmas from multiple points with cost-effective means and measuring of phenomena with higher resolution and better coverage to address outstanding science questions;
- Achieving unique vantage points such as upstream at L1, solar polar orbit, or, desirably, beyond the edge of the heliosphere;
- Enabling the prompt, light-speed return of vast new data sets from anywhere in the solar system;
- Synthesizing to enrich our understanding by means of system-wide measurements exploiting new data analysis and visualization techniques.

A number of NASA and ESA space missions delivering data of significance to space weather are currently in operation. Among them, missions targeting the Sun, such as the long-standing Solar and Heliospheric Observatory (SOHO), but also Hinode and the Solar Dynamics Observatory (SDO). Pending advances in basic research, these missions can provide valuable clues towards an understanding of the onset and dynamical evolution of solar eruptive phenomena such as solar flares, coronal mass ejections and solar energetic particle events. In the near future, ESA's Solar Orbiter (SolO) and NASA's Solar Probe Plus (SPP) missions promise to advance our understanding substantially, by providing vantage points near the Sun (SolO) or, in-situ, at the regime of the genesis of the supersonic, super-Alfvenic solar wind (SPP). Solar wind variations are currently monitored by WIND and the Advanced Composition Explorer (ACE) at L1, while the response of the terrestrial magnetosphere is being recorded by the Cluster and THEMIS missions. The currently operating heliophysical space missions are schematically illustrated in Figure 1.

Our goal was to test the capability of Space-Data Routers to efficiently distribute to registered end-users these and future voluminous data from missions observing from different heliospheric locations.

NETSPACE- NETworking technologies for efficient SPACE data dissemination and exploitation
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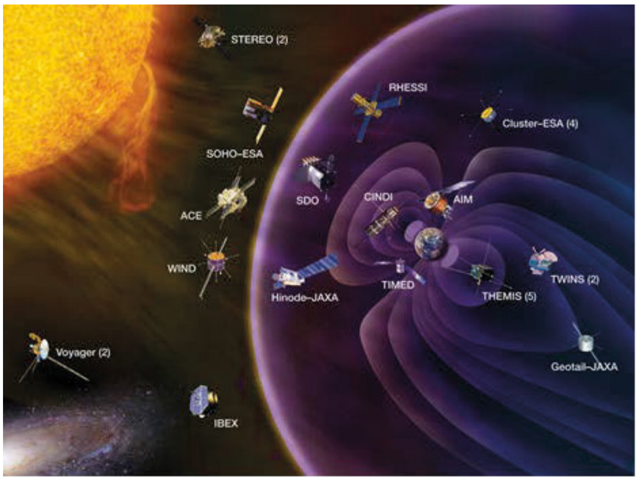

Fig.1 Illustration of the Heliophysics missions

II. SPACE WEATHER SCENARIO

The objective of this scenario was to now-cast and, ultimately, forecast the influence of solar disturbances (which propagate through interplanetary space and impinge on the terrestrial magnetosphere) on the development of electromagnetic waves in the magnetosphere and the wave effect on radiation belt variability. This scenario serves the purpose of a cross-mission single thematic space data scenario. In the following we are presenting the missions and the relative data that we used for the space weather scenario in the framework of the SDR project.

A. The Cluster and THEMIS missions

We outline here the Cluster and THEMIS missions that we used, in order to monitor the electromagnetic wave activity in geospace for the purposes of the SDR project.

The Cluster mission is a collection of four spacecraft flying in formation around Earth, relaying the most detailed ever information about how the solar wind affects our planet in three dimensions [3]. The solar wind (the perpetual stream of subatomic particles given out by the Sun) can damage communications satellites and power stations on Earth. The operation lifetime of the Cluster mission ran from February 2001 to December 2009. In October 2009, the mission was extended until the end of 2012.

The launch of Cluster was performed in 16 July and in 9 August 2000 (two launches of two Cluster satellites each, using two Russian Soyuz rockets from Baikonur, Kazakhstan). At each launch, two Cluster satellites were placed in elliptical orbits with an altitude varying from 200 to 18 000 kilometres above Earth. The two satellites of each launch were then released one after the other and used their own onboard propulsion systems to reach the planned operational orbit (between 19 000 and 119 000 kilometres from the planet).


Fig.2 Illustration of the Cluster mission

Having four identical spacecraft, Cluster was the first space project ever having to establish a production line for four spacecraft. Using identical instruments simultaneously, three-dimensional and time-varying phenomena can be studied.

The THEMIS (Time History of Events and Macroscale Interactions during Substorms) mission answers long-standing fundamental questions concerning the nature of the substorm instabilities that abruptly and explosively release solar wind energy stored within the Earth's magnetotail [4]. The primary objectives of the mission are to

1. Establish when and where substorms begin;
2. Determine how the individual components of the substorm interact;
3. Determine how substorms power the aurora, and
4. Identify how local current-disruption mechanisms couple to the more global substorm phenomena


Fig.3 Illustration of the THEMIS mission

THEMIS accomplishes these tasks by employing 5 identically-instrumented spacecraft in carefully chosen orbits whose apogees line up once every 4 days over a dedicated array of ground observatories located in Canada and the northern United States. Three inner probes ~10 Earth radii (RE) from Earth monitor the current disruption onset, while two outer probes at 20 and 30 RE remotely monitor plasma acceleration due to lobe flux dissipation. THEMIS was launched on 17 February 2007.

B. Design and deployment of a pilot application for retrieval & dissemination of magnetospheric data

Our overall objective was to demonstrate the potential of the proposed architecture to carry through data queries and transfers of large data volumes via multiple ground terminal nodes (as well as space nodes in the future) and multiple transmission paths.

In order to accomplish our objective, we have ingested in the SDR data base, the magnetic field data form the Cluster (four satellites in CDF format) and the THEMIS (five satellites in ASCII format) missions. This selection served as an evaluation test for the sufficiency of DTN Space-data overlays to administer thematic cross-mission space data.

A DTN network of several nodes, located in different sites has been set up constituting the data dissemination overlay on top of the Internet. DTN architecture and the accompanying Bundle protocol (RFC 5050), in conjunction with space transport, space link layer protocols and the corresponding convergence layers, are in deployment phase. In addition, new routing and transport features have been integrated into the DTN architecture along with the resource sharing and data dissemination policy, in order to complement the necessary functionality of DTN nodes. Regarding the underlying network, namely the Internet, due to a novel naming scheme that has been developed, automatic mapping between DTN identifiers and underlying network addresses is possible.

A high-level pilot application interface has been designed in order to comply with the various data structures and hierarchies encountered both in planetary and earth-observation data. A user-friendly GUI for querying the database and submitting the relevant tasks has been implemented (see Figure 4).

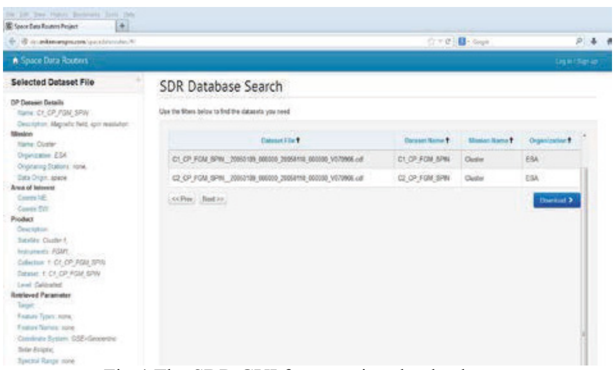

Fig.4 The SDR GUI for querying the database

C. Impact using SDR

The main requirement for this application scenario is the real-time availability of electric field, magnetic field and charged particle data as recorded by multiple missions in geospace and in the solar wind. The use of a DTN-based network architecture is expected to offer a) real-time data acquisition from multiple missions for monitoring ULF/VLF wave occurrence and its effects on radiation belt dynamics and b) low bit error rate data transmission even under harsh/challenged communication conditions.

III. CONCLUSIONS

The availability of multi-spacecraft distributed observation methods and adaptive mission architectures require computationally intensive analysis methods. Moreover, accurate space weather forecasting and future space exploration far from Earth will be in need of real-time data assimilation technologies. The collaborative research project "Space-Data Routers" (SDR), relies on space internetworking and in particular on Delay Tolerant Networking (DTN), which marks the new era in space communications, unifies space and Earth communication infrastructures and delivers a set of tools and protocols for space-data exploitation. The main goal is to allow space agencies, academic institutes and research centers to share space-data generated by single or multiple missions, in an efficient, secure and automated manner. Here, we present the architecture and basic functionality of a DTN-based application specifically designed in the framework of the SDR project for data query, retrieval, and administration that will enable the addressing of outstanding science questions related to space weather, by providing simultaneous real- time sampling of space plasmas from multiple points with cost-effective means and measuring of phenomena with higher resolution and better coverage.

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