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Advanced Platform Technologies for Earth Science

Loren Lemmerman[1], Carol Raymond[1], Robert Shotwell[1], James Chase[1], Kul Bhasin[2], Robert Connerton[3]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[2]Glenn Research Center, Cleveland, OH 44135, USA
[3]Goddard Space Flight Center, Greenbelt, MD 20771, USA

ABSTRACT

Historically, Earth science investigations have been independent and highly focused. However, the Earth's environment is a very dynamic and interrelated system and to understand it, significant improvements in spatial and temporal observations will be required. Science needs document the need for constellations to achieve desired spatial and temporal observations. A key element envisioned for accomplishing these difficult challenges is the idea of ad istributed, heterogeneous, and adaptive observing system or sensor web. This paper focuses on one possible approach based on a LEO constellation composed of 100 spacecraft. A cost analysis has been done to indicate the financial pressures of each mission phase and conclusions are drawn suggesting that new technology investments are needed, directed toward lowering production costs; that operations costs will need to be reduced through autonomy; and that, of the on-board subsystems considered, advanced power generation and management may be the most enabling of new technologies.

1 EARTH SCIENCE NEEDS

Tremendous progress has been made in understanding the trends of individual Earth system variables (such as atmospheric temperature and ozone content) since the advent of remote sensing from space. The next advancement needed for improving the understanding of the Earth system will come from the monitoring of complex, dynamic interactions rather than individual Earth system variables. This will enable the prediction of these dynamic processes and interactions and to initialize, correct, and validate models of complex behavior. Monitoring these complex interactions requires continuous global data sets across multiple variables, each with distinct 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 frequently.

Applications that require high resolutions attempt to characterize complex non-steady system behavior such as severe storms, floods, volcanic eruptions, or earthquakes. Typically, these measurements would require temporal revisit times on the order of 15-30 minutes over a field of view of tens of kilometers. Such requirements imply an observing system consisting of some type of constellation, regardless of the orbit selected. The orbit simply dictates the requirements on the number of spacecraft in the constellation. A Low Earth Orbit (LEO) orbit, for instance, would lead to relatively large numbers of spacecraft and would require spacecraft of small size and mass to minimize launch costs.

Not all of science measurements can be addressed with constellations of small spacecraft. Power limitations prohibit high-power active instruments, and small size prohibits large apertures. Thus, possible scientific motivation for a dense small spacecraft constellation is limited to low-demand measurements such as temperature and water vapor sounding, precipitation monitoring, or thermal infrared imaging. Other applications include monitoring aerosols, ozone, carbon dioxide, methane and trace gases in the atmosphere, along with radiative flux to determine the forcings and feedbacks of these substances on short-term climate and the hydrologic cycle.

A LEO constellation already in development (COSMIC Global Positioning System (GPS)) serves as an excellent example. It will launch ~100 spacecraft to measure atmospheric temperature using GPS signal radio occultation methods and measure atmospheric water vapor using microwave crosslinks between satellites. An important characteristic of this architecture is envisioned to be dual-use functionality in which the science measurement system would constitute the navigation system (GPS), host the avionics, and also perform inter-spacecraft communications. Onboard processing and autonomy, integrated into the GPS receiver, would complete the low-cost spacecraft approach. The constellation would operate autonomously collecting dense occultation data, and would also respond to emerging phenomena identified by cooperating master spacecraft, such as a geostationary imager or infrared sounder. Such innovations will doubtless be necessary for successfully fielding all large constellations.

2 SYSTEM CONSIDERATIONS

Typically, Earth science space missions are driven by a unique set of demanding requirements, and the resulting spacecraft implementations are customized and massive. This result implies large spacecraft development and launch costs. Historically, operations costs are also high because much of the intelligence needed to operate the mission is provided by humans on Earth. Collectively, these problems have caused high overall costs, and each problem must be addressed to bring the cost of large constellations within reach.

The size and mass of the spacecraft must be reduced to minimize the launch costs. Launching a single spacecraft with a small vehicle offers considerable flexibility in the available orbits, but launch cost per spacecraft can be quite high compared to other options. Using secondary payload slots offers low launch cost per spacecraft, but it is extremely dependent on a limited number of available launches and their orbital parameters. In contrast, launching multiple spacecraft on ad edicated vehicle can provide low launch cost per spacecraft while retaining adequate launch flexibility [3]. This is the option evaluated here.

In the case of constellations with many spacecraft, the individual spacecraft must be especially low cost given the large number of satellites required. Thus, it is important not only to use the spacecraft building-block approach but to also make all spacecraft physically identical, while allowing some differences in software parameter tables and sequences. In this environment, developers must take advantage of mass production approaches, learning curves, large component number buys, and methodologies that effectively employ COTS parts.

2.1 Constellation Architecture Study

There is extensive experience with satellites in GEO, especially with communications satellites. Satellites in GEO have the advantages of having a large field of regard (allowing full earth coverage with a minimum number of satellites) and the relatively easy capability of returning data by direct distribution to user terminals. The drawbacks to the GEO constellations are the high launch costs associated with GEO and stringent pointing requirements. Summarized, the GEO vantage point primarily stresses the instrument capabilities, but does not represent a serious challenge to platform capabilities.

Conversely, a LEO constellation requires a large number of distributed spacecraft to meet the same latency and frequency of revisit requirements. While this vantage point can provide much higher resolution and observational capability than a GEO constellation (with the same instrumentation), it does so at the expense of stressing every aspect of system development, launch, and operations. Both of the extremes of vantage points, LEO and GEO constellations, deserve close inspection to assess their limiting factors and their cost and technical feasibility of deploying such systems. The emphasis of this paper, however, is on large constellations of spacecraft in LEO.

2.2 Assumptions of Cost Analysis

The analysis approach was to create a simple breakdown of costs by mission phases, including development, implementation, production, launch, and operations. The resulting table includes a life cycle cost (LCC) over a ten-year period (Table 1). As a starting point, several assumptions were made for each of the phases. These include:

Development: $150M over 4 years regardless of the number of s/c produced.
Implementation: $220M over 4 years for one s/c and $435M over four years if multiple s/c are produced. This additional cost is for increased parts and qualification testing of the prototype production units prior to commitment to production.
Production: The initial spacecraft production cost is $15M. Later satellites are produced under the assumption of an 85% learning curve.
Launch: It is assumed that <= 5 s/c may fit on a Pegasus ($30M) and 6 to 24 s/c fit on a Delta II ($60M).
Operations: 1-9 s/c are $5 M per year, 10-19 s/c are $10M per year, 20-49 are $20M per year, and 50+ s/c are $30M per year.

Cost Analysis for a Generic Satellite Constellation										
	Constellation Development (10 years)									
Costs are in $M	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
Development										
Spacecraft development	30	50	40	15	-	-	-	-	-	-
Carrier development	3	5	4	2	-	-	-	-	-	-
Total	**33**	**55**	**44**	**17**	**0**	**0**	**0**	**0**	**0**	**0**
Cumulative R&D Total ($M)	**33**	**88**	**132**	**149**	**149**	**149**	**149**	**149**	**149**	**149**
Implementation										
Spacecraft implementation	-	70	150	125	50	-	-	-	-	-
Carrier implementation	-	7	15	13	5	-	-	-	-	-
Total	**0**	**77**	**165**	**138**	**55**	**0**	**0**	**0**	**0**	**0**
Cumulative R&D Total ($M)	**0**	**77**	**242**	**380**	**435**	**435**	**435**	**435**	**435**	**435**
Spacecraft Production										
Spacecraft per year	0	0	0	0	16	16	16	16	16	20
Cumulative spacecraft	0	0	0	0	16	32	48	64	80	100
Hardware	0	0	0	0.0	24.3	20.5	18.6	17.4	16.5	19.5
Payload	0	0	0	0.0	14.6	12.3	11.2	10.4	9.9	11.7
Flight software *(non-recurring)*	0	0	0	0.0	5.0	0.0	0.0	0.0	0.0	0.0
Integration & testing	0	0	0	0.0	9.7	8.2	7.5	7.0	6.6	7.8
Total + 50% margin	**0**	**0**	**0**	**0.0**	**80.3**	**61.6**	**55.9**	**52.2**	**49.5**	**58.6**
Cumulative	0	0	0	0	80	142	198	250	300	358.1
Cost per Spacecraft	**0**	**0**	**0**	**0.0**	**5.0**	**3.9**	**3.5**	**3.3**	**3.1**	**2.9**
Launch Costs										
# of launch vehicles	0	0	0	0	1	1	1	1	1	1
Cumulative launch vehicles	0	0	0	0	1	2	3	4	5	6
Carrier hardware	0	0	0	0.0	0.7	0.6	0.5	0.5	0.5	0.5
Carrier Flight software *(non-recurring*	0	0	0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
Carrier Integration & testing	0	0	0	0.0	0.2	0.2	0.2	0.2	0.2	0.2
Carrier Propellant	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Launch vehicle	0	0	0	0	60	60	60	60	60	60
Launch operations	0	0	0	0.0	0.4	0.4	0.4	0.4	0.4	0.4
Total	**0**	**0**	**0**	**0.0**	**61.9**	**61.2**	**61.1**	**61.1**	**61.1**	**61.0**
Cumulative	0	0	0	0	62	123	184	245	306	367.4
Cost per LV	**0**	**0**	**0**	**0.0**	**61.9**	**61.2**	**61.1**	**61.1**	**61.1**	**61.0**
Operations										
Operational spacecraft	0	0	0	0	16	32	48	64	80	100
Flight operations	0	0	0	0	10	20	20	30	30	30
Total	**0**	**0**	**0.0**	**0.0**	**10.0**	**20.0**	**20.0**	**30.0**	**30.0**	**30.0**
Cumulative	0	0	0	0	10	30	50	80	110	140.0
Total	**30**	**130**	**210**	**150**	**210**	**140**	**140**	**140**	**140**	**150**
Cumulative Total	**30**	**160**	**370**	**520**	**730**	**8701,**	**010**	**1,150**	**1,290**	**1,440**
			*** All figures in $M**							
Total Program Cost (10 yrs)	**1,440**	**$M**	*** Constant FY03 dollars assumed**							

Table 1: Simplified cost analysis for a generic satellite constellation (over 10 years)

No. s/c	Budget ($M)	# LV	Devel.	Impl.	Prod.	Launch	Ops	Total LCC	$ per s/c ($M)
1	470	1	0.32	0.46	0.03	0.08	0.06	1.0	470
10	760	2	0.20	0.57	0.08	0.08	0.07	1.0	76
15	810	3	0.18	0.54	0.11	0.12	0.17	1.0	54
20	890	4	0.17	0.49	0.11	0.12	0.12	1.0	45
40	1,070	4	0.14	0.41	0.17	0.19	0.10	1.0	27
60	1,190	4	0.12	0.37	0.20	0.21	0.12	1.0	20
80	1,320	5	0.11	0.33	0.23	0.23	0.11	1.0	17
100	1,440	6	0.10	0.30	0.25	0.26	0.10	1.0	14

Table 2: Fractions of Life Cycle Cost by Mission Phases

2.3 Results of Cost Comparison

Following the construction of Table 1, several scenarios were introduced by varying the number of satellites from one to 100, shown in Table 2. These results agree with intuition in that as the number of satellites increases the development and implementation LCC fractions decrease. In contrast, the LCC fractions of production, launch, and operations increase. The final result is that increasing from one to 100 spacecraft triples the cost of the mission while the cost per spacecraft decreases significantly.

Figure 1 shows the results as a plot of LCC with respect to the number of spacecraft produced. This plot is useful as it illustrates the economies of scale achieved as the number of spacecraft increases.

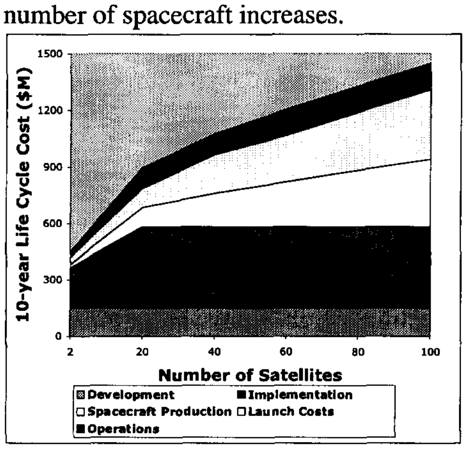

Figure 1: Life Cycle Cost by Phase

2.4 Summary of Results and Conclusions

1) Spacecraft will be driven to the smallest practical package to allow multiple deployments from each launch vehicle. This implies
   i. Size constraint precluding certain classes of mission from consideration, such as spacecraft requiring large apertures.
   ii. Integration of functions normally performed by multiple subsystems into one subsystem, to reduce integration and test costs.
2) Total spacecraft delivery costs will have to be minimized beyond any previous attempts, and this will no doubt require several significant changes. Implications:
   i. Traditional approaches to spacecraft design discarded and replaced with a manufacturing mentality.
   ii. Emphasis on subsystem technology development aimed not at improving performance but instead at reducing production cost
   iii. Increase in spending on upfront design (NRE) to save more during fabrication and I&T. (Increase the breadth of validation and verification during implementation and reduce it during production)
   iv. Mass production approaches, learning curves, large component number buys and methodologies that effectively employ COTS parts

v. Use of 6-sigma for parts purchases to substantially reduce I&T costs.

3) Operations costs will have to decrease dramatically from today's practice to keep the system affordable. This implies:

i. A significant amount of built-in-test and self-diagnosis on the spacecraft
ii. High-level commanding for maneuvers
iii. On-board orbit self-maintenance
iv. Significantly reduced ground staff

With these results as a backdrop, it seems clear that significant attention must be focused on the individual subsystems to provide at least a qualitative assessment of the feasibility of addressing these challenges.

3 SUBSYSTEM CONSIDERATIONS

From the discussion, it is clear that technology isa key to enabling large constellations, but with a difference: in addition to technology investments to improve a performance metric (e.g., advanced communication capability [4] etc.), technology investments now are needed that will allow production of spacecraft and components much more cost effectively. Ultimately, trade studies are needed to determine where the biggest payoffs occur. For this paper, qualitative evaluations are provided for some of the key subsystems.

3.1 Power

There are many technical challenges that must be overcome to realize the full potential that small satellites can provide. One of the most immediate, prominent, and limiting is that of power production. In a small spacecraft configuration, as proposed here, there is a very limited area available for solar cells onboard. Deployment of additional arrays with complicated mechanisms is possible, though limited, and it would substantially increase the cost of the overall power subsystem.

The limited availability of power restricts the capabilities of all subsystems and forces expensive design costs. Currently, solar cell technology is limited to expensive, multi-junction, multi-material cells that can achieve a maximum of 30% theoretical efficiency with an actual efficiency of 25%. A recent discovery at Berkeley may pave the way toward a revolution in low cost power production by developing a cell that could achieve a theoretical 50% efficiency. By adding more layers, these cells could go as high as 70%.

The development of highly efficient solar cells, small power management systems and highly efficient batteries (such as Li-Ion) are paramount for the future of small satellite platforms. If these new technologies can be proven, the capabilities and low cost production of microsatellites will be enhanced by an order of magnitude. With excess power available, thermal design and control becomes easy (i.e. low cost), sensor suite options are greatly widened, and communications pathways are eased considerably. Advanced power production capabilities are probably the single largest cost reduction avenue for microsatellites.

3.2 Propulsion

Until microspacecraft can employ propulsion capabilities, their functions will always be limited: (i) formation flying of any form will not be possible, (ii) 3-axis stable platforms will be hard to implement and be power hungry, and (iii) constellation fault recovery will be impossible. Numerous organizations have been developing micropropulsion technologies to address these needs. Many oft he approaches being considered are forms of electric propulsion and pose unique requirements on microspacecraft buses such as high instantaneous currents, high input voltages, or both. These devices, while operating in a perfect range of Isp and minimum impulse bits for fine 3-axis control and precision flying, have too low a thrust level to perform significant ΔV maneuvers and fast slewing of the spacecraft. To provide that function, devices with very high thrust to power ratios must be used.

Traditionally these devices have been forms of cold gas or small monopropellant thrusters with extremely low Isp (efficiency) and requiring a large, high-pressure tank to provide a reasonable lifetime. Extremely small hydrazine thrusters, less than 0.9 N do not currently exist. Efforts are underway at JPL, MIT, Surrey and elsewhere to develop micro-sized versions of monopropellant thrusters to eventually satisfy this requirement.

					Performance Characteristics							
Technologies	Isp	Minimum I-bit	Min Power	Max Power	Thrust	T/P	Efficiency	Total Impulse	Thruster Dry Mass	System Dry Mass	TRL Level
	s	N-s	W	W	mN	uN/W		N-s	kg	kg	
TFPPT	200-1200	5.00E-05	5	70	0.1 - 4.5	14	0.08	7,000	1.500	5	6
GFPPT	5000	1.00E-05	5	150	0.1-1	6	0.15	11,000	1.500	6.5	4.5
Micro-PPT	200	2.00E-06	1	20	.002 - .03	1-64		7500	0.025	2.5 - 8	4
VAT	908	1.00E-06	1	100	0.2	19.44	0.087	10,000	0.090	1.2	4
Cs FEEP	9000	1.00E-08	3	370	.01 - 2.8	15	0.6		0.450	2 - 3	4
ILMIS	10,000	1.00E-08	5	13	.001 - 0.1	7	0.6		0.450	2-2.5	6
VLM	50-100	1.00E-06	1	10	.05 - .5		0.3		0.002	3	3.5
Small Ion Thruster	1800-3500	N/A	100	1000	5-20		.3 - .65			2.5 - 5	6
Micro-Ion Thruster	2000-3000	N/A	10	100	.05-.5		<0.5		<1		2-3
Colloid Thruster	500-1450	1.00E-08	2	10	.001-.3	30	0.7				3
Micro-Colloid Thruster	500-1000	1.00E-08	0.5		0.05	100			0.002	5	1
Vacuum Arc Ion Thruster											1
Hydrazine mN Thruster	SS170/LDC110	5.00E-05	2	8	20-50				0.060	4	3.5
Minimum Impulse Thruster	Pulsed190/LDC140	2.00E-03	2	8	800-900				0.160	4.5	3.5
Cold Gas	70	1.00E-04	0.5	15	5-500	**		inf?	0.010	4	6
Micro-Cold Gas	65	2.00E-06	0.7	4	.3 - 17	**		inf?	0.010	3	2
Digital Micro-propulsion	200	5.00E-05	0.5	10	5-10				0.002-.5		3
H2O2 Micro-Thruster	150	0.1			10-20				0.100	4.5	3
FMMR	50-100	1.00E-08	0.5	5	0.1-5		0.35		0.002	3	3
Small Resistojet	190	N/A	100	600	15-500	460	0.43	17,000		6	5
Small Hall Thruster	600-1750	N/A	70	500	2-35		.06 - .4		0.250	8	3-4?
Micro Hall Thruster	900	N/A		126	2		0.06				2-3
Small Solids	200-270	10's			40,000+					.35 - 5	2
LAPPT	100	1.00E-07	0.1	10	.01-1	100	0.05	500	0.200	2-5	4
Micro-Hybrids	280-300	5.00E-05			10000+					7	1-2
Trydine Thrusters	265	5.00E-07	5	15	10-10000					2.5-6	3
Warm Gas Thruster	180										3-4

Table 3. Partial survey of micro-propulsion technologies, generated as part of a NASA-wide Integrated In-Space Transportation Propulsion study.

Many of these devices are ideally suited for microspacecraft applications and can provide a large array of functionality depending upon the desired application. All of these micropropulsion efforts still require substantial investment to become reality. Once finally developed however, they can largely be fabricated and delivered for relatively low cost. For example, with devices using MEMS technology, once the masks have been developed, processes certified, and reliability determined, it is a relatively simple matter to make large quantities of these. Devices that use a more conventional (though miniaturized) approach, especially in valve technologies, will always remain somewhat costly. Substantial reductions in system mass are readily achievable.

3.3 Avionics

The tools for obtaining cost reductions in the satellite avionics are standardization, integration, and miniaturization. Furthermore, to capture the cost advantages of mass production, the subsystems and buses should all be nearly identical, with only slight differences needed so as to accommodate a variety of science instruments and/or mission objectives.

Standards for satellite avionics, interfaces between subsystem and science instrument hardware, software architectures, and means of routing data all serve to keep interface cost issues in check. Interface standards being implemented for space use include IEEE 1394, SpaceWire, Ethernet, PC104 bus, etc. Most of these standards are available in the commercial arena with minimum modification needed for use in space. Once standards for a satellite bus are defined it will be left to the subsystem and instrument designers to make their equipment compatible with the standards, and very little will need to be invested by NASA into developing those same standards.

High levels of integration (Figure 2) enable reduction in cost by providing significant reductions in design complexity, parts count, software code base, fabrication and assembly effort, mass, and volume of science instruments, and spacecraft subsystems. Ifs ubsystems such as the communication subsystem, star trackers, horizon sensors, reaction wheels, electrical power distribution unit, and others share the resources of one avionics unit a large amount of hardware design effort disappears and the parts count is greatly reduced. The overall satellite system software becomes simpler. A standard operating system for a satellite, chosen from COTS or open standards, could become the framework for later addition of new capabilities that might be required as mission needs expand in the future.

The high level of functionality made available by Application Specific Integrated Circuits (ASICs), Field Programmable Gate Arrays (FPGAs), and modern, low power, high-speed microprocessors enable those parts to eliminate many others by assuming their function. More cost reduction is possible with the miniaturization and modularity enabled by advanced packaging technologies [5] that can allow extreme reductions in subsystem mass and volume (Figure 3). Mass and volume reductions of 10 to 1a re possible using alternate chip packaging technologies such as flip chip and High Density Interconnect (HDI) modules. This leads to higher satellite mass fraction available to science instruments and higher numbers of satellites atop each launch vehicle. Finally, tools to improve the efficiency of human involvement will also significantly reduce costs.

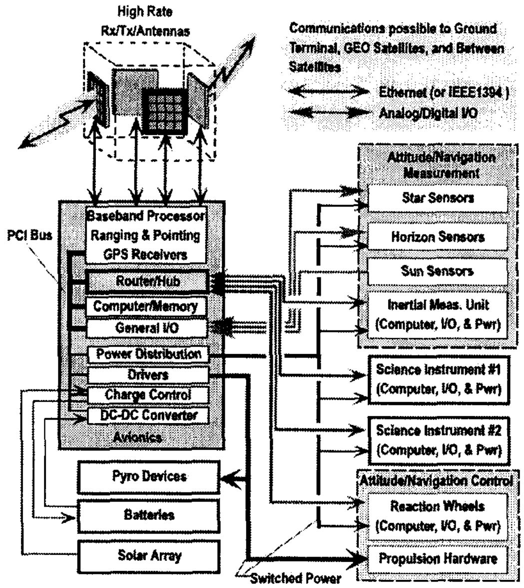

Figure 2: High degrees of avionics integration will be necessary for reducing the cost of developing and producing large numbers of small satellites.

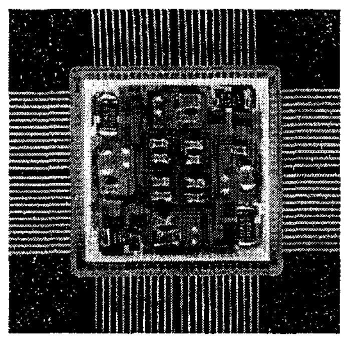

Figure 3 Four Smart Power Switches capable of crowbar circuit protection and power monitoring are contained in this very compact HDI module that operated successfully on NMP - ST1.

As another example of integration, technology providers have begun incorporating the GPS functionality into newer, lower power transceivers. An architecture developed within NASA's New Millennium Program (NMP) is taking the concept one step further and is also incorporating a large processing and storage capacity, interfaces for star trackers and built in, single chip accelerometers in a single unit. The result is a single, highly integrated, communications and GN&C device that also has the excess processing storage and capability to perform onboard autonomy functions. It is intended for use in a future networked application with uplink, downlink and crosslink capabilities and is being proposed for a future NMP Intelligent Distributed Spacecraft testbed.

3.4 Communications

The integrated *Sensor Web* approach, shown in Figure 4, requires intelligent crosslink communications and will generate very high data content transfers in real time from space to ground. Communication requirements scale more to the size of the *Sensor Web* and less with the size of an individual spacecraft. It is clear that small spacecraft with limited power will not have the luxury of large, robust communications systems. Development of compact, low power, highly efficient communications systems that can transfer data both to and from the ground and between spacecraft is a high priority.

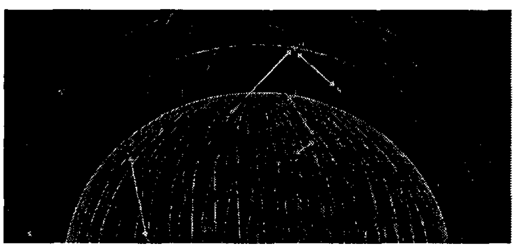

Figure 4: Agile communications will be needed between satellites in different orbits to implement the *Sensor Web*.

Inter-spacecraft communication packages that are on-board multiple satellite missions enable coordination and synchronization of measurements between each satellite's instruments as well as a means to obtain relative inter-spacecraft distances and angles. High data rate inter-spacecraft links further enable large amounts of data to be passed between the satellites for in-space distributed processing and for relaying data to neighboring satellites for transmission to ground.

Highly miniaturized modules are being created today by NASA using high degrees of chip integration and dense packaging for transceiver packages that operate from L-band to Ka-band. Very small multi-beam antenna packages are also being developed for use with the transceivers. These communications packages, while small, are capable of data rate operation to 10's and 100's of megabytes per second. Future developments in small agile optical systems for inter-spacecraft communications will be capable of sending data at gigabytes per second. These developments provide new means of reducing overall mission costs for all of the Earth science missions by enabling satellites to interact autonomously, exchanging data rates for in-space aggregation, and filtering so that reduced data may be sent to ground users without continuous human interaction.

3.5 Guidance, Navigation And Control (GN&C)

Guidance, Navigation and Control capabilities will dictate the applications that can be performed. Both visible imaging applications and RF applications require pointing capabilities. Star trackers are needed that produce rapid update rates and large star catalogs with limited processing power. Effort is underway in many organizations to develop micro-sensor technologies for highly miniaturized sun sensors, horizon sensors, inertial sensors and star trackers. Many are taking advantage of newly available Active Pixel Sensor (APS) technology for low power applications.

On-board autonomy is necessary to minimize continuous human ground intervention and can provide substantial operations cost reductions. If the spacecraft has sufficient processing and storage capacity, autonomy functions can be employed to control the spacecraft attitude and maintain its orbit, assist in mission planning, science measurements, and data handling operations.

3.6 Materials and structures

The need to fit multiple spacecraft on a single launch vehicle requires dramatic reduction in the mass and volume of each of the individual spacecraft. However, frequently the physics of the phenomena being measured requires large structures. Large, lightweight deployables with high packing densities are therefore desirable.

Low mass and low cost production are challenges for spacecraft structures that are much more compact. Combining functions is an avenue to reduce overall mass and facilitate integration. Multi-functional structures will likely become normal in microspacecraft construction.

4 SUMMARY

An analysis of large Low Earth Orbiting constellations has been done suggesting that significant changes will be required to make such constellations feasible and affordable. These changes suggest technology investment policies addressing subsystem production cost, changes in development to allow more thorough testing prior to production commitment, and changes in production methods to minimize unit testing. If such changes were accepted, the result would be a substantial increase in scientific observational capabilities.

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Four Smart Power Switches capable of crowbar circuit protection and power monitoring are contained in this very compact HDI module that operated successfully on ST1.