Earth Science Vision: Platform Technology Challenges

Loren Lemmerman
Kevin Delin
Fred Hadaegh
Michael Lou
Jet Propulsion Laboratory
Pasadena, CA 91109-8099

Kul Bhasin
Glenn Research Center
Cleveland, OH 44135

John Bristow
Robert Connerton
Michael Pasciuto
Goddard Space Flight Center
Greenbelt, MD 20771

Abstract—Advanced new platform technologies are critical to the realization of the Earth Science Vision in the 2020 timeframe. Examples of the platform technology challenges and current state-of-the-art capabilities are presented.

I. Introduction

NASA's Earth Science Enterprise (ESE) is poised to revolutionize our understanding of the Earth's environment and climate, through radical, new science data collection methods. Historically, earth science investigations have been independent highly focused science investigations. However, the earth's environment is a very dynamic and interrelated system. Concentrations of ozone, CO_2 and pollutants are not confined to any single area, certainly not confined to geographical borders. In addition some elements of the earth's environment, such as natural hazards (fires, hurricanes, volcanoes for example) require real or near-real time identification and notification of an event to be of any value to the community. Single snapshots of a single ground area or the composition of any single column of air are not sufficient to understand the interdependencies and complexities of the earth environment. The old ("stove-pipe") method of science data collection from a single platform is no longer adequate. A fuller understanding of the intricacies of the earth environment will require: accessing extensive amounts of data, and providing global timely coverage. Observing systems must be flexible, reconfigurable, autonomous, and cooperative. A key element envisioned for accomplishing these difficult challenges is the idea of a distributed, heterogeneous, adaptive, cooperating observing systems or "Sensor Web". Most of the technology challenges associated with our Sensor Web concept require substantial investment in new platform capabilities.

Indeed, even the traditional concept of an "aperture" being on a single instrument, or even being on a single "platform" may not fit. The aperture may be made up of elements on multiple platforms on Earth and/or in space, which need to cooperate in order to operate as a single element. While some measurements may require very large deployable elements, others may need in-situ micro- or nano-sensors. The old concept of a single "campaign" will evolve into a dynamically adapting continuous "campaign of campaigns".

While some of these ideas may seem far-reaching and seem potentially unobtainable, there is work already in progress within NASA, other agencies and the private sector which when developed, will facilitate many elements of this vision. NASA, for instance, has already established some of the first elements of a prototypical Earth Science Vision Sensor Web. Currently NASA is coordinating the flight paths and observations of a number of different Earth science spacecraft into a train-like arrangement to provide near simultaneous observations of the same area of the earth from with multiple sensors on distinct satellites. While this train of satellites still relies on ground-based data fusion, cannot communicate among vehicles, and has no "alert" system, this prototypical Vision Sensor Web is already demonstrating enormous benefits to the earth science community. This is only a first step. What if the satellites were designed a priori to communicate and be "cooperative"? What if this satellite train could communicate with a ground-based Sensor Web?? In such a scenario, we would have the beginnings of a global-scale Sensor Web. What we would have created is a distributed, heterogeneous, adaptive, cooperating observing system. These sub-space elements of the Sensor Web could provide ground truth or signal alerts. These alerts could cause adaptive behavior throughout the Sensor Web, from ground to space. Imagine what new science discoveries we could enable! To accomplish this requires revolutionary changes in the design of the system itself.

II. Sensor Web Prototyping

The NASA New Technology Report on Sensor Webs [1] defines the Sensor Web is a macroinstrument concept that allows for coordinated efforts between multiple numbers and types of sensing platforms, including both orbital and terrestrial and both fixed and mobile. The most unique feature of the Sensor Web is that information gathered by one sensor is *shared and used* by other sensors in the web. Each sensor communicates within its local neighborhood and thus distributes information to the instrument as a whole. NASA has already established some of the first elements of a prototypical Earth Science Vision. These Sensor Web instruments exploit recent advances in miniaturization, wireless networking, and mass production to deploy, augment and replenish large networks of inexpensive sensors. Obsolete or damaged elements may be replaced with minimal impact and the web expanded over time as resources and budgets allow. This expansion is enabled using the same techniques employed today to create

and add to networks on Earth.

A. Terrestrial Applications of Sensor Webs

Three generations of prototype Sensor Webs have been developed. See, for example, http://sensorwebs.jpl.nasa.gov/. The first generation at JPL was fabricated using commercial components and demonstrated the concept and the data communication protocols using commercial components. In addition to demonstrating low power operation, these pods were lab tested to demonstrate capabilities for data hopping and for eliminating redundant data paths. As a second-generation system, 12 botanical pods (Fig. 1.) were developed and operated at the Huntington Gardens in San Marino, California. These pods included six on-board sensors (2 temperature, light level, oxygen level, humidity, and soil moisture) and demonstrated energy harvesting via solar collection. This Sensor Web operated continuously for 22 weeks, recording data snapshots across the entire web every 5 minutes, and was fully successful. A third generation of Sensor Web pods is in development that will extend the scope of the web to larger systems and will minimize power consumption significantly [2].

The specifications of the Sensor Web are highly dependent on the applications. Further work needs to be done to understand the unique requirements of relevant applications, to understand the key issues involving communications (especially the interface from terrestrial systems to space systems), to establish scaling laws, especially for large scale applications, and to track carefully commercial technologies so that they can be exploited at the earliest opportunity. Additionally, the extraction of knowledge from measurements taken and the exploration of ways of using the information collected by the web to enable bionomic control and autonomous operation are areas of further research.

B. Space Applications of Sensor Webs

The Earth Science (ES) Constellation is the first step toward Sensor Webs in space. NASA's Earth Science Enterprise (ESE) is striving to coordinate and identify coincident imaging among the ES missions. To achieve this, the operational coordination of the entire Sun-synchronous ES Constellation will be viewed as a whole. The planned constellation currently consists of at least 9 identified missions, four (Landsat-7, EO-1, SAC-C and Terra) with AM node crossings (morning train) and five (Aqua, Picasso-Cena, CloudSat, Aura and Parasol) with PM node crossings (afternoon train).

1) AM or Morning Train: Landsat-7 and Terra, launched in 1999, are arranged such that Terra trails Landsat-7's ground track by just over 30 minutes. In 2000, EO-1 and SAC-C joined this constellation when they were co-launched into orbits that trail Landsat-7's ground track by one and 15 minutes, respectively. EO-1 actually maintains a formation

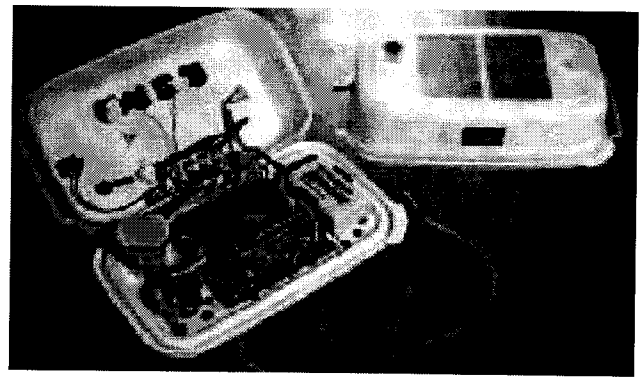

Fig. 1. Botanical Sensor Web

with Landsat-7, remaining one minute behind to +/-3 seconds.

The primary purpose of the AM train (Fig. 2) is to enhance the science benefits from sensors carried on individual satellites. This is done by using observations of similar parameters to calibrate and validate observations, and by using complimentary observations of the same areas to allow estimates of parameters that would not be adequately constrained by sensors on individual satellites. A secondary purpose of the train is to develop and demonstrate formation flying technologies that are required for future Sensor Webs. Even though no ranging or cross communications between spacecraft in the AM train exists, this activity can be viewed as a prototype Sensor Web using bent pipe ground communication and post processing to coordinate science data gathering

2) PM or Afternoon Train Still in development: The spacecraft and concepts for the PM Train are still under development and may include enhanced Sensor Web concepts such as cross communication between satellites. Expanding upon the Landsat-7/EO-1 formation, the PM train will include a formation of Aqua, Picasso-Cena and CloudSat with Aura and Parasol completing the constellation. Again, however, much of the coordination will be ground based and human initiated.

While the AM and PM Trains touch on some of the initial challenges such as coordinated observations and science data fusion, future Sensor Webs will extend capabilities to fully autonomous data gathering, processing, and high-rate transmission nodes These extended capabilities, however, create new challenges. As Sensor Webs are employed, data quantity will increase exponentially, creating huge processing, storage and transmission problems, making distributed processing and onboard data fusion critical.

Unlike the ES Constellation, future spacecraft will be launched with the capability to communicate and initiate on orbit interactions. Small, low-cost sensorcraft will become commonplace. Networks with latency tolerant protocols will

Fig. 2. AM Train Depiction

cover the Earth and space linking these sensors. From the humble Trains, Sensor Webs will revolutionize exploration and understanding of the environment.

III. Precision Guidance and Control

For many future ESE missions extreme pointing stability and precision are required. These needs are driven by activities ranging from calibration of radar altimeters to repeat path interferometry using radar. The control of spacecraft in low Earth orbit poses significant challenges. Low-Earth-orbit formations are subject to several non-uniform perturbations that can potentially destabilize the formation geometry. Many of NASA's future Earth Science missions will involve precision formation flying of multiple coordinated spacecraft (Fig. 3.). For example, for the Time Varying Gravity Field Mapping (EX- 5/Grace Follow-on), position knowledge in the order of 100 nanometers will be required. In another example, co-observation of a phenomenon on earth, spacecraft and instrument alignment and precision metrology in the nanometer range will be needed. Formation flying technology will allow deployment of a large number of low cost, miniaturized spacecraft and introduction of new members to the formation over time. The collective behavior of all the spacecraft in the formation will determine the quality and the magnitude of the science return. The formation flying system must act collaboratively as a single collective unit to perform a task.

The formation-flying missions can only be cost-effective as autonomous coordinated systems with no or minimal involvement from ground. The guidance and control system for formation flying must be onboard with autonomous formation position determination capability, autonomous navigation, formation estimation, and path planning functions. Generalized reasoning capability offered by advanced distributed software technology and artificial intelligence must have the potential to cope with unexpected events and uncertainty and allow closing the loop of perception, decision making and eventually deliberation [3]. Significant technology breakthroughs will be needed in control algorithms, noise free reaction wheels, autonomous formation sensors (AFF), precision thrusters and formation communication technology for a successful deployment and operation of a this type of mission.

IV. Communication Needs

Supporting the seamless flow of information and the spacecraft/ground sensor control desired will require low-cost, efficient, modular and dynamically reconfigurable network

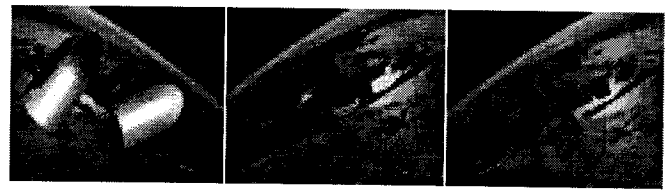

Fig. 3. Earth Orbiting Spacecraft Formation for Co-observations

communication solutions. The resulting multi-spacecraft and sub-space topologies will effectively create a wide area network that would enable authorized users anywhere to control sensors in near real time and obtain information immediately. Such a network would consist of very high data rate backbone links, access networks, and multi-spacecraft links. In Table 1, we show the state of the practice data rates and the desired data rates to realize the vision.

Development, implementation and operation of a Sensor Web network in a dynamic space environment present major technical challenges in the areas of protocols, information security, network reliability and miniaturized and agile hardware elements for the physical layer. Sensor Web protocol technologies are being developed as an open architecture based on those portions of the Open Systems Interconnections (OSI) model that account for the uniqueness of the space environment such as: infrequent contacts, asymmetric links, high time delays, and increased bit error rates. While the challenges in the sub-space portion of the Sensor Web should not be minimized, the sub-space portion of the Sensor Web will leverage existing and evolving (e.g. mobile ad-hoc networking) terrestrial Internet protocols.

Advanced hardware technologies under development for the high rate backbone include microwave links based on space-based tracking antennas and optical communication links. Multi-element phased array antennas which can electronically steer to acquire and track moving spacecraft, and rapidly re-acquire new spacecraft during hand-offs must be made as small, lightweight and affordable as possible. For the optical

Table 1 Earth-GEO Link Characteristics

Types of Links	State-of-the-Practice	2010	2015	2020
a. DD from LEO Spacecraft	X-D and 150 Mbps	10 Gbps gateway 1 Gbps D/L	25 Gbps	100 Gbps
b. DD from GEO spacecraft	150 Mbps	10 Gbps	25 Gbps	100 Gbps
c. LEO to GEO relay	2 Mbps	150 Mbps 1 Gbps		
d. Multi-spacecraft links	4 Mbps	45 Mbps	155 Mbps	N/A
e. Sensor Webs	300 bits/sec (grid sensor to sky)	Multiple links of A, B, C, D	Multiple links of A, B, C, D	Multiple links of A, B, C, D

links, acquisition and tracking techniques are also needed for fast moving spacecraft. Work has also been initiated across several NASA Enterprises, other agencies, and industry to develop a small communications device providing a router, cross-links, GPS receiver, on-board processing, and reprogrammability. The approach is to develop this device along industry standards using a modular physical architecture to allow for future upgradability.

In conclusion, internetworking of space and sub-space nodes via an on open-architecture, standards-based approach will greatly improve the timely availability of information to users and will enable new ways to perform Earth Science. The Earth Science Enterprise is working within NASA, with other agencies, and industry to jointly enable the development of key communications technologies to enable our vision.

V. Large Lightweight Deployable Antennas

Large-aperture planar and reflector antennas are essential to many missions planned by NASA to monitor Earth systems changes. These large apertures are dictated by the physics of the observations and include missions to monitor precipitation, soil moisture, snow, freeze and thaw, ocean salinity, tropospheric winds and cloud properties. To reduce the life-cycle cost of these missions, technologies are being developed to minimize the mass and launch volume of the flight systems.

Two examples of Earth Science applications of lightweight deployable structures include synthetic aperture radar (SAR), deployable antennas for radiometers and telescope reflectors for light collection. In support of these types of measurements, two approaches for an inflatable synthetic-aperture radar (ISAR) antenna, the AstroMesh® antenna for radiometry and the inflatable reflector antenna for light collection will be reviewed.

A. Inflatable SAR (ISAR) Antenna

The ISAR antenna [4] under development at the Jet Propulsion Laboratory is an L-band radar that has an aperture size of 10 m x 3 m, an operating frequency of 1.25 GHz, dual-linear (vertical and horizontal) polarization, 80-MHz bandwidth, and electronic beam scanning. The antenna aperture consists of three layers of thin-film membranes that form the radiating plane, the ground plane, and the transmission line plane.

Two 1/3-scaled, but fully RF functional, engineering models were designed and fabricated to demonstrate the feasibility of the inflatable antenna concept. The first of these proof-of-concept engineering models (Fig. 4), built by ILC-Dover, features a planar inflatable frame formed by 13-cm thick urethane-coated Kevlar flexible tubes. The tubes deploy by inflation pressure and are controlled by several constant force springs embedded in the tube wall.

A second proof-of-concept ISAR antenna model, built by L'Garde, has a support structure consisting of rigid end bars and longitudinal inflatable booms that can be rolled up for stowage. These inflatable booms have a diameter of 9 cm and are made of 0.08 mm-thick rigidizable stretched aluminum material. Controlled deployment of this model is accomplished by Velcro® strips glued onto the inflatable booms.

Both ISAR designs are ultra-lightweight. Excluding the inflation systems the L'Garde model has a total mass of 11 kg and the ILC-Dover model has a mass of 12 kg. Based on these data, it was estimated that a full-size (10 m x 3 m aperture) ISAR antenna (with inflation system) would have an areal mass density of 1.6 kilograms per square meter of aperture area. This is almost one order of magnitude lighter than the lightest SAR ever flown. JPL is currently developing a full-size ISAR for RF and mechanical testing, based on the innovative Spring-Tape-Reinforced (STR) system [5].

B. Inflatable Reflector Antenna

The aperture of an inflatable reflector is typically made of a thin-film material, such as Mylar or Kapton that can be deployed to a lenticular parabolic shape by inflation pressure. The deployed lenticular aperture is supported by a toroidal inflatable structure. Even though the inflatable lenticular reflector concept was first proposed and demonstrated by Goodyear in the 1950's, such a concept was not demonstrated in space until May 1996, when the NASA Inflatable Antenna Experiment (IAE), carried by a recoverable Spartan spacecraft, was launched from the Space Shuttle. The IAE experiment successfully demonstrated space deployment of a 14-meter off-axis parabolic aperture made of 0.25-mil Mylar film. It was supported by a torus, which in turn was attached to the Spartan by three 28-meter-long tubular struts. Both the torus and the struts were also inflation deployed in space. Additional details of the IAE mission can be found in several publications, e.g., [6].

Research efforts sponsored by NASA and the U.S. Air Force are currently developing inflatable reflectors of improved surface accuracy and for sizes over 20 m diameter.

Fig. 4. ISAR Antenna Proof-of-Concept Model

C. AstroMech® Antenna

Small-scale reflector antennas with mesh apertures have long been used on space missions, including the Galileo mission to Jupiter. Recently, TRW/Astro successfully developed a 12.25 m diameter lightweight AstroMesh® reflector and demonstrated an areal density 0.37 kg/m^2 [7]. These reflectors have parabolic-shaped mesh apertures and can be stowed in a small package (Fig. 5). The lightweight composite truss that supports the mesh aperture is deployed in space by electromechanical means. A 12.25-meter unit

was flown on a Hughes telecommunication satellite late last year.

Future work will focus on demonstrating the performance of each of these concepts, qualifying deployment reliability, demonstrating lifetimes and evaluating their applicability in systems studies.

VI. Conclusion

To better comprehend the Earth's environment, accurately predict and understand climate change, and provide natural hazard warnings, data must be gathered both globally and temporally. To collect and process that data, Sensor Webs are critical. Sensor Webs enable distributed data collection and processing on a global scale. NASA, academia and industry are only beginning to develop the tools and technologies that enable Sensor Webs. As discussed, significant challenges and investments are necessary particularly in the areas of autonomy, communications, precision control, large deployable antennas, distributed processing, and data fusion. To meet the goals of the ESE Vision and provide the public with potentially life saving resources and critical data, much remains to be done. Twenty years ago, personal computers were isolated but today computers across the world are connected in a living network. Today, sensors are largely isolated but twenty years from now will be as prolific as today's cell phones; their connection and collaboration will revolutionize Earth Science.

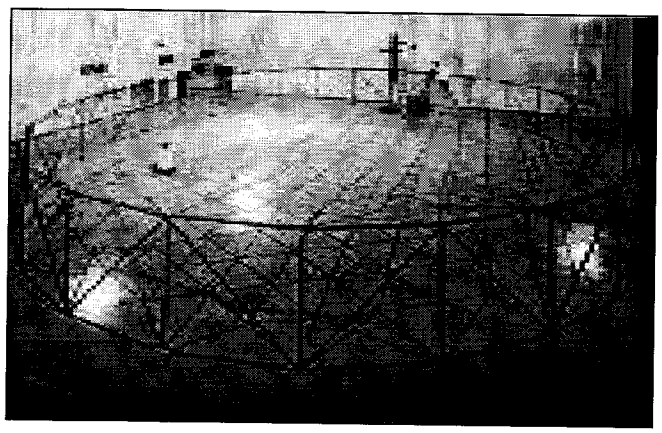

Fig. 5. An AstroMesh® Antenna

References

[1] K.A. Delin, S.P. Jackson, and R.R. Some, "Sensor Webs," *NASA Tech Briefs*, **23**, 80 (1999).

[2] K.A. Delin and S.P. Jackson, "The Sensor Web: A New Instrument Concept," *SPIE's Symposium on Integrated Optics,* San Jose, CA, January 2001.

[3] S. Mandutianu, F. Y. Hadaegh, P. Elliot, "Multi-agent System for Formation Flying Missions," IEEE Aerospace Conference, 2000.

[4] Huang, J., Lou, M.C., Feria, V.A., and Kim, Y., "An Inflatable L-Band Microstrip SAR Array," presented at the IEEE AP-S Symposium, Atlanta, Georgia, pp. 2100-2103, June 1998.

[5] Lou, M.C., Fang, H., and Hsia, L., "Development of Space Inflatable/Rigidizable STR Aluminum Laminate Booms," presented at the AIAA 2000 Aerospace Conference, September 2000, Long Beach, CA.

[6] Freeland, R.E., Bilyeu, G.D., Veal, G.R., and Mikulas, M. M., "Inflatable Deployable Structures Technology Summary," presented at the 49th International Astronautics Congress, Melbourne, Australia, September 1998.

[7] Thomson, M., "The AstroMech Deployable Reflector," presented at the IUTAM-IASS Symposium on Deployable Structures: Theory and Applications, Cambridge, U.K., September 1998.

Acknowledgments

The author gratefully acknowledges the contributors to this article: Fred Hadaegh (JPL) for guidance, navigation and control, Michael Lou (JPL) for lightweight antennas, John Bristow (GSFC) and Kevin Delin (JPL) for Sensor Webs, Kul Bhasin (GRC) for communications and Michael Pasciuto (GSFC) and Robert Connerton (GSFC) for their assistance in overall formulating and editing.