Needs for an Intelligent Distributed Spacecraft Infrastructure

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Abstract - Future Earth science observing systems will involve multiple space assets and capable models to advance understanding and enable prediction of Earth system variables. There are several types of distributed spacecraft architecture that contribute to an overall integrated sensor web future vision. Many technologies needed to enable the Vision essentially mimic commercial developments in the electronics, network and communications industry, suggesting that low-cost, capable micro-spacecraft will be realized in the near future. Spacecraft autonomy and capable compact sensor suites represent the most significant investments that will decrease cost and improve the capability and reliability of sensor webs.

I. THE FUTURE OF EARTH OBSERVATIONS

Predicting far into the future is always uncertain since unknown technological innovations sharply limit our ability to linearly extrapolate from the present. However, current trends suggest that space observations of the earth will become increasingly important to a range of users, both scientific and commercial. As an example, over 90% of the information used in current NOAA weather forecasting systems comes from space observations. The increasing capability and cost-effectiveness of sensors and sensor systems suggests that we will become more reliant on space-based observations in the future. In addition, the goal of understanding interactions of Earth system components on a global scale requires consistent, reliable global data that are most easily collected from space. There are many emerging measurement needs and capabilities that will drive space mission architectures of the future towards multiple observing platforms and networks of sensors. These emerging areas include high spatial and temporal resolution: land imaging, surface hydrology and precipitation, ocean salinity, vegetation recovery, atmospheric chemistry, surface deformation, and radiative flux.

While tremendous progress has been made in the past decades in understanding trends in isolated Earth system variables (such as atmospheric temperature), there are many dynamic processes and linkages that require dense observations both spatially and temporally to resolve. Modeling capabilities extend the "observability" of complex phenomena by making efficient use of existing data to validate physics-based models. However, the next wave of advances in understanding of individual Earth system components and their interactions requires understanding and modeling of complex, non-linear systems. This next step in understanding the Earth system and enabling reliable predictive capabilities will require abundant observations to initialize and validate models of complex behavior. While it is difficult to predict how much data are needed, an educated guess is that increasing spatial, temporal and spectral resolution will be needed to improve predictability. On the other hand, for some systems, once we develop an understanding of the phenomena, either through model validation or data mining, then the data density requirements could decrease. An example of this scenario is current weather prediction capabilities, where models ingest sparse data but make decent predictions over large regions by advecting information from better observed regions. Also for weather prediction, it is well-understood that accurate wind profiles, especially in certain areas on the planet, will significantly improve predictability. For many other disciplines, the complex physical models of system behavior do not exist, because the non-linear interactions of the various scales of the system are not well understood. For these systems, dense data are needed to build and validate models that may lead to predictive capabilities.

Distributed spacecraft observing systems offer an attractive architecture for achieving high spatial and temporal resolution, but that architecture is far from one-size-fits-all. The observing system and its flexibility must be optimized around the science requirements. Various phenomena which may be observed from space have different temporal and spatial scale requirements. For example, severe storms evolve quickly, and observations every 15 minutes or less may be required. On the other hand, ice sheets evolve slowly and thus may be observed less continuously. Similar arguments can be made for spatial requirements. Thus it is important to consider various vantage points – ice sheet observations could be made from low Earth orbit (LEO) while severe storm observations should probably be made from geostationary orbit or highly elliptical orbits to meet the revisit requirement. Surface deformation occurs on a variety of temporal scales ranging from long-term volcanic inflation to seasonal hydrologic variations to earthquakes. The spatial and temporal coverage provided by dense LEO constellations, sparser mid Earth orbit (MEO) and elliptical constellations, geosynchronous (GEO) constellations or geostationary orbits must be traded-off with the cost of the observing system and operating and data processing costs. Advances in autonomous operations, computing, communications, and lightweight miniaturized spacecraft and instruments will all contribute to making distributed spacecraft observing systems a cost-effective solution for the future.

II. Evolution of multi-platform observations

A. *Virtual Observing Systems*

Currently meteorological observations from a variety of sources are brought together as part of the data assimilation process. The platforms that are making the observations are not coordinated nor commanded to alter their observing strategy. The data is simply gathered from wherever it is supplied. Nonetheless, when considered as a whole, the current meteorological observing system constitutes a virtual single observing system with multiple components.

It is anticipated that virtual observing systems will be numerous in the future, as science questions are addressed with diverse observations from heterogeneous, uncoordinated satellites, combined with ground, balloon, and buoy networks, as well as Uninhabited Autonomous Vehicles and sonde data. Data assimilation models will be used to merge various data types.

B. *Simple Formations*

Formations of satellites are being used to replace very large spacecraft. The advantage of the formation compared to a single large spacecraft is flexibility, redundancy and lower systems engineering costs. It has also been argued that simple formations maybe more successful to implement.

One of the first formations is the Terra, Landsat –7, New Millennium Program (NMP) Earth Observing –1 (EO-1), and Satellites de Applicaciones Cientifica (SAC) -C satellites for land imaging. This group is called the Morning, or AM, Constellation. EO-1 is flying in close formation with Landsat-7, one minute behind to +/- 3 seconds tolerance, to provide atmospheric correction information, and to test new instrumentation and techniques. EO-1 has on board formation management software for targeting and maintaining relative position – but the other spacecraft are managed from the ground. By 2004, a second formation will be assembled comprising the Aqua, Aura, Cloudsat, CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations), and PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a LIDAR) missions. This afternoon constellation is discussed in Schoeberl [1]. All these spacecraft will be managed from the ground, since the formation control is not as tight as EO-1/Landsat-7.

These simple formations developed in a rather unplanned way, with new missions taking advantage of existing assets somewhat like hitchhikers. These are formations that accrete, and are characterized by separate management centers, heterogeneous payloads, and separate data processing systems. Coordination takes place on the ground (EO-1 excepted); although the formation is managed, intense management is not required except for drag make-up maneuvers.

In the future, simple formations will likely be the rule, as observing assets become distributed amongst multiple platforms. The Global Precipitation Mission (GPM) and the COSMIC LEO GPS constellation are two examples of the planned application of this architecture. Simple or loosely coordinated formations allow flexibility to replace and upgrade observing components, and to add elements incrementally to expand capabilities (Fig. 1). In addition, loose formations allow cross-calibration of sensors such as is being done for Topex/Poseidon and Jason-1. Advances in micro/nanospacecraft and spacecraft autonomy enable the vision of affordable satellite formations.

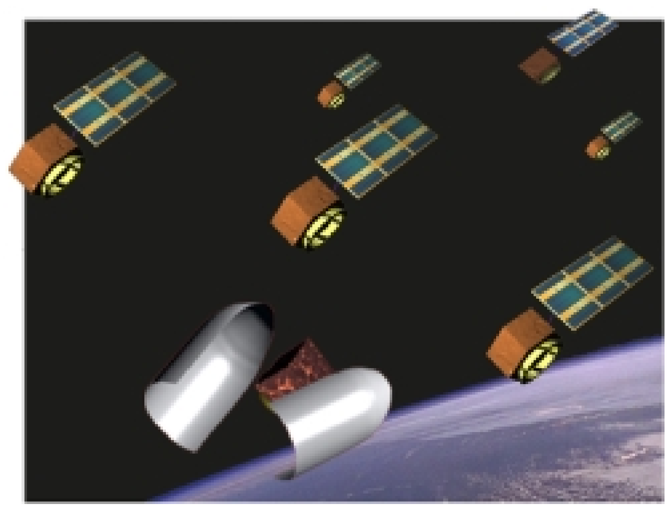

Fig. 1. In simple or loose formations, fleets evolve over time to maintain and extend capabilities. Spacecraft autonomy will reduce the dependence on ground intervention and simplify operations

C. *Virtual Instruments*

Multiple satellites which together provide a single observation can be considered a virtual instrument. Examples include the Gravity Recovery and Atmospheric Change Experiment (GRACE) mission, that performs satellite-to-satellite tracking (SST) with 2 microsatellites to measure precise gravity variations; the NMP Space Technology (ST) -5 (three nanosatellite constellation) that will make particle and fields measurements in near-Earth space; the TechSat 21 (multiple coordinated microsatellites) constellation of synthetic aperture radars (SAR); and the proposed Leonardo and Constellation for Aerosols and Cloud Heights (COACH) missions. COACH and Leonardo are concepts where a group of satellites are managed by a mother ship.

Virtual instrument formations require careful, sometimes intense management, since the proximity of the satellites has an impact on the observations. In the case of TechSat 21, ST-5, and GRACE, the satellites are identical. TechSat 21, a distributed synthetic aperture radar mission, uses the satellite separations to adjust the aperture of the virtual instrument. For Leonardo (Fig. 2) and COACH, the satellites include a mothership and daughter microsats to provide measurements of backscattered radiation from different angles. The COACH concept would provide true stereo imagery, while Leonardo would measure multi-angle backscatter flux. In addition to Leonardo and COACH, future missions that would operate as virtual instruments include laser SST missions (GRACE follow-on), tandem synthetic aperture radars and possibly cloud-probing missions.

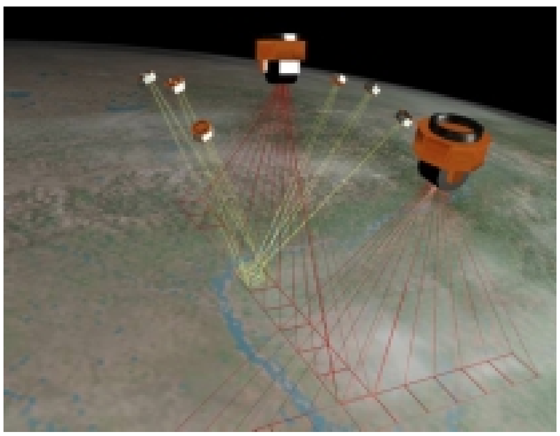

Fig. 2. Leonardo, a conceptual virtual instrument to measure the bi-directional reflectance distribution function. The virtual instrument architecture eliminates the need for complex multi-instrument observatories, and autonomous pointing and data acquisition planning reduce the need for extensive ground managment.

D. *The Sensor Web*

The sensor web is the next step in the evolution of formations. It would include virtual instruments, and simple formations, but the whole system would be actively managed. This means that observation needs would be predicted (based upon previous observations) and the sensor web would respond to the emergent measurement needs. For example, geostationary scanners might revisit a single location more frequently if a severe storm might be forming. LEO or GEO radars might change frequency, or change modes from scanning to fixed viewing to achieve higher spatial and temporal resolution of an earthquake. Hyperspectral imagers might adjust their spectral resolution if an interesting signature was recognized. In the true sensor web architecture, many different types of observing platforms would work cooperatively to investigate interesting phenomena, such as rain radars, wind profilers, cloud imagers, and temperature and moisture sounders in the case of monitoring severe storm formation (cyclogenesis).

III. Required Technologies

Making the sensor web a reality will require significant technological advances in the sensor area, data management, and spacecraft technologies. Here we focus on needed advances in spacecraft technology. There are three major technology thrust areas within the intelligent distributed spacecraft infrastructure area: communications, micro/nano spacecraft, and autonomy.

A. *Communication*

In the area of communications, the needs of distributed spacecraft architectures drive the need for standard protocols and interoperability of communication systems. Required technologies needing validation include acquisition, tracking and pointing algorithms, protocols, networking, ranging, command and control, and data handling and processing. To enable homogeneous and heterogeneous networks of spacecraft, an interoperable communication protocol layer must be established. A communication backbone, allowing each individual satellite to plug-in as a node, satisfies this constraint. Requirements of low data latency (for hazard warning) and high bandwidth drive the requirement for real-time data pipes to the ground utilizing MEO or GEO repeaters and optical communications. Some applications will require onboard data processing [2].

B. *Microspacecraft*

Clearly, to be cost-effective, distributed spacecraft architectures will rely on low-cost, micro/nanospacecraft with multiple spacecraft launching on a single vehicle. Some specific validation needs include advanced solar arrays/batteries, micro star trackers, micropropulsion, and spacecraft design/testing tools. Inflatable/deployable solar arrays and high energy density batteries offer a means of reducing weight and volume, while advanced attitude control components enable precision control of spacecraft and reduce the weight of needed fuel. An important need in this area is for methods to build and test spacecraft in batches and modularize bus designs to minimize cost and maximize reusability. A useful paradigm for thinking about future spacecraft acquisitions is the current personal computer or automobile model where a base cost, plus packages of options, are offered at fixed, competitive pricing. Such a paradigm requires a robust market that can support assembly-line manufacturing processes. The confluence of increased demand for large numbers of micro/nanospacecraft and intelligent risk management in the manufacturing/testing process would enable such a paradigm shift.

The sensor web will not just consist of microspacecraft, as there are many observation systems that are not amenable to that approach; however, it should be noted that investment in microspacecraft technologies will also benefit medium and large spacecraft.

C. Autonomy

Autonomy, computing and data management present a number of challenges both in hardware and algorithmic areas.[3] Autonomy is critical for closed loop control, for achieving cost savings, and for maximizing science return. Very high performance, low-power, computing devices are necessary for formation flying, sensor webs and nanosatellites. Autonomy and algorithm validation needs include high-level planning and scheduling, fault diagnosis and recovery, command and control, low-level navigation and pointing, instrument control, science data processing, and distributed resource management, processing and control, as well as, relative navigation, collision avoidance and collective pointing. A similar analogy to the paradigm shift in the computer industry as used above can be drawn and should be leveraged. Just as information technology has evolved from large centralized mainframes to distributed networks of computers with specialized devices such as print or file servers, spacecraft are evolving from the large Terra-type observatories to collaborative constellations of small sensorcraft and specialized mirrors or processors.

With this evolution, comes complexity. Not only is communication critical to create a virtual instrument and bus, but planning and scheduling of a distributed constellation requires new levels of resource management. If not carefully done, the useful life of the constellation could be as short as the fuel supply of a single spacecraft, or data may be lost because available processors were not properly utilized.

While EO-1/Landsat-7 validated onboard formation control between two spacecraft, significant challenges remain including safely managing multiple-vehicle maneuvers, and pointing, and spacecraft failures, across a formation. Graceful degradation of constellations and sensor webs is essential. Just as a single spacecraft requires intelligent onboard fault detection and recovery, a constellation is particularly vulnerable and must be able to determine when an entire element has failed, avoid it, and reconfigure itself to compensate for the loss.

With large numbers of spacecraft collecting potentially huge amounts of data, serious research into data management, compression and reduction is critical. In some formation or mission concepts, the data must be shared among spacecraft, and allowances must be made for large communication bandwidths and latencies. Also, the spacecraft will need to determine what data should be sent to the ground, what can be thrown away, and what needs to be kept on board in case the ground requests it or further processing is necessary. Aging of the data must be managed and data collected from several sources may be necessary to select the next observation or action of the constellation.

The introduction of autonomous systems to address some of these issues can, however, create its own problems. The nondeterministic nature of autonomy complicates testing. New techniques and tools are necessary to determine and fully understand system behavior. It is no longer possible to use structured testing and try to cover all the “expected” paths or outcomes. Formal languages and methods may be necessary to validate functionality.

IV. Conclusion

Global data gathering with high spatial and temporal resolution is critical for better understanding of the Earth system and its interactions, including accurately comprehending and predicting climate change, and providing natural hazard assessments and warnings. As discussed, spacecraft formations and sensor webs are essential for acquiring the necessary data. Sensor webs ultimately enable distribution of data collection and processing on a global scale. They provide a system to autonomously observe, process, and distribute spatial and temporal data directly to users.

The development of tools and technologies that enable formations and sensor webs has just begun. As discussed, significant challenges in the areas of autonomy, communications, and microspacecraft remain. Today, efforts are just beginning to address these technology challenges, and prototype sensor webs are being developed. However, to meet the vision of the NASA Earth Science Enterprise and provide the public with potentially life saving resources and critical data, significant effort is required. Twenty years ago, personal computers were only beginning to populate the workplace. Today’s computers, large and small, are connected in a living network. Years from now, with sensors as prolific as today’s cell phones, networked scientists utilizing distributed computing and evolvable models will revolutionize Earth science.

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