INTERNATIONAL STUDY ON COST-EFFECTIVE EARTH OBSERVATION MISSIONS OUTCOMES AND VISIONS

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Commission I, WG I/6

KEY WORDS: Earth observation, small satellites, systems, sensors, platforms

ABSTRACT:

Cost-effective Earth observation missions – how can it be achieved, what are the cost drivers and what the application areas, what are the possible obstacles and how to overcome them? The study (Sandau, 2006) intends to provide a single reference of all aspects connected with cost-effective missions from background material like previous studies and organisational support, that is institutions having related programs or supporting up-to-date information exchange through conferences, to Earth observation application areas which gain from the information and approaches presented in this study. This paper concentrates on some of the outcomes of the study. User communities which start to conduct or participate in Earth observation missions using small, economical satellites, and associated launches, ground stations, data distributions structures, and space system management approaches will gain from this information the most.

1. INTRODUCTION

Cost-effective missions can be achieved by using different approaches and methods. One of the possible approaches is taking full advantage of the ongoing technology developments leading to further miniaturization of engineering components, development of micro-technologies for sensors and instruments which allow to design dedicated, well-focused Earth observation missions

Since the advent of modern technologies, small satellites using off-the-shelf technologies or missions focused on specific physical phenomena have also been perceived to offer an opportunity for countries with a modest research budget and little or no experience in space technology, to enter the field of space-borne Earth observation and its applications. This is very much in line with the charter of the IAA Study Group on Small Satellite Missions for Earth Observation. One of its intentions is to bring within the reach of every country the opportunity to operate small satellite Earth observation missions and utilize the data effectively at low costs, as well as to develop and build application-driven missions. In this context the study group supports all activities to develop and promote concepts and processes by various user communities to conduct or participate in Earth observation missions using small, economical satellites, and associated launches, ground stations, data distributions structures, and space system management approaches.

The study provides a definition of cost-effective Earth observation missions, information about background material and organizational support, shows the cost drivers and how to achieve cost-effective missions, and provides a chapter dedicated to training and education. The focus is on the status quo and prospects of applications in the field of Earth observation. The conclusions and recommendations of the study are the focus of this paper. They are summarized in terms of

- more general facts that drive the small satellite mission activities,
- outcomes from the background material used in the study which show that good work have been done before and the lessons learned process started soon after beginning of the small satellite activities,
- additional outcomes of the study which go beyond the information of the background material, and
- some visions concerning the future of cost-effective Earth observation missions.

2. CONCLUSIONS AND RECOMMENDATIONS

The study presented the state of the art of small satellite missions and examined the factors that enable one to produce a cost-effective small satellite mission for Earth observation. We find that, while there are several examples of such missions flying today, the lessons that must be learned in order to produce cost-effective small sat missions have neither been universally accepted nor understood by all in the space community. In the study we intended to point out how a potential user can produce a cost effective mission. One of the key enablers of designing a cost-effective mission is having the key expertise available. As the number of successfully space-faring nations grows, the pool of expertise available to meet the challenges of small mission grows.

2.1 General Facts

Cost-effective missions can be achieved by using different approaches and methods.

Since the advent of modern technologies, small satellites have also been perceived to offer an opportunity for countries with a modest research budget and little or no experience in space technology, to enter the field of space-borne Earth observation and its applications.

One of the possible approaches is taking full advantage of the ongoing technology developments leading to further miniaturization of engineering components, development of micro-technologies for sensors and instruments which allow to design dedicated, well-focused Earth observation missions. At the extreme end of the miniaturization, the integration of microelectromechanical systems (MEMS) with microelectronics for data processing, signal conditioning, power conditioning, and communications leads to the concept of application specific integrated micro-instruments (ASIM). These micro- and nano-technologies have led to the concepts of nano- and pico-satellites, constructed by stacking wafer-scale ASIMs together with solar cells and antennas on the exterior surface, enabling the concept of space sensor webs.

More generally small satellite missions are supported by four contemporary trends:

- Advances in electronic miniaturization and associated performance capability;
- The recent appearance on the market of new small launchers (e.g. through the use of modified military missiles to launch small satellites);
- The possibility of ‘independence’ in space (small satellites can provide an affordable way for many countries to achieve Earth Observation and/or defense capability, without relying on inputs from the major space-faring nations);
- Ongoing reduction in mission complexity as well as in those costs associated with management; with meeting safety regulations etc.

These trends are complemented by

- the development of small ground station networks connected with rapid and cost-effective data distribution methods
- and cost-effective management and quality assurance procedures

The advantages of small satellite missions are:

- more frequent mission opportunities and therefore faster return of science and for application data
- larger variety of missions and therefore also greater diversification of potential users
- more rapid expansion of the technical and/or scientific knowledge base
- greater involvement of local and small industry.

After some years of global experience in developing low cost or cost-effective Earth observation missions, one may break down the missions into categories like:

- Commercial – Requiring a profit to be made from satellite data or services
- Scientific/Military – Requiring new scientific/military data to be obtained
- New technology – Developing or demonstrating a new level of technology
- Competency demonstration – Developing and demonstrating a space systems competency
- Space technology transfer/training – Space conversion of already competent engineering teams
- Engineering competency growth – Developing engineering competence using space as a motivation
- Education - Personal growth of students via course projects or team project participation

In the study we consider large satellite missions and small satellite missions being complementary rather than competitive. The large satellite missions are sometimes even a precondition for cost-effective approaches.

2.2 Conclusions and Recommendations Drawn from the Background Material

The background material reviewed in Chapter 3 of the study summarizes the key conclusions and recommendations that are also applicable to cost-effective Earth observation missions.

IAA Position Paper on Inexpensive Scientific Satellites: The IAA Position Paper on Inexpensive Scientific Satellites provided some particularly useful background material on management. In particular, the program must be started with a clearly identified specification and the program duration must be minimized. To achieve control over the program duration one must reduce the number of models of the subsystems, avoid technical risk in mission-critical areas, and minimize the total number of people on the team. To hold the team size to a minimum one must minimize the number of external interfaces and minimize the administrative burden. That Position Paper pointed out that innovative engineering solutions should be sought out but care must be taken to only count on or implement technologies with an acceptable risk. Risk can be reduced by reducing complexity – and interfaces add complexity. Therefore one should adopt simple well-defined subsystem interfaces, encourage a modular design and use “off-the-shelf” solutions where practical. These should be tested at the box- and system-level. The cost to launch and the reliability of the launcher has long been recognized as a key to whether the mission will be cost-effective. Part of that process is the identification of reliable flight opportunities, especially shared rides (with the proviso that the interface as a secondary payload must not interfere with the primary payload and must use a well-proven interface to that primary payload). That report also identified the need for a robust infrastructure that could provide local expertise to solve problems and pointed out that small companies and universities can provide assistance at times.

IAA Position Paper: The Case for Small Satellites: The Position Paper concludes that there is a rationale for considering small satellite missions as a means of satisfying the needs of developed as well as developing countries. Governments and research institutions of all countries are urged to study, undertake and support small satellite programs for research, educational and applications purposes in accordance with their current technical and financial capabilities. The industrialized countries should take the lead in gathering and disseminating information, the developing nations should undertake to accede to, and to increase, such information. Particular encouragement should be given by the industrialized countries to projects that provide education motivation and launch opportunities should be made available by the operators of launch systems with reasonable conditions; raw data from Earth observation should be made available on a non-discriminatory basis for research and civilian applications to all countries.

EC Study COCONUDS: COCONUDS noted that while much current attention is on high resolution satellite systems, there is a considerable body of users who would welcome a more modest – but more frequent – imaging capability (that is 30-50m; 4 band). Invariably these users are quasi-operational, locally focused and resource-poor (either in funding or equipment). One key finding has been in the dissemination of appropriate data. Broadly speaking COCONUDS confirms the user-attractiveness of low cost direct data reception of a local region. This concept, championed by NOAA meteorological satellites for many generations, has a limited audience among the more classical Earth observation satellites because of their large data sets. COCONUDS, however, concludes that many users simply require local data and would be satisfied with compressed imagery. As a result low cost reception is entirely feasible.

Conclusions from UN Activities: The Committee on the Peaceful Uses of Outer Space (COPUOS) set up by the General Assembly in 1959 currently forms the focal point of United Nations activities in the field of outer space. This Committee (with its two Subcommittees) has, since its inception, promoted international co-operation in developing the peaceful exploitation of outer space, in this regard functioning successfully against the changing political background characterising the transition from the pre to the post cold-war era. At UNISPACE III, it was recommended that the joint development, construction and operation of a variety of small satellites offering opportunities to develop indigenous space industry, should be undertaken as a suitable project for enabling space research, technology demonstrations and related applications in communications and Earth Observations.

2.3 Additional Recommendations from this Study

The situation in the field of small satellite missions for Earth observation has matured in the last ten years. This may be, for instance, observed from the topics and the quality of contributions to the series of, to date, five biannual IAA Symposia on Small Satellites for Earth Observation in Berlin, Germany. The 5th Symposium took place in April, 2005.

We propose a simplified nomenclature for subsets of small satellites:

mini satellites	< 1000 kg
micro satellites	<100 kg
nano satellites	<10 kg
pico satellites	<1 kg.

At UNISPACE III, the costs of developing and manufacturing a typical mini-satellite was indicated to be US$ 5-20 million, while the cost of a micro-satellite was correspondingly US$ 2-5 million. The cost of a nano-satellite could be below US$ 1 million (prices as of 1999). Whereas the development and production time for large satellites is observed to be 15+ years, the corresponding time for minis should be 3–5 years, for micros 1.5 years, for nanos about 1 year, and for picos less than 1 year. Of course, cost and duration figures are to be considered ball park figures. They are bases on the usage of state-of-the-art technology by professional teams. They may deviate considerably if key technology is to be developed and/or the implementation teams are at the beginning of the learning curve.

There is no single, accepted, broad method for reducing mission cost. Instead, the builders of low-cost missions are aggressive competitors, just like their more expensive colleagues who create large programs for ESA, NASA, or the US Department of Defence. Each low-cost program has found and have to find a set of solutions to fill its particular need and programmatic style. Table 1 gives a summary of cost reduction methods which are selectively used by the builders of low-cost missions.

To reduce cost, alternatives to dedicated launches of satellites should also be taken into consideration (see Table 2). Although each of the alternatives has limitations, dramatic reductions in cost are possible for missions such as equipment testing that do not necessarily need a long period on orbit.

Cost-effectiveness also depends on the quality and engagement of the specialists participating in planning and implementing an Earth observation mission. Countries taking their first steps in space need to learn relevant techniques from more experienced space users, thereby acquiring a cadre of appropriately trained personnel before going on to establish a national agency and to maintain a presence in space. Technology transfer through small satellite related training programs has been successfully implemented between Surrey University in the U.K. and customers in Chile, Malaysia, Pakistan, Portugal, the Republic of Korea, South Africa and Thailand.

Small satellites programs provide a natural means for the education and training of scientists and engineers in space related skills since they allow direct, hands-on, experience at all stages (technical and managerial) of a particular mission (including design, production, test, launch and orbital operations).

3. THE FUTURE OF COST-EFFECTIVE EARTH OBSERVATION MISSIONS

In the study we have considered the past experience of the global small satellite community and reviewed and incorporated the work of other studies and bodies that deal with disseminating information about small satellite missions and in promoting the appropriate use of such technology and we have surveyed the state of our current knowledge. The study brings to light new capabilities as well as challenges that must be addressed in order to produce successful, cost-effective small satellite missions.

3.1 New capabilities

There are three new developments that may prove to greatly enhance the capabilities of small satellite missions. These are:

1) the convergence of data acquisition and data visualization technologies
2) the ready availability of new small launchers and the rise of “space tourism”
3) the development of smaller, lighter, lower power satellites that can act as a constellation or independently

While there are many other developing technologies that hold promise, these factors may well transform the small satellite enterprise in the next ten years. A mission can be cost-effective and achieve all its measurement requirements without having to actually make all the measurements itself. To put this in concrete terms, NASA has a series of research satellites (Aqua, CloudSat, CALIPSO, PARASOL, Aura, and OCO) called the “A Train” that fly in formation. These satellites make individual measurements that support cross platform science. Many of the instruments that image the surface also use ancillary information, such as digital elevation maps, to add context to their products. One could readily envision a small satellite mission that was intended to provide some niche product, such as crop yield forecasting, in a particular region. Such a small satellite could produce a very specific measurement, say normalized difference vegetative index (NDVI), which would be corrected for aerosols and clouds using data from the A Train. With such a tightly defined measurement requirement, the spacecraft resource requirements could be quite small and the data system could be designed for “store and forward” operations with the data pushed to the analysis site over the internet. Another approach, as evidenced in SSTL’s DMC, is to

Table 1: Cost Reduction Methods

Method	Mechanism	Comments
Programmatic		
Schedule Compression	Reduces overhead of standing army; forcing program to move rapidly does drive down cost	Often results in a poor design due to lack of up-front mission engineering; must reduce work required to be consistent with schedule
Reduce Cost of Failure	Allows both ambitious goals and calculated risk in order to make major progress	Fear of failure feeds cost-growth spiral; major breakthroughs require accepting the possibility of failure—particularly in test
Continuous, Stable Funding	Maintains program continuity; maintains team together	Program delay will be funding break + 2–4 months
Minimize Documentation	Reduces programmatic overhead for creating, reviewing, and maintaining	Critical to document reasons for key decisions and as-built design
Personnel		
Improved Interpersonal Communications	Dramatically reduces errors and omissions; conveys understanding as well as data	Large programs use formal, structured communications through specified channels
Small Team	Clear, nearly instantaneous communications; high morale; strong sense of personal responsibility	Problem if a key person drops out — but in practice it rarely happens.
Co-located Team	Improves communications	Best communications are face-to-face, but AMSAT and others don't seem to need it
Empowered Project Team	Rapid decision making; strong sense of personal responsibility; can make "sensible" decisions	Eliminates a major function of the management structure
Systems Eng.		
Trading on Requirements	Eliminates non-critical requirements; permits use of low-cost technology	Makes traditional competition difficult
Concurrent Engineering	Allows schedule compression; reduces mistakes; increases design feedback	High non-recurring cost relative to lowest cost programs
Design-to-Cost	Adjusts requirements and approach until cost goal has been achieved;	Spacecraft have rarely used it
Large Margins	Reduces testing; better flexibility; reduces cost of eng, manufac., and ops	Margins traditionally kept small for best performance — drives up development cost
Technology		
Use COTS Software	Immediate availability; dramatically lower cost; tested through use	May need modification and thorough testing; typically not optimal
Use COTS H/W	Same as software	Same as software
Use Existing Spares	Reduced cost; rapid availability; meant for space	Only works so long as spares exist — not applicable for operational programs
Use of Non-Space Equipment	Takes advantage of existing designs and potential for mass production	Typically not optimal; must be space qualified
Autonomy	Reduces operations costs	Can increase non-recurring cost
Standardized Components and Interfaces	Reduces cost and risk by reusing hardware; standardization is a major req. for other types of manufacturing	Has been remarkably unsuccessful in space; sub-optimal in terms of weight and power
Extensive Use of Microprocessors	Minimizes weight; provides high capability in a small package; allows on-orbit reprogramming	Problem of single-event upsets; high cost of flight software; very difficult to manage software development
Common S/W for Test and Ops	Reduces both cost and schedule; avoids reinventing the wheel	May be less efficient, user-friendly than ops group would prefer

decrease the ground repeat delay by forming a cooperative that shares data which are produced among the elements of the constellation. Membership is acquired by contracting for the production of an element of the constellation. Each member of the cooperative then gets the benefit of a much shorter revisit time. In short, the economies of scale begin to operate as more members join the cooperative.

Getting into space is still a challenge. During the last ten years there have been more small launchers available and at prices that are quite reasonable compared to the cost of a small satellite. One of the newest and, potentially, most vigorous areas of development of small launchers has come about under the impetus of "space tourism". On October 4th, 2004, Burt Rutan and Paul Allen, built and flew the world's first private spacecraft to the edge of space to win the $10 million Ansari X PRIZE. Perhaps the early history of the development of commercial aviation presages the next twenty years of space access. At the turn of the century, air travel was relatively risky and quite expensive. As the commercial market for air transport grew costs dropped as did risk. Now, air transport is so cost-effective that it is used to ship bulky agricultural goods, such as apples, half way around the world at prices that are competitive with local transport and production. To make space tourism viable the cost of putting a person in space will have to be reduced to of the order of $1M. At those kinds of costs for mass to orbit, small satellite missions will no longer be strongly constrained by launch costs. If we step back from the purely speculative, commercial launch services are now available on most launch systems, many of which are new vehicles designed or modified specifically for international commercial market. The most dramatic shift has been the entry of the Russian and

Ukrainian launch systems operated as joint ventures with US or European companies. New launch systems around the world are even beginning to use major components built in other countries, further blurring national divisions. This international trend is important because some nations still insist on the use of a "national" launch capability. The increasing availability of these low-cost launchers and the development of dispensers has opened up possibilities for single launches of a constellation as well as individual payloads. The launch of the NASA / DLR GRACE satellites used Eurockot Launch Services, the joint venture owned by Astrium and the Russian company Khrunichev, to place two satellites in a closely controlled formation via a dispenser. This launch was the first commercial use of the Russian SS-19 ICBM which provides the two booster stages for the ROCKOT launch vehicle with a heritage of 150 flights. At the other end of the cost and mass spectrum, Ariane 5 has been used to launch 6 auxiliary payloads along with the primary Helios satellite. This included Nanosat, Spain's first small satellite, built by the country's INTA national space agency (Instituto Nacional de Técnia Aeroespacial), with a mass of less than 20 kg. In another example, the Cluster mission formed a constellation of four satellites, flying in formation, using two separate launches.

Table 2: Alternatives to Dedicated Satellites

Option	Characteristics	Mass Limits	Principal Constraints	Approximate Cost	Sources
Balloon Flights	Hours to days at ≈ 30 km altitude	Up to 70 kg for low- cost flights	Not in space, not 0-g, weather concerns	\$5K to \$15K	U. of Wyoming, USAFA, NSBF
Drop Towers	1 to 10 sec of 0-g with immediate payload recovery	Up to 1,000 kg	Brief "flight," 5 to 50 g landing acceleration, entire experiment package dropped	≈ \$10K per experiment	ZARM, JAMIC, NASA LeRC and MSFC, Vanderbilt U.
Drop Tubes	1 to 5 sec of 0-g with immediate sample retrieval	<0.01 kg	Brief "flight," 20 to 50 g landing acceleration, instrumentation not dropped with sample	≈ \$0.02K per experiment	ZARM, JAMIC, NASA LeRC and MSFC, Vanderbilt U.
Aircraft Parabolic Flights	Fair 0-g environment, repeated 0-g cycles	Effectively unlimited	Low gravity is only 10^{-2} g	\$6.5K to \$9K per hour	NASA LeRC and JSC, Novespace
Sounding Rockets	Good 0-g environment, altitude to 1,200 km, duration of 4 to 12 minutes	Up to 600 kg	Much less than orbital velocities	\$1M to \$2M	NASA GSFC, NRL, ESA/ Sweden, OSC, EER, Bristol Aerosp.
GAS Containers	Days to weeks of 0-g on board the Shuttle	Up to 90 kg	Very limited external interfaces	\$27K for largest container	NASA GSFC
Secondary Payloads	Capacity that is available in ex- cess of primary's requirements	Up to ≈ 1,000 kg	Subject to primary's mission profile	<\$10M	Ariane, OSC, MDA, Russia
Shared Launches	Flights with other payloads having similar orbital requirements	Up to ≈ 5,000 kg	Integration challenges	Up to ≈ \$60M	Ariane, OSC, Russia

Once the spacecraft are in orbit, the remaining costs are largely associated with operating the spacecraft (including monitoring its health and safety) and collecting the data. As the number of spacecraft increases in a constellation there would be, without a change in the operations paradigm, a concomitant increase in the costs to operate the constellation. In order to have a cost effective constellation of micro- or nano-satellites the operations costs have to be low on a per satellite basis especially since some of these constellations are envisioned as consisting of tens or even hundreds of micro- or nano-satellites. Powerful, cheap, microprocessors provide the means for increased autonomy at the individual satellite level and across the constellation. At issue, though, is developing the software to perform these operations and subsequently testing the software so that its operation can be verified before flight. Qualifying these systems for spaceflight will be a challenge that must be addressed.

3.2 Challenges

The biggest long-term challenge for the small satellite community is that of developing a robust commercial market that supports the infrastructure that has been developed to produce small satellites. Small satellites have appealed to some nations as an instrument of national pride and as a means to focus and enhance the industrial base as well as providing a means of attracting students to a high tech industry. This is, of course, a finite market. After the first few satellites there has to be reason other than becoming a space-faring nation to invest in, develop, and fly the next space mission and continue the development and training of students. To develop a robust market, small satellite manufacturers must remain relevant and cost-effective. It appears that in many markets space technology has entered the era of diminishing returns – for example, if you can achieve imagery from space with a spatial resolution of about one meter, do you really gain anything marketable by imaging at one centimeter? This plateau effect means that more vendors can aspire to provide the same product. How many suppliers can the market support? It may be that the market can support more suppliers of imagery if revisit time is a key driver. The user then must draw products from several sources and understand enough about each independent data source so that the desired product can be produced. Raw data products, though, are not likely to capture many more users: tailored products that address specific needs can be supplied by small satellites. The vertical integration of the industry, to provide instruments, data and integrated data products, is likely to spur significant growth.

Until that robust commercial market has been developed, government support will continue to be the financial mainstay of the small satellite community. This situation will remain in force until some economies of scale can be achieved. At this time, SSTL and RapidEye are two notable examples of commercial ventures that have achieved some stability. They did this by identifying and cultivating a niche market that they are able to address. Much of the small satellite community is still tied to education and research activities – activities that rely on government support. Inter-government cooperative agreements provide the means of broadening the opportunities available to the community. Bureaucracies are averse to risk, however, and small organizations and cooperative agreements are often viewed as risky.

Managing risk is a key problem, then. Since no complex system can be designed and tested against all failure modes, experience is often the best and only guide to making trades. Large organizations tend to have more restrictions on what can fly and may have stringent risk assessment processes. In NASA terms the confidence in a subsystem or system is called the Technology Readiness Level or TRL of the item. Higher TRLs mean the element has significant flight experience. The highest TRL is assigned to elements with direct flight heritage. Small satellites can be quite effective as platforms to raise the TRL of an element to be used in a latter design. The challenge faced by the small satellite community is to gain a broader acceptance of the notion that TRLs can be raised as an integral part of a mission rather than by implementing a dedicated mission such as the JPL-led Deep Space missions.

Making small satellites more cost-effective calls for new technologies but who then pays to certify these new technologies for spaceflight? There is certainly a higher risk associated with unproven technology. For example, the ready availability of large format detectors at relatively low cost shifts the design choices from being driven by the detector resolution to being driven by other factors such as the interplay between spacecraft stability and off-nadir pointing capability or downlink bandwidth and onboard storage, etc. Can a system be designed that can use these new detectors? How do they behave in space? A small mission is arguably the best way to perform a flight verification because even a failure to operate on orbit, or even to achieve orbit, can still be a successful demonstration from an educational or developmental viewpoint. Cost-sharing between a larger richer, risk-averse partner and a smaller, poorer more risk-tolerant partner may prove beneficial to both parties.

3.3 Success and Failure of Cost-effective Missions

The study examined both what we know about small satellites and their uses for Earth observation. What makes a mission cost effective? The simplest answer is that the desired end is achieved for a price that is acceptable to all parties. While some mission objectives may only be achieved by the large, complex instruments and spacecraft, there are many uses for small missions. For many potential customers the best price point is established by sharing risk. If the risk is borne broadly, even a failure to achieve launch can still yield a cost-effective mission because the partners view the educational and infrastructure return as sufficiently high and the other shared aspects of the partnership yield some of the required information. To remain cost-effective in the commercial arena, small missions must be able to incorporate new technologies that reduce costs and improve performance. Small satellite missions face growing competition in regional markets from GPS-based solutions, UAVs, balloons, and sensor webs, for example. The chief advantage of satellites is their global access. Exploiting that, and successfully marketing that advantage will hold the long-term key to keeping small satellites cost-effective.

Assessing whether a mission is successful or not involves many different measures. Assuring that a small-satellite mission is considered successful means that these differing measures must be addressed and considered in the design of the mission. Some of these measures of success are, in fact, much more likely to be fulfilled by a small-satellite mission than a large one. For example, students are much more likely to be involved in a small satellite mission. The experience gained in the design, construction, test, flight, operation, and data analysis phase of the mission will guarantee “success” in terms of the educational experience of the students. Small satellites can demonstrate new technologies or measurement techniques. If they achieve these goals they are “successful” even if the scope of the goal is small (for example, a small satellite mission need not inventory the global carbon budget but it could provide a measure of the amount of carbon produced in boreal forest fires). In terms of impact at the national level, a small satellite that is produced by a country may well evoke more pride of ownership than an instrument or participation in a large-scale investigation. In this study we have laid out the reasons how to design and implement a small cost-effective Earth-observation mission. In the end, success is subjective: the true measure is whether the program continues and flourishes.

REFERENCES

1. Sandau, R. (ed.), 2006. International study on „Cost-Effective Earth Observation Missions“. Taylor & Francis, London/Leiden/New York/Philadelphia/ Singapore

2. Sandau, R. (ed.), 2006. International study on „Cost-Effective Earth Observation Missions“. http://iaaweb.org/iaa/Other%20Publications/earthobservation.pdf