IAA POSITION PAPERS

THE CASE FOR SMALL SATELLITES

Version 3

Prepared by the

Subcommittee on Small Satellites

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1. INTRODUCTION

1.1 Purpose

The purpose of this document is to provide a rationale for considering small satellite missions as a means of satisfying the needs of developed as well as developing countries.

For those who have not yet had experience working in space activities, it is also intended to provide a guide as to how and where to begin to get the technical support needed, and to indicate the initial thought processes necessary to put together a space mission. Since each entity will have its own political structure, there is no attempt made to provide a path to available funding within any particular country. There are, of course, various potential international sources of funding, for example, the World Bank and the United Nations.

Points are provided for orbit selection and launch possibilities. There is a brief description of the components required to build a spacecraft, key management techniques, and decisions that must be made. Suggestions for possible missions are included. Finally, an address is provided where you can write to get help and advice.

1.2 Scope

Space activities began from a particular desire to expand our knowledge base. In their early days, space operations were a technical challenge which led to the establishment of the technologies needed for the execution of space activities, for example, computers, advanced materials, and miniaturisation. There was also the perception that space activities were beyond the purview of all but the most sophisticated countries and organisations.

After a modest beginning with small, simple, lightweight satellites, space systems have evolved into large, complex and expensive space platforms for science and applications, which often require up to 10 to 15 years of development prior to launch. While such large platforms exist and will continue to exist , there has recently been a growing interest in returning to the use of small satellites which can be launched within a few years after program initiation. As a consequence of the evolution of the state of the art space-related technologies, this class of spacecraft can make significant satellite capabilities accessible to a wide number of users, from high school and university students to engineers and scientists in every country in the world.

The International Academy of Astronautics (IAA) called attention to the potential for "Small Inexpensive Scientific Satellite Missions" through a study by an international working group (at Bordeaux, France in May 1989). The conclusions of that study have been reinforced by NASA's Small Explorer and proposed University Explorer Programs, as well as ESA's 1990 "Call for Ideas on Small Missions," which was recommended by the European Science Program Review Team, chaired by Professor Pinkau.

Another consequence of that study was the creation of the IAA Subcommittee on Small Satellite Programmes as part of the Academy's Committee on International Space Plans and Policies. After several preliminary meetings, this Subcommittee convened a Workshop in June 1991 near Toulouse, France, to identify the concepts and processes needed by any international user community to initiate, manage, acquire and launch its own small economical satellite(s).

Such small satellites could serve a wide range of purposes, for example, learning high technology and how to manage such programs, as well as fulfilling the basic purpose of increasing the world's scientific knowledge or providing a country with a communications system or enhancing the education of its people.

While the Bordeaux study had concentrated on scientific missions worldwide, the Toulouse Workshop expanded that concept to include applications. It did not, however, consider microgravity missions or sample return mission, since it was felt that the added complication of retrieval was not compatible with "inexpensive". Although the definition of "small satellites" was deemed to include those weighing up to 500 kg and with a total mission cost up to the equivalent of 50 million U.S. dollars, there are many much smaller, less expensive missions that are appropriate for a space mission.

2. RATIONALE

2.1 Applications of Spaceflight

Space techniques can provide direct and indirect economic benefits that may be characterised as follows:

- direct benefits:
  - collections of valuable scientific data,
  - provision of functional services,
  - current applications concern mainly the collection and transmission of information (communication services) and Earth observations.
- indirect benefits:
  - acquisition of technological know-how,
  - economic stimulation,
  - "spinoffs", ie. applications of space-derived technology to other fields. (There are also "spinoffs" from other fields used in space techniques; the latter have become large in recent years.)

In the various disciplines of science, space technology has contributed substantially and will do so also in future in various ways:

- the environment of space has been studied in-situ, near the Earth, in the interplanetary regions, as well as in the interactions between the Sun and Earth;

- all other planets in the solar system (except Pluto) have been visited by space probes; this work has led to the birth of comparative planetology, which promises to improve the understanding of the Earth as well, including the predictive power of our planet's models;

- access to the orbital environment has enabled an enormous extension of the astrophysical observations in the electromagnetic spectrum: infrared, ultraviolet, X- and gamma-ray observations of the universe have increased by many times our ability to detect, correlate, and interpret astronomical events;

- even in the visible and the radio bands, space technology allows substantial improvements of both sensitivity and resolution, in particular through the use of interferometric techniques;

- the study of corpuscular radiation, of solar, planetary, interplanetary or cosmic origin, has similarly been expanded;

- the Sun, both for its direct influence on terrestrial life and as our "sample star" has been the object of an increasing number of observations;

- solid Earth studies have measured the shape of our planet, its gravitational field, and the behaviour of its crust;

- in space, zero gravity effects have been studied on various biological samples as well as on chemical reactions and on specific physical systems.

Space technology has thus become an important tool to observe, study, and monitor our planet since it provides unparalleled access to large spatial and spectral ranges. Table 1 lists some areas in which the contribution of space-based Earth observations has been demonstrated.

Table 1: Earth Observation Satellites

CLASS	APPLICATION	SPACECRAFT
Meteorology	Global Observation	TIROS, METEOSAT
	Medium Term predictions	TIROS, METEOSAT
	Catastrophe warning (hurricane, etc.)	GOES, GMS, METEOSAT
Land surface sensing	Water resources, incl. runoff predictions & flood warnings	LANDSAT,SPOT
	Forestry and rangeland studies	LANDSAT,SPOT
	Observation of air pollution phenomena	LANDSAT, NIMBUS
	Crop predictions	LANDSAT, SPOT
	Mineral resources' studies	LANDSAT, SPOT
	Impact of large-scale phenomena (volcanic eruptions, forest fires, etc)	LANDSAT, SPOT
	Mapping & cartography	LANDSAT, SPOT
	Land use studies	LANDSAT, SPOT
Sea surface sensing	Sea surface conditions (temperature, currents etc.)	SEASAT-A, ERS-1
	Coastal and marine resources	NIMBUS-7
	Land/ocean interface phenomena	NIMBUS-7
	Determination of wind fields over the ocean	SEASAT-A,ERS-1
	Topographic and dynamic ocean studies	SEASAT-A, TOPEX
	Pollution investigations	LANDSAT, TOPEX, SPOT
	Sea ice monitoring	SEASAT-A, ERS-1
	Support of fisheries activities	ERS-1
Climate Studies	Long-term, global data collection;	METEOSAT
	Study of anthropogenic changes (atmospheric carbon dioxide content, stratospheric ozone layer, etc.);	NIMBUS -7, UARS
	Study of trends in the energy balance (variability of the solar constant, atmospheric and oceanic temperatures, etc.)	ERBs, NOAA, METEOSAT, ERS-1
Solid Earth Studies	Determination of the Earth's shape and gravitational field	LAGEOS, STARLETTE

Communication satellites represent the first space application to reach commercial enterprise status. They have enabled the advent of high-quality, global telephone and television exchanges. Mainly based in geostationary orbit, these spacecraft offer today a wide range of services, summarised in Table 2.

Navigation systems, originally developed for military applications, were opened to civilian use twenty-five years ago. They allow position determination to a resolution better than 1 m, using ground equipment that has continuously become smaller in size and more economical in terms of acquisition and operation. Already however, these satellite constellations allow more sophisticated operations, such as air and ship navigation. Already services have been established relaying navigational and other data from mobile objects to, for example, the owner's organisation: such systems may also evolve into providing a means for the surveillance of hazardous or otherwise important items.

Table 2: Space Communications Services

Fixed-site Services	Global telephony trunking Regional systems Television distribution for networks Television feeder to cable systems
Mobile Services	Maritime systems Aeronautical systems Airtraffic control Land systems
Broadcasting Services	Radio Television Data
Business Services	Voice conferencing Video conferencing Private line telephony Data links (incl. text, pictures) VSAT
Data Services	Electronic mail High-rate digital data relay Satellite data networks Data collection Radiolocation
Data Relay Services	Earth orbital space Search & rescue

2.2 Rationale for small satellite missions

In the beginning of space exploration, all space missions were small, primarily because the launch capability was small. As launchers grew, so did satellites, but it must not be forgotten that an incredible increase in our knowledge base came from those early, small satellites. Some argue that we must have big satellites today to have that same step function in our knowledge base, but it is more likely that incremental steps forward are just as effective. Furthermore, today's technology still lets us do remarkable science and applications of that science using small satellites.

Table 3: Early Satellites

COUNTRY	NAME	LAUNCH DATE	MASS (KG)	MISSION
USSR	SPUTNIK-1	4/10/57	83.6	Technology
US	EXPLORER 1	1/02/58	13.0	Ionospheric and solar studies
UK	ARIEL 1 (UK 1)	26/04/62	61.7	Ionospheric and solar studies
CANADA	ALOUTTE 1	29/09/62	143.7	Ionospheric studies
ITALY	SAN MARCO 1	15/12/64	113.0	Aeronomic and ionospheric
FRANCE	ASTERIX (A-1)	26/11/65	41.9	Technology
AUSTRALIA	WRESAT	29/11/67	73.0	
ESA (ESRO)	IRIS (ESRO-2B)	17/05/68	73.7	X-ray and cosmic radiation
GERMANY	AZUR	8/11/69	73.6	Magnetospheric and cosmic ray
JAPAN	OHSUMI	11/02/70	23.8	Technology
NATO	NATO 1	20/03/70	243.0	Communications
CHINA	CHINA 1	24/04/70	173.0	Communications
NETHERLANDS	ANS	30/08/74	129.3	X-ray and UV Astronomy
SPAIN	INTASAT	15/11/74	20.0	Ionospheric studies
INDIA	ARYABHATA	19/04/75	360.0	High energy astrophysics and aeronomy
CZECHOSLOVAKIA	MAGION	24/10/78	15.0	Magnetospheric and ionospheric studies
SWEDEN	VIKING	22/02/86	283.0	Auroral plasma physics
ISRAEL	OFFEQ 1	19/09/88	13.0	Technology

Table 3 summarises some of the early satellites launched by the 17 nations or organisations that developed them. The average mass of these first satellites was about 100 kg. Several of these countries have also acquired their own national launch capabilities.

Planning for small satellite missions does not repalce large satellite missions, as the goals and issues are often different. Small missions can however be a complement to large missions. By exploring new methods and techniques, small satellites can be a pioneering tool for new experiments and technologies for future larger missions.

Small satellites have several advantages over larger ones for both large and small countries: more frequent and larger variety of mission opportunities; more rapid expansion of the technical knowledge base; greater involvement of local industry; and greater diversification of potential users.

2.3 Rationale for Specific Users

The preceding sections have provided an overview of the rationale for engaging in space activities. This thesis was essentially independent of individual national aspects, for example, economic power or technical competence. Some of the reasons supporting space involvement for developing nations are compared in Table 4 with equivalent criteria for countries which are already industrialised.

Table 4: Reasons for Space Technology

DEVELOPING COUNTRIES	**INDUSTRIALISED COUNTRIES**
Improved services (shortcuts in the introduction and development thereof)	Improved services
Improved inventory and management of resources	Improved inventory and management of resources
National health and health services	Improved data exchange
Development of national resources	Access to new resources
Transfer labour to modern economic sectors (higher productivity, capital formation)	Development of new industries (improved economic strength and balance of payments)
Environmental considerations	Environmental considerations
Transition to industrialised lifestyle	Assistance to developing countries

Space science activities are obviously valuable per se, and it is with small scientific satellites that most "space powers" have begun their involvement Weather, Communications and Earth resources satellites were quick to follow. Although scientific satellites are naturally connected with education and training, all types of space activities accomplish that goal. A university environment is an ideal locale for inaugurating space activities. Since the realisation of such projects often requires the creation of new laboratories, these improved facilities are a lasting consequence of the project. Thus the usual spin-offs of a space program, the acquisition of technology and development of industrial organisation and management methods, will begin to accrue at the national level as students leave the university and enter local industry.

Space science studies that can be supported by small satellite missions range from aeronomy to astrophysics, for example, low-orbiting satellites can provide important daily coverage in the atmospheric sciences, leading to better weather prediction. Other small low-orbiting satellites can bring communications to remote areas not currently served by telephones; small satellites in geostationary orbits can do the same. Camera systems can view the country both for weather and land data, offering help identifying the country's resources and early warnings for catastrophes. It can also be used to monitor the country's borders, evaluate crops and predict their yield, and improve mapping accuracy.

Small satellites are ideal for environmental studies, monitoring biological reservoirs, rain forests, marine habitats and the progress of the mass destruction of living species and renewable natural resources. They can also be used to provide country-wide surveillance of illegal activities, including those in inaccessible land and ocean areas.

3. MANAGEMENT ISSUES

There is no unique foolproof way to conduct a space flight mission. There are, however, fundamental aspects that are common to all missions and must be addressed to ensure their success. The philosophy and approach taken toward the implementation of each of these is what defines the resources required to complete the mission.

3.1 Project segmentation

There are four basic segments that must be considered in a space project:

1 the program/project office segment which includes the management, coordination, product assurance, interfaces among all segments, organisation, and resources management,

2 the launch segment which includes the launch vehicle and related support services and facilities,

3 the space segment which includes the development of all components of the spacecraft, the payload, and systems engineering and tests,

4 the ground segment which includes the facilities, equipment, hardware and software required to link the operations centre(s) on the ground and the spacecraft, and carries out all the data processing tasks.

3.2 Project life

Typically the project life is divided into four phases:

Phase I: Concept and Feasibility

During this phase, the general approach to meet the mission objectives is set and studied for its feasibility. The mission objectives must be clearly understood; concepts for operation, overall schedule, cost constraints, interfaces, facilities, development items, long term plans, national policies, ground rules and assumptions are identified.

An organisational structure is established to develop the concepts for the mission, obtain estimates of performance, define cost models and profiles, assess risk, and develop strategies for implementation.

It is important to understand that concept development requires very close interaction between the user and the developing organisation. This will help to ensure that requirements are both realistic and achievable, as well as necessary.

The end result of this phase should be a broad definition of the mission and the basic requirements to support it. The four basic segments must be addressed in sufficient detail to determine the technical and programmatic feasibility of the mission.

Phase II: Detailed planning and design development

Once the feasibility of the mission is proven, the phase can proceed to a more detailed level of planning and design. The general organisation supporting this phase of the mission can be similar to that supporting Phase I. Interface agreements are formalised, the system design is developed to the point where the procurement and/or fabrication of the hardware and software systems can proceed, and the schedule, cost, and other resource requirements are further detailed and planned. At the end of this phase, design should be considered complete.

Phase III: Production and deployment

This phase concentrates on the efficient implementation of the strategies for procurement, fabrication, assembly, installation and test of the systems designs and plans developed in Phase II. It usually requires that the organisation be expanded to include supporting personnel as needed. This phase of the program is the most demanding and intensive from a project management point of view and requires the most control. Its success depends highly on the adequacy and completeness of the planning and design phase.

Phase IV: Operations and support

This final phase in the project's life deals with the daily operation and maintenance of the space and ground segments. Clearly there needs to be some overlap between the production and deployment and the operations and support phase. Phase III will provide the basis for the understanding of the operations, and verification and maintenance of all of the segments through their final integration, launch, and in-orbit performance. After verification in orbit, the project organisation is usually reduced to key management, flight operations, data management and distribution, and overall system maintenance.

3.3 Organisation

The development and implementation of any space mission requires good interaction among and within each of the segments of the project to ensure its success. The Project organisation and management will be centred on the space segment with the launch and ground segments becoming important support services.

The size of the project organisation will vary with the complexity of the mission. However, it is always advantageous to have a dedicated core team of people (as shown in Fig. 1), with clearly defined responsibilities and necessary expertise, supervising and organisation spread over a large matrix. It is recommended that the core team be located within close proximity. This makes the much needed interaction readily available and essentially immune to external disturbances. Support personnel outside of the core team should be added as needed for very specific tasks. These tasks are bound by strict schedule and cost constraints and should have a clearly defined end objective.

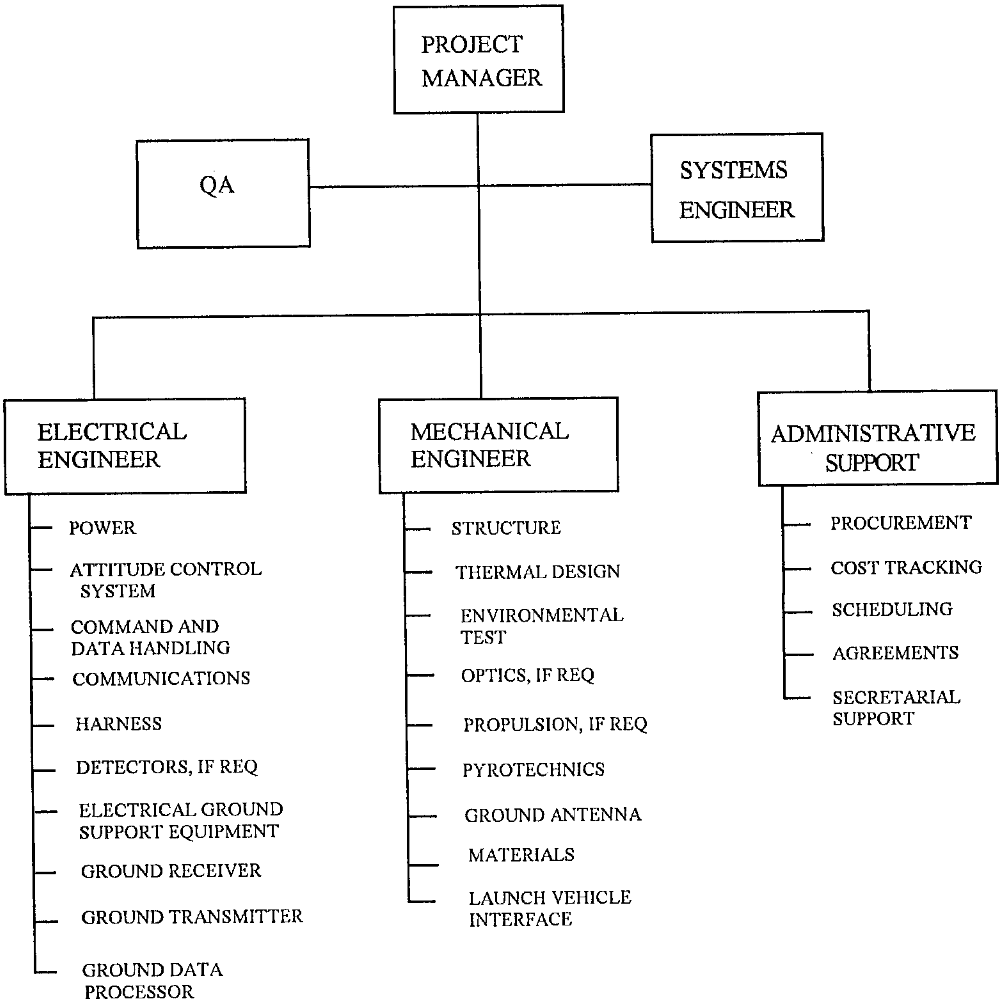
3.4 Planning

It is important to recognise the value of early detailed planning. A thorough planning exercise is critical and should be completed as early as possible in the project's life. A key element of this activity is a work breakdown structure of the components and activities required to complete the mission. The work breakdown structure should be used to prepare and provide traceability for the schedule and cost phasing plan throughout the mission. Development of new technologies are items that require early and continuous attention. These are the ones that usually require extensive commitment of resources to complete. It is useful to identify areas that can be descoped early in the program as a measure to control cost.

3.5 Reliability and Quality Assurance

It is difficult to define exactly how much reliability and quality assurance is adequate. Many times this issue is addressed in terms of the willingness of the user to accept risk. However, it should be addressed more from a point of view of the minimum requirements to ensure the success of the mission. Why is a certain level of reliability and quality necessary? Consider, for example, the differences between the environment on the ground versus that encountered in putting a payload in orbit. Structural excitation during ground handling and launch, vacuum, radiation and temperature extremes are some of the basic differences that drive the need for careful analysis and monitoring. It should be kept in mind that the longer the space segment has to survive in this environment, the greater the need for reliability and quality control. There are, however, specific measures that can be taken to reduce the need for an extensive reliability and quality assurance program and the associated documentation. The use and enforcement of design and interface standards and standard parts across the system are extremely helpful in reducing the integration and test time and cost. Components and equipment with flight qualification heritage should be used as much as possible. Emphasis should be placed on a verification and test program designed to show the flight worthiness of the space segment and the adequacy of other supporting segments.

Figure 1: Minimum Management Structure



3.6 General recommendations

The following are some additional general recommendations that always prove to be helpful in the development and control of a mission.

Keep a watchful eye on the evolution of the system design to keep it focused on meeting the minimum requirements. Creeping requirements are extremely difficult to stop if allowed to evolve without control.

A commitment to complete the mission at a cost "not to exceed" should be in the mind by all of the team members.

Define all internal and external interfaces early in the program and make sure that they are clearly understood and agreed upon by everyone supporting all segments of the mission. Take the necessary measures to reduce administrative burdens on technical personnel.

4. MISSION DESIGN

In order to design a satellite mission, it is necessary to define the mission objectives and requirements, keeping in mind that these may have to be modified when the design process is underway. Having established the mission goals, the four segments of the project, as identified in Section 3.1, must be examined in detail to determine the suitability of the design, its coherence and its cost. The overall system design, the launch segment, the space segment and the ground segment will now be examined. (There is no direct discussion of the payload since it is directly derived from the mission objectives and therefore varies widely for each mission).

4.1 Mission and system considerations

4.1.1 General

The mission objectives defined by the user organisation need to be translated into technical specifications and a configuration for all segments of the space project.

To satisfy the mission requirements, an instrument package or payload will be defined which meets the objectives of the user. Possible orbits and pointing modes will be identified. Trade-off analyses will be made on the resultant spacecraft definition, launcher alternatives, ground segment configuration and operational complexity. Overall resulting costs and satisfaction of the mission objectives will be key elements in the analysis. At this point, "nice to have" requirements must be discarded in order to contain costs.

The main purpose of the system activity is to ensure coherence among all the elements and to conceive and develop a well balanced overall project within budget limitations.

4.1.2 Orbit selection

To illustrate how all launch, space and ground segments must be considered in the system analyses, several aspects of the orbit selection will be discussed.

Three general classes of orbits may be suitable for small satellites.

Geostationary Earth Orbit (GEO). In such orbits, the satellite appears fixed relative to the ground, thus allowing continuous visibility over one spot on the Earth and therefore a permanent communication link: it may simplify the ground segment and the operations, but because of the large space-to-ground distance the data rates will be small, or larger ground antennas and higher RF power on board the spacecraft will be required. This orbit is reached usually from a standard Geostationary Transfer Orbit (GTO) provided by a large launch vehicle. The circularization of the orbit from the GTO to the GEO will require an apogee propulsion system which will roughly double the mass of the satellite at launch. Small launch vehicles will not usually offer enough performance for such missions.

An interesting derivative may be to conduct the mission from the GTO, thus benefitting from frequent piggyback launch opportunities, but avoiding the complexity and extra costs associated with the apogee propulsion system.

High-Eccentricity Orbits (HEO). Small satellites may be put into high-eccentricity orbits. Orbits inclined at 63.4 degrees are particularly attractive because the plane of such an orbit is unaffected by the aspherical Earth, thus it remains practically at rest in a geocentric inertial frame. High-eccentricity fixed orbits allow one to minimise the number of satellites covering certain desired areas which remain visible for long periods of time. These are undoubted advantages for certain ground operations.

Certain launchers are able to deliver satellites into HEO orbits, thus simplifying or obviating the need for an on-board propulsion system. However, such orbits are not particularly useful for remote-sensing missions. In fact, not only does the geometrical area seen by the on-board sensors change drastically, but the attitude varies rapidly, thus rendering the whole pointing and pointing-rate requirements difficult to meet in terms of both mass and cost. For a telecommunication satellite, these orbits usually exhibit a high altitude apogee and the associated high power requirements, which, in turn, mean large solar panels and significant power conditioning. As for GEO, this orbit is not very compatible with assumptions of low mass and low-cost satellites.

Low Earth Orbits (LEO) - Such orbits will generally be preferred for small satellite missions. Small launch vehicles can be used, offering flexibility in the selection of the orbit parameters, or piggyback launches may be available. Low on-board RF power is sufficient because of the short distance from the ground, but infrequent and short visibility periods are a drawback which will lead to some ground segment and operational complexity. One should also distinguish between the near equatorial or low inclination orbits for which the visibility zone will be limited to the tropical zone, and the polar and quasi-polar (sun synchronous) orbits which allow accessibility to any point on Earth, either for communication (e.g. store and forward) or for Earth observations.

4.2 Launch segment

The launch opportunities for the small payload owner might seem unlimited when one considers all the alternatives: dedicated launch on a small Expendable Launch Vehicle (ELV); sharing or piggyback on a larger ELV; or negotiating a Joint Endeavor Agreement for a free ride on the Space Shuttle or similar programme. However, once the payload owner assesses the unique requirements of the individual spacecraft against the capabilities, costs and constraints of each of the potential launch service providers, the field of realistic space transportation options will often narrow down to a very few vehicles for the unique mission under consideration.

4.2.1 Considerations for launch vehicle selection

A spacecraft owner needs to critique each launch vehicle option with respect to the following considerations prior to making a launch vehicle selection decision, the most important consideration being the spacecraft value, an assessment of the profit potential and the costs associated with its replacement. Is a re-flight option included in the proposed launch service package under consideration? How many payloads will be launched? Is this a one-of-a-kind spacecraft, or a low-cost series of identical payloads?

A second consideration should be the potential launch vehicles reliability record or flight history. A series of low-cost payloads may be willing to take the risk of a new lower-cost launch vehicle with an unproven record.

A third factor in the selection process is an assessment of launch service costs when compared to the anticipated commercial return on investment, value of the payload at risk, and the associated vehicle reliability record. Schedule certainty is important to most payload owners with a commercial product in mind, but may be of less importance to a scientific experiment where time is not a primary driver. Corporate stability and long-term viability of the launch vehicle manufacturer is a critical factor all customers would be advised to consider. Once a commitment is made to a particular vehicle, the spacecraft and its payload will typically require some modifications if it is necessary that it be launched on a vehicle different from the one for which they were originally designed.

The insurance requirements of a given launch vehicle and the insurance package included in the launch service price should be closely examined. Although insurance costs for most small ELV's are significantly lower than those attributable to larger ELV's, the total launch service costs can fluctuate widely between vehicle manufacturers based upon the insurance package each one has negotiated.

Any customer looking to launch a payload with US component technology on an international ELV would be wise to consider the applicability of technology transfer export regulations. At present, the US State Department is reviewing applications to allow US payloads to be launched on Chinese and Russian launch vehicles on a case-by-case basis.

A new trend in the larger commercial communication satellite market has been the purchase of a satellite on-orbit. A satellite operator in effect buys both a spacecraft and a launch service in a single package and takes ownership on-orbit. It is not likely that such an option would be viable with the small satellite market, but may be a factor in the future.

A final consideration: is a dedicated flight required or will launch as a secondary or piggyback payload meet the mission's requirements? A brief description of capabilities, constraints and costs associated with small launchers will be discussed further, along with secondary launch options on Ariane/Delta II/Space Shuttle. The aforementioned series of considerations, although not necessarily an exclusive list, should be prioritised by each small payload owner prior to committing to a final launch vehicle selection.

4.2.2 Dedicated launchers

During the past thirty years, many countries have invested in development of indigenous launch vehicle capability, pursuing the lucrative commercial market or strengthening their own civil and national defence. International space policies and programs are emerging with developments in commercial and government support and advances in related technologies.

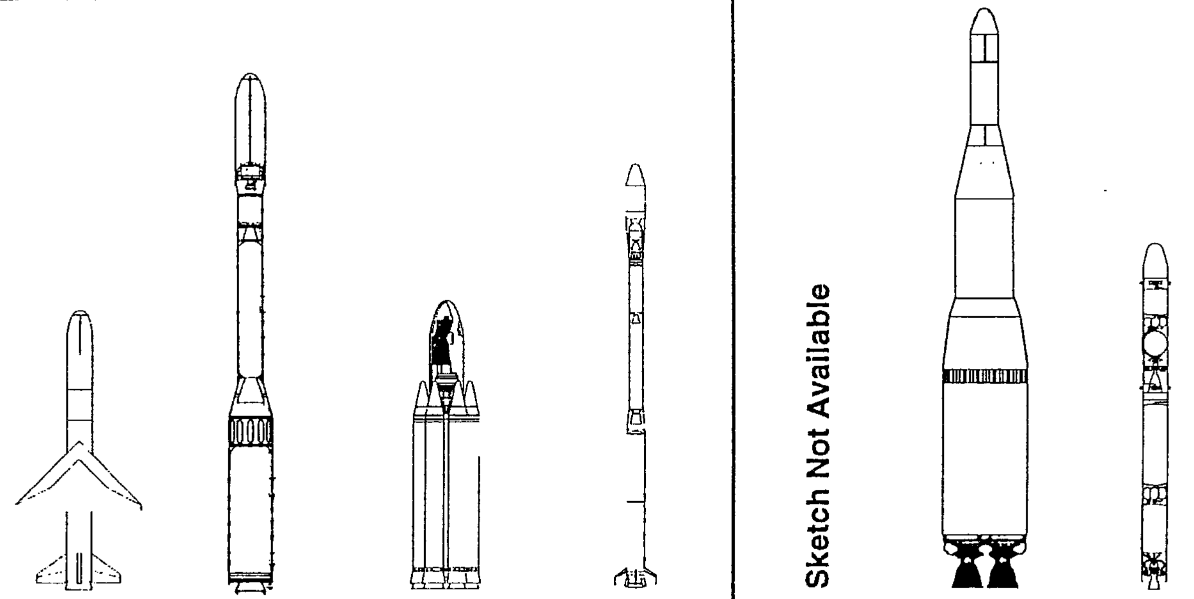
The small class of ELV's is the most dynamic one and has experienced the largest entry of commercial entrepreneurial activity both in the United States and abroad over the past few years. Small class ELV's can deliver payloads weighing from as little as 25 kg to as much as 1500 kg to Low Earth Orbit. Until 1989, the only flight demonstrated vehicles in this class were the United States Scout, Atlas-E/F and Titan II; the Japanese MU-3IIS; and the Chinese Long March I. All these vehicles were developed under government contracts to meet specific government requirements.

With the emergence of a potential commercial small class market in the late 1980's, industry has responded by offering a range of new services. Currently, there are a number of US ELV Companies interested in servicing the small launch service market. These include, but are not limited to, the following vehicles: Pegasus; Taurus; Conestoga and Orbital Express. Of these, only Pegasus has any orbital flight history. Pegasus has had two demonstration flights, one in 1990 and one in 1991. Scout , the United States workhorse smaller launcher will be phased out in 1993 when the last two Scout boosters in NASA's inventory are launched. Although there has been much industry interest in offering commercial services in this class, a real commercial customer base has not yet materialised. A dedicated launch service on one of these small ELV's ranges from between 10 to 20 million US dollars. A dedicated launch at this price is a luxury few scientists, universities, radio amateurs, or other commercial entrepreneurs can afford.

Tables 5 and 6 provide a summary of the availability, performance capability and costs quoted for commercial ELV's. Payload operators considering launch on a nonmarket vehicle must take into account technology transfer and trade constraints.

Table 5

U.S. COMMERCIAL SMALL-CLASS EXPENDABLE LAUNCH VEHICLES*



	EXISTING OR UNDER CONTRACT								PROPOSED		
VEHICLE	PEGASUS		TAURUS		CONESTOGA		ORBEX		AQUILA	SEAEAGLE	PACASTRO-1
Performance	Basic	XL	Basic	XL	1229	1620	1E	2E			
LEO (i = 38°)											
LBS	719	910	3,030	3,330	665	1,980	500	540	3,200	4,000	500 (i = 0°)
KG	326	413	1,374	1,510	302	898	227	245	1,452	1,814	227
(100 NM / 115 KM CIRC)					(300 NM / 556 KM CIR)		(300 NM / 556 KM CIR)			(275 NM / 510 KM CIR)	(648 NM / 1,200 KM CIR)
POLAR (i = 90°)											
LBS	558	711	2,275	2,550	456	1,347	400	440	2,500		500
KG	253	323	1,032	1,157	207	611	181	200	1,134		227
(100 NM / 188 KM CIRC)											(405 NM / 750 KM CIR)
MANUFACTURER	ORBITAL SCIENCES		ORBITAL SCIENCES		EER SYSTEMS		INTERNATIONAL MICROSPACE		AMROC	SEALAR	PACASTRO

* DOES NOT INCLUDE USG VEHICLES NOT MARKETED COMMERCIALLY, i.e., SCOUT, ATLAS-E, TITAN II

Table 6

INTERNATIONAL SMALL EXPENDABLE LAUNCH VEHICLES
(EXISTING AND PROPOSED)

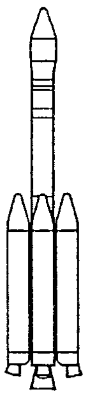
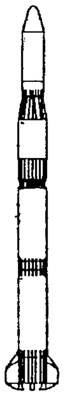
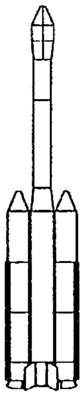
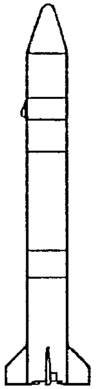
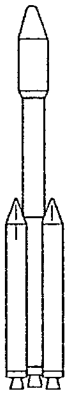
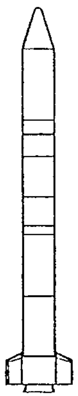
	Sketch Not Available							Sketch Not Available		Sketch Not Available	Sketch Not Available
VEHICLE	ALV (Australia)	VLS (Brazil)	Long March 1D (China)	ASLV (India)	Shavit (Israel)	SMS (Italy)	M-5 (Japan)	J-1 (Japan)	KOSMOS (Russia)	START-1 (Russia)	Capricornio (Spain)
PAYLOAD TO LOW EARTH ORBIT (lbs / kg)	2,000 / 907	500 / 227 (300 nm / 556 km equatorial)	1,740 / 789 (186 nm / 345 km circ, 57° incl)	330 / 150 (216 nm / 400 km circ, 43° incl)	350 / 159 (100 nm / 185 km circ, 143° incl)	2,200 / 998 (100 nm / 185 km equatorial)	4,300 / 1,950 (135 nm / 250 km circ, 31° incl)	2,000 / 907 (300 nm / 556 km circ, 31° incl)	3,000 / 1,361 (320 nm / 593 km circ, 51° incl)	1,100 / 499	220 / 100
PAYLOAD FAIRING DIAMETER	N/A	~ 3.5 ft. (~106.7 cm)	6.7 ft. (204 cm)	3.3 ft. (100.6 cm)	47 in. (119.4 cm)	65 in. (165.1 cm)	8.2 ft. (249.9 cm)	5.4 ft. (164.6 cm)	7.9 ft. (240.8 cm)	N/A	N/A
LAUNCH SITE(S)	Woomera, Cape York	Alcantara	Jiuquan	Sriharikota	Negev	San Marco	Kagoshima	Tanegashima	Plesetsk, Kasputin Yar	Mobile	El Aranosillo
STATUS	On Hold	In Devel.	Operational	Operational	Operational	In Devel.	In Devel.	In Devel.	Operational	In Devel.	Proposed
INITIAL AVAILABILITY	N/A	1995?	1971	1987	1988	1995?	1995	1995	1964	1993?	1996?
COMMERCIALLY AVAILABLE	TBD	TBD	Yes	No	Yes	TBD	No	TBD	Yes	TBD	TBD
PROJECTED COST PER LAUNCH	N/A	N/A	$10M	N/A	$10 - 15M	N/A	N/A	N/A	N/A	N/A	N/A

Table 7

U.S. SMALL EXPENDABLE LAUNCH VEHICLES: CONSTRAINTS

VEHICLES UNDER FIRM LAUNCH CONTRACT (EXISTING / IN DEVELOPMENT):

VEHICLE	AVAILABILITY	LAUNCH PADS	PAD AVAILABILITY	LAUNCH RATE	PAYLOAD FAIRING DIAMETER	ESTIMATED LAUNCH COST	COMMER-CIALLY AVAILABLE?	LAUNCH RECORD	FIRM LAUNCH CONTRACTS
LVSC (LTV) SCOUT	Operational (1960)	WFF → VAFB →	Mothballed (In Refurb.) Operational	10-12 / Year	2.9 ft. (88.4 cm) and 3.5 ft. (106.7 cm)	N/A	No	101 / 115 = 87.8%	NASA (3 Launches Remaining Before Closeout)
OSC PEGASUS	Operational (1990)	Mobil Air - Launch: NASA B-52 → L-1011 → (ER/WR/WFF)	Operational Mid-1993	6-12 / Year	46 In. (116.8 cm) Dynamic Envelope	$11-15 Million	Yes	1 / 2 = 50%*	DARPA USAF SDIO U.S. NAVY NASA BRAZIL ORBCOMM
OSC TAURUS	In Development (1993)	VAFB → CCAFS →	1993 1994 (?)	3-6 / Year	54 In. (137.2 cm) Dynamic Envelope	$17-21 Million	After Initial USG Launch	0/0	DARPA
EER CONESTOGA	In Development (1993)	WFF Pad "0"	1993	Not Defined	72 In. (182.9 cm)	$10-20 Million	Yes	0/0	NASA / CCDS COMET
IMI ORBEX	In Development (1994)	VAFB → WFF, Poker Flat, Andoya	1994 (?) TBD	5 / Year	42 In. (106.7 cm) and 50 In. (127.0 cm)	$10-15 Million	Yes	0/0	SDIO

OTHER VEHICLES IN DEVELOPMENT OR PROPOSED:

VEHICLE	AVAILABILITY	LAUNCH PADS	PAD AVAILABILITY	LAUNCH RATE	PAYLOAD FAIRING DIAMETER	ESTIMATED LAUNCH COST	COMMER-CIALLY AVAILABLE?	LAUNCH RECORD	FIRM LAUNCH CONTRACTS
AMROC AQUILA	Proposed (1994-95?)	VAFB	TBD	N/A	N/A	$10 Million	Yes	0/0	None to Date
SEALAR SEA EABLE M1	Proposed (1996?)	Mobile Sea Launch	N/A	N/A	10 ft. (304.8 cm)	$10 Million	Yes	0/0	None to Date
PACASTRO PA-1	In Development (1995?)	Kiruna, Andoya, WFF, Hawaii (?)	TBD	12 / Year	59 In. (149.9 cm)	$5 Million	Yes	0/0	None to Date

* SECOND PEGASUS LAUNCH 7/17/91 PARTIAL FAILURE

Each vehicle should be considered from a total launch system perspective with an understanding of both the hardware's performance capability and the attendant operational launch constraints. As an example, a few of the most critical constraints have been summarised in Table 7 for all of the aforementioned US ELV's. Launch pad location and availability have a direct impact on the performance capability achievable by a specific vehicle to accomplish unique mission objectives.

Available launch azimuths dictate the range of orbits a vehicle can perform, with or without dogleg manoeuvres. Pegasus has unlimited launch site opportunities, since it begins its flight on an aircraft, and can also accommodate twelve missions a year to a range of orbits. The payload fairing diameter dictates the physical payload size that each vehicle is designed to accommodate. Individual vehicle users' manuals should be consulted to compare other critical environmental constraints (e.g., acoustics, loads). Launch site location is a factor that also requires consideration since campaign costs associated with launches from international sites can pose a financial burden on small payload operators.

4.2.3 Secondary/Piggyback launches

In an effort to reduce the cost of access to space and to make use of surplus performance capabilities, larger ELV manufacturers are interested in offering the small payload community the option of flying as a secondary or piggyback payload on those missions where the primary payload does not fully utilise the vehicle's capability. The primary payload schedule and reliability remain unaffected by the companion payload, and the small payload owner is provided with a potentially cost-effective alternative to the purchase of a dedicated small ELV.

A primary payload owner purchases a dedicated launch service on an ELV to achieve the primary payload mission objective, which in turn drives the vehicle configuration, orbital trajectory, launch schedule and security requirements of the mission. The primary payload owner incurs the price of the launch service. An experiment, sensor, instrument or fully integrated payload whose mission objective is different from that of the primary payload may gain access to space as a secondary or piggyback launch on that ELV. In a piggyback launch, the secondary payload owner utilises excess capacity on the ELV once the primary payload requirements are satisfied. The secondary payload is constrained in weight, size, orbital trajectory, vehicle configuration and launch schedule by the primary payload when purchasing a dedicated launch. However, the piggyback launch costs may be only a very small fraction of the launch service price plus the cost of integrating the secondary payload into the ELV.

NASA has a history of successfully flying secondary payloads on Delta and has recently initiated a program to continue similar flight opportunities on Delta II. Arianespace also offers launch opportunities for secondary payloads. Secondary flight opportunities on Long March, Proton, H-II, and Atlas/Centaur may be viable options in the future for small payload owners to consider and explore. At this time, secondary launch opportunities are available primarily on Ariane and Delta II. The US Space Shuttle is also mentioned briefly; however, actual flight opportunities are sparse at this time.

Arianespace is offering secondary flight opportunities for up to six satellites, each weighing up to 50 kg, on a circular platform called Ariane Structure for Auxiliary Payloads (ASAP). The ASAP carrier has been designed for use on Ariane missions with a single primary payload; it has been used and is intended to continue to be used to place satellites into a polar Low Earth Orbit or a Geostationary Transfer Orbit. Approximately five Ariane 4 missions currently scheduled through the mid-1990's offer the potential use of the ASAP carrier into polar orbits. Arianespace has set a price of $600,000 for launch of the ASAP platform; this cost may be split among as many as six different small satellite customers. Arianespace has already identified a number of candidate secondary payloads interested in taking advantage of the ASAP carrier for the upcoming flights.

McDonnel Douglas is offering piggyback flight opportunities for experiments/payloads that are small and light enough to fit on the Delta II second stage. The Delta II second stage avionics package can provide limited command, power, telemetry and attitude control services to the secondary payload. Based on current contracts, secondary flight opportunities are available on Delta II (7925 model) developed to launch the US Air Force Global Positioning Satellites beginning in early 1990. Sufficient excess performance margin is not available on any of the commercial Delta launches currently under contract; hence, the only flight opportunities are on government launches. NASA is identified as the appropriate point of entry for any non-DOD civilian/educational/non-profit organisation interested in reserving an available secondary flight opportunity and has developed a Delta II secondary payload users guide. Costs to the secondary payload owner include integration costs, additional range support and any costs associated with additional security requirements. NASA recently launched the Diffuse Ultraviolet Experiment as a secondary payload on the Geotail Delta mission in July 1992, and plans to launch a series of small experiments as piggybacks on Delta II GPS missions beginning in 1992, at an average cost of 1-2M US dollars/launch.

National space policy directives preclude NASA from providing Shuttle launch services to commercial communications satellites or other commercial payloads unless they require the Shuttle's unique capabilities or manned intervention. NASA's Office of Commercial Space Programs has established several types of joint arrangements that offer flight time on the Space Shuttle for applied research until the commercial potential of a product has been established. Shuttle secondary payload flight opportunities are available for a variety of users: US Government, domestic/international research and technology ventures. Flight assignments for secondary payloads can be made as much as 19-20 months or as late as 5 months prior to launch. The number of available secondary flight opportunities on any single Shuttle mission is highly variable and dependent on the primary mission objectives and requirements. The most popular arrangements offered by NASA are the Joint Endeavour Agreement (JEA) and the Space Systems Development Agreement. The JEA is available for company-sponsored and directed flight experiments. The JEA is a no-cost arrangement and, therefore, very attractive to the small payload community. The reduced Shuttle flight rate, and resultant downtime of the Shuttle fleet after the Challenger accident has resulted in a lengthy queue of commercial payloads awaiting launch.

4.2.4 Launch cost considerations

Reducing the cost of transporting payloads to orbit has been an elusive but much touted goal of every proposed launch system since the early Space Shuttle days as a necessity to develop commercial space goods and services. The cost quoted by a commercial launch service supplier may not always include all the components of cost associated with launch of a payload into a specified orbit. A brief list of the major components of cost is presented in Table 8 below:

In addition, some large commercial spacecraft manufacturers make launch reservations on more than one vehicle to provide schedule insurance, should one of the vehicles experience a failure or become unable to provide a launch as requested by the customer. This option is probably too costly for most small payload customers to consider. The launch campaign costs associated with a launch from a remote launch site (Australia/San Marco/China) may, in some cases, pose an additional financial burden on the small payload customer. When it comes to launch selection, the total value of the resources at risk drives the cost/reliability trade-off ultimately made by the payload owner.

Table 8: Components of Cost

LAUNCH SERVICE
* VEHICLE
* RANGE SERVICES
* SPACECRAFT PROCESSING
* PROPELLANTS

MISSION UNIQUE REQUIREMENTS
* UPPER STAGE

LIABILITY INSURANCE
* THIRD PARTY
* DAMAGE TO GOVERNMENT PROPERTY

REFLIGHT INSURANCE

DUAL COMPATIBILITY
* SCHEDULE INSURANCE

CAMPAIGN COST
* REMOTE LAUNCH SITES

4.3 Space segment - Spacecraft design considerations

Having established the main mission parameters, including its overall aims, the orbit, available ground stations and likely launch vehicle, the detailed design of the satellite can begin. The subsections which follow summarise the factors which must be considered in this design process, most of which are applicable to all types and complexities of spacecraft. They focus on spacecraft bus subsystem design and do not cover any payload aspects, which are mission specific. An important point to note is that virtually all the subsystems mentioned are available off-the-shelf, and many of them in low-cost versions, ideally suited to small satellite missions.

4.3.1 Space environment

Earth satellites fly ballistic trajectories in the Earth's gravity field influenced by atmospheric drag and solar radiation pressure. Drag is a function of altitude, and the orbits of near-Earth satellites are affected as solar activity increases/decreases the height at which air molecules interact with the spacecraft. Solar illumination also exerts a pressure of $\sim 4.4 \times 10^{-6}$ N/m^2 and thus drag and solar radiation pressure provide perturbing forces which influence the spacecrafts' orbit and must be accounted for during the tracking process. The Sun also provides an energy source of ~1.36 kW per square meter of surface, which can be converted by solar cells to provide electrical power, albeit at low (~20%) efficiency.

The Earth, orbiting the Sun, is immersed in the solar wind and the interplanetary magnetic field. It possesses its own magnetic field which resembles that of a bar magnet with north and south magnetic poles offset from its geographic poles. The magnetic field is a haven for charged particles, and both electrons and protons are trapped in this field. This fact is a very fertile area of research in magnetospheric physics. In addition, the effect of these charged particles must be considered during spacecraft design, particularly relative to the power generating system and certain types of electronic components.

4.3.2 Structure and launcher interface

Structural design is an iterative process that begins after the generation of a top-level systems diagram containing the major spacecraft subsystems. The first task of the mechanical designer is to propose a composite design based on the block diagram. This design is influenced by the choice of launch vehicle, particularly because of the form factor of the fairing and the mechanical interface with the vehicle. The launch configuration will not necessarily resemble the orbital configuration since deployable structures may be used.

The designer begins with the orbital configuration that will meet the mission goals and then proceeds to the launch configuration. This process identifies those structural elements that must be deployed to form the orbital configuration.

The structure will usually comprise a number of aluminium alloy honeycomb panels with attachment points and fittings for all the various subsystems and deployable elements. Some more advanced materials such as carbon-fibre reinforced plastics are now becoming available, which can reduce the mass of the structure from typically 15% of the spacecraft mass to perhaps 10%. The interface with the launch vehicle will usually comprise a V-shaped strong ring around which a clamp band is fixed. This band is released by a pyrotechnic device and a set of separation springs is used to deploy the satellite.

4.3.3 Thermal aspects

For small spacecraft with moderate power consumption, thermal control can usually be accomplished passively through the use of external surface coatings with appropriate absorption/reflection properties and multi-layer thermal insulation. Heat transfer is accomplished through conduction and radiation. The design must start at the systems level with the location and dissipative power of each package. The thermal designer works with the mechanical designer to make sure that adequate heat paths to radiative surfaces are considered in the structural design. The ultimate heat dump is by radiation to space.

This process is not as simple as it appears since the spacecraft will experience varying thermal conditions as loads are cycled on/off or as the spacecraft experiences eclipse or full sunlight. Active systems employing heaters may be required in some instances to maintain minimum survival temperatures when loads are switched off. Thermostatically controlled shutters or louvres may also be employed as an active means of temperature control, although these devices tend to be expensive and should be avoided for a small satellite if possible. If active control is required, it is often possible to achieve a low-cost solution by the use of innovative engineering techniques without having to employ louvres.

4.3.4 Attitude sensing and control

There are two general classes of attitude control for spacecraft, namely spinning and 3-axis stabilised. Sometimes a combination of the two is used. An attitude sensing system is required to determine the spacecraft attitude, usually with respect to the Sun and the Earth or stars. A reaction control system is needed to establish and modify the attitude, when required to point the spacecraft in a new direction or to correct for any disturbances experienced by it.

4.3.4.1 Disturbances

The attitude of a spacecraft will be affected by a number of forces acting on it, including the following:

a Aerodynamic drag, which is a retarding force caused by the Earth's atmosphere, also resulting in a torque if the spacecraft centre of mass is not coincident with its centre of pressure,

b Solar radiation pressure, a small but often non-negligible force pointing away from the Sun, again resulting in a torque if the centres of mass and pressure are not coincident, c Gravity gradient torques, due to the small difference in gravitational attraction between extremes of the spacecraft,

d Magnetic torques due to interaction between the spacecraft's magnetic field and the Earth's field.

4.3.4.2 Attitude sensing equipment

Spacecraft attitude can be determined, provided the position of the spacecraft in its orbit is known and at least two reference vectors can be measured. The easiest references to measure are to the Sun and to the Earth, and a variety of sensors are readily available to perform this task.

a Fan-Beam Sun and Earth Sensors. These are very simple devices which can be used on spinning spacecraft to determine the angle between the spin axis and the Sun and Earth respectively. One Sun sensor is mounted vertically to provide a reference every time its fan-beam field of view (typically 140° x 1°) sees the Sun. Another Sun sensor and an Earth sensor are mounted at an inclined angle and these will trigger at different times, depending on the Sun and Earth angles.

b Digital Sun Sensors. These devices can be used on either 3-axis stabilised or spinning spacecraft to determine the Sun angle with respect to the spacecraft axes. A digital Sun sensor consists of a narrow slit, a coded shadowmask, and a one-dimensional photo-sensitive array that allows accurate measurement of the Sun angle in one plane. The output from such a sensor is an eight bit binary word which gives a direct representation of this angle. Two Sun angle measurements from two perpendicular axes fix the orientation of the Sun in the spacecraft frame of reference.

c Earth Horizon Sensor. An Earth horizon sensor consists of a narrow Field-Of-View (FOV) telescope which is scanned across the surface of the Earth. In a spinning spacecraft the sensor will be fixed and the rotation of the spacecraft used to scan the FOV across the Earth.

For the 3-axis stabilised case, the sensor FOV is rotated by a mirror mechanism so that it scans the orbital plane and hence it sees the Earth's albedo at a given azimuth angle. Since, in general, the position of the orbital plane relative to the z-axis of the spacecraft is not known, a scan in two planes may be required in order to ensure that the Earth's horizon will be scanned.

All types of Earth horizon sensors detect the transition in optical intensity between the Earth/Space boundary. The location of the Earth's horizon is poorly defined at visible wavelengths due to the effect of the atmosphere. The horizon is best defined in the infrared spectral region and most sensors utilise the 14 μm to 16 μm band. Infrared sensors are unaffected by the presence of the terminator and are less susceptible to solar interference problems than sensors operating in the visible part of spectrum.

d CCD Camera-Based Earth Sensor. Developments are now in progress to produce an Earth sensor whose detector is a simple (CCD) camera, and thus has no moving parts. The problem of determining the Earth's centroid under varying conditions of Earth size and brightness or phase is being tackled by advanced image processing techniques and an on-board processor.

e CCD Camera-Based Star Sensor. Another option for an attitude sensor uses a CCD camera to measure star co-ordinates in the spacecraft frame and provide attitude information when the observed co-ordinates are compared with known star directions from a star catalogue. Using only 3rd Magnitude and brighter stars, 4π steradian coverage of the galactic sphere can be obtained by storing around 200 star fields in memory. By comparing the camera image with stored patterns, attitude measurement accuracy of around 0.5 degree can be obtained.

f Magnetometer. A magnetometer provides a reliable and well-proven method of determining attitude providing the requirements for attitude knowledge are not greater than around 1 degree. The accuracy of such sensors is limited by knowledge of the Earth's magnetic field at the height of the orbit and also the variability of such data with time e.g., due to solar activity (flares, magnetic storms, etc.).

g Inertial Systems. Any type of inertial guidance systems based on conventional or ring-laser gyros will provide highly accurate attitude information, but at a high cost, and may not be justified for use in small low-cost satellites.

4.3.4.3 Reaction control equipment

The Reaction Control System provides the actuating torques necessary to accomplish attitude manoeuvres and correct for attitude perturbations induced by disturbance torques of the types described above. A number of subsystems exist to fulfil this function:

a Momentum Wheels. These wheels may be thought of as electrically driven flywheels storing angular momentum which can then be transferred to or from the spacecraft by either slowing them down or speeding them up, thus causing an angular rotation of the spacecraft. For a simple Earth or star-pointing mission, only a single momentum wheel need be used to control the pitch manoeuvre. However, for full 3-axis control, a suite of 3 orthogonally-mounted wheels will be required, often with a fourth wheel inclined at 45° to all the others for redundancy. In this configuration, the spare wheel can take over the function of any of the 3 primary wheels, albeit with more complicated control algorithms.

When a momentum wheel is slowed down or spun up to one of its extremes, which may happen if it is compensating for a continuous disturbing torque, its momentum must be "unloaded" or "restored" by use of an opposing torque on the spacecraft. This can be provided by a magnetic torquer or gas jet system as described below.

b Reaction Wheels. Reaction wheels are very similar to momentum wheels, except that they operate at nominally zero angular velocity (they can rotate in both directions). They are useful in situations where cyclic manoeuvres are required, necessitating bi-directional changes in angular momentum, e.g., observational manoeuvres, etc. Reaction wheels are usually more massive.

c Cold Gas Thruster. A "Cold gas" system may be used to generate thrust by expelling gas (typically nitrogen or xenon) from a high pressure storage vessel, through a regulator and out through a nozzle. Such systems are useful for small orbit or attitude manoeuvres, including dumping momentum from wheels.

d Hot Gas Systems. A "Hot gas" system is similar to the above, except that the gas is burned or oxidised in a combustion chamber prior to being expelled, which results in a higher efficiency in terms of thrust to fuel mass. However, these systems are hazardous to handle in the spacecraft preparation phases and have significantly higher costs as a result. They should be avoided for small satellites if possible.

e Magnetic torquers. These offer one of the most attractive solutions for a small satellite because of their simplicity and low cost. A magnetic torquer is basically a coil that is driven by an electric current to produce a magnetic field which will then interact with that of the Earth to produce a torque. These coils can be implemented either as large diameter coils around the periphery of the spacecraft, or as small diameter coils wound around a long rod of ferro-magnetic material.

Magnetic torquers can be mounted orthogonally to provide a degree of 3-axis control and can be coupled to a magnetometer sensor to provide spin control. However, their use is always restricted by the strength and knowledge of the Earth's field in a particular orbit.

4.3.5 Orbit acquisition and control

In most cases, a small satellite will be injected into its final orbit by the launch vehicle and no additional propulsion system is required. However, for some missions it may be necessary to carry such a system to achieve a particular orbit which is not accessible directly by the launch vehicle.

Such "primary" propulsion systems could include a small solid rocket booster, or a hot-gas system similar to that used for attitude control, but with a more powerful thruster. Another option is an electric propulsion system which results in a highly efficient use of propellant, but only low-thrust systems are currently available; thus any orbit adjustment manoeuvre may take place over an extended time period, perhaps many weeks.

A further requirement could be for orbit maintenance to compensate for atmospheric drag effects, or for orbit trim manoeuvres, perhaps to station-keep with another satellite. These "secondary" propulsion manoeuvres would normally be accomplished by a hot-gas system, or by an electric propulsion system.

4.3.6 Power

The choice of a primary power source depends on the type of mission envisioned. For example: a short lifetime experiment could be performed using primary batteries with no recharge required. A long-life orbiting spacecraft (years) will require solar cells and rechargeable batteries. Another lower cost possibility is to employ only solar cells (i.e., no eclipse operation) with a primary cell (e.g., lithium) to prevent loss of memory data. Missions to the outer planets use radioisotope heat sources with thermoelectric converters and, normally, batteries to handle peak loads. This system is utilised where the solar energy diminishes as a function of distance. The goal of the power system engineer is to seek a system that is reliable, reasonably efficient, lightweight, compatible with the spacecraft/launch vehicle configuration, available on a reasonable time scale and low in cost. The technology needed for power subsystems is readily available at a low cost.

4.3.6.1 Solar Array

A solar energy system starts with a power input of about 1.36 kW per square meter at a distance of 1 AU from the Sun. Silicon solar cells convert this illumination to electricity at about 13 to 14% efficiency; gallium arsenide cells are also available and offer 18% efficiency but at about five times the cost. Solar cells are installed with packaging efficiency of about 85%. This energy is usually used to charge secondary batteries which provide power to meet those times when the spacecraft is eclipsed or during peak load demands. DC/DC converters provide the appropriate voltages to the spacecraft electronics.

Solar cells may be mounted on deployable panels or more simply mounted directly to the spacecraft body. Solar cell performance is influenced by the:

a spectral characteristics of the illuminating source,

b intensity of the illuminating source,

c solar cell temperature,

d illumination incidence angle.

Solar cells are covered with transparent slides of glass, quartz or sapphire with appropriate optical coatings. This cover slide serves two purposes:

1 to protect the cell from particle radiation,

2 to selectively reflect certain wavelengths of the solar spectrum to control cell temperature.

The angle of incidence illumination variations will affect the panel orientation or the body-mounted cell configuration. Shadow studies must be performed, and the power generated at all incidence angles must be understood in order to produce a power management plan.

4.3.6.2 Batteries

Batteries that can be recharged for many cycles are required for solar array configurations. In use today are nickel-cadmium cells with potassium hydroxide electrolyte. Nickel-hydrogen batteries are being introduced, but their bulk and cost currently make them unattractive for most small satellites

Primary batteries (e.g., lithium) are acceptable for short term missions, as a development step towards future missions, and where simplicity and high power density are desired.

4.3.6.3 Charge control

Charge control is required to prevent excessive overcharge of spacecraft batteries and to enhance their lifetime. One example is the simple voltage limiting shunt regulator which senses battery voltage and temperature and shunts the excess array current to external dissipating resistors.

4.3.6.4 Power conversion

Power conversion provides four major functions:

1 voltage/current transformation and regulation (70/85% efficient),

2 containment of severe electrical noise,

3 protection and command capability. An alternative, more suitable for Low Earth Orbits is the series regulator which can be adjusted to extract maximum power from the array at varying temperatures and radiation doses. This reduces the time needed to recharge the battery,

4 electrical ground isolation.

Power conversion may be performed centrally or within experiments and subsystems. It is worth noting that many readily available items of equipment run from single 28 V supplies.

4.3.6.5 Power distribution

Power is usually distributed to loads through power switching relays or transistors which are under command control. This unit can become surprisingly complex if there are several voltage rails and more than a few experiments. The command system, however, is "hard wired" to the main power bus as a critical non-switchable spacecraft electrical load. Various spacecraft systems can be turned on/off via the command/power switching system.

4.3.7 On-board data handling

An on-board data handling subsystem is required to process commands and to gather experimental and housekeeping data and to format it ready for transmission. The remarkable recent reduction in the power consumption, mass, volume and cost of electronic components allows very capable data handling systems to be quite easily constructed for small satellites by any group with general electronics knowledge.

The very simplest satellite might have a downlink communication channel consisting only of an analogue-to-digital converter selecting various channels in turn plus a number of bilevel status channels. These data are then formatted into a telemetry format compatible with the ground station equipment.

The command capability requires a command decoder based on digital logic. A further stage in sophistication is to provide an on-board computer with memory (solid state); this has the significant advantage of enabling "out-of-contact" operations, i.e., the use of delayed-action commands or programs and the storage of data from experiments for downlinking at a convenient time. Although suitable hardware for on-board computers is now very readily available, there is a need for considerable caution in the area of on-board software since complexity, cost and management problems can quickly escalate. In order to prevent a satellite failure due to software "bugs", the most basic satellite functions should not rely upon on-board software.

The choice of components for the data handling subsystem will be driven to a large extent by the orbital environment. In Low Earth Orbits the radiation dose is fairly benign and it is usually possible to use ordinary semiconductor integrated circuits at the lowest cost. On-board data stored in memories may need to be protected by coding techniques to alleviate cosmic-ray induced data corruption, but again very low-cost memories can be employed. If the spacecraft is to be placed in a severe radiation environment (e.g., GTO) then more expensive, radiation-tolerant semiconductor technologies (such as silicon-on-sapphire) will be needed for all but the shortest missions. The much longer procurement times (up to 2 years) and the restricted availability (e.g., export embargoes) should be considered for any "high-reliability" or "radiation-tolerant" component types. A recent promising technology for small spacecraft applications is the programmable-logic-array (PLA) which can significantly reduce the physical bulk of logic circuits and component count. Some PLAs currently available promise a high radiation tolerance.

Some form of electrical check-out equipment for the data handling subsystem is required. This is essentially a mini-ground-station. The most cost-effective means of obtaining this is to use standard personal computers which are also small and easily transportable.

4.3.8 Telecommunications

A radio-frequency (RF) telecommunications subsystem enables the transmission of telemetry data from the satellite and the reception of telecommands by the satellite. The currently preferred frequency band for most small spacecraft operations is S-band (2.2-2.3 GHz) since the original VHF/UHF allocations are now being phased out, except for amateur satellites. Transmitters, receivers, diplexers and general antenna designs are available already, some at low cost. For a large number of small satellite applications it will not be necessary to have ranging capabilities, thus allowing a simpler system. System link budgets need to be performed carefully to determine appropriate power and sensitivity figures compatible with the ground station.

The simplest satellites might have only a single antenna used for both receiving and transmitting functions: in this case a diplexer is required as well.

If S-band is the preferred frequency band for telecommand and telemetry, one must be aware that specific services (i.e., communication services) are assigned dedicated frequency bands.

4.4 Ground segment

The cost of mission operation represents a significant portion of the programme costs. The ground segment configuration (i.e., hardware, software) and the operational modes (i.e. complexity) have a definite influence on this segment cost.

The ground segment fulfils several functions:

- the operations include the status and health monitoring of the satellite, and the command preparation and validation,
- the tracking, telemetry and command (TT&C) functions are ensured by a TT&C station which ensures the communications with the satellite. The station may be combined with the operation centre,
- the mission data are transmitted to the ground via satellite telemetry. The data have to be transferred from the operation part of the ground segment to the user before being processed.

The following are some general considerations concerning the ground segment configuration and operation.

4.4.1 System modularity

In exactly the same way as satellite costs can be significantly reduced by greater use of common modularised subsystems, ground system configurations can also be modularised. Instead of developing individual EGSE (Electrical Ground Support Equipment) and Ground Segment equipment for every instrument and/or satellite, there are now being developed standardised off-the-shelf equipment that can subsequently be customised to the individual needs, at much lower cost. Within the ground system itself, computing power is sufficient these days to combine the tasks of TT&C into a single low-cost workstation. Of even more potential benefit is the reuse of previous mission software for many of the data analysis functions. As an example of this, the data analysis software for the Jet-X Instrument, which is scheduled to fly in 1995 as part of the Spectrum-X mission, is almost entirely based on software developed for the ROSAT mission launched in 1990. This scenario alone has cut the software development cost for this mission by a factor of 2.

4.4.2 National facilities

Probably the greatest potential for cost reduction of the ground system is by making greater use of national facilities. Agency facilities are clearly required for large (manned and unmanned) missions, but are often too cumbersome and inflexible for small missions. It has usually proven far more cost-effective to employ national facilities - ideally utilising just a single ground station. For instance, the two European AMPTE spacecraft were controlled from single stations in Germany and England, respectively. The UK station was developed at very low cost by updating the original IRAS control centre to the requirements of the AMPTE mission. Although new software and operational procedures were necessary, very little new hardware was required. As an example of this, the 12 m S-band tracking station and control centre at the UK Rutherford Appleton Laboratory can be used for TT&C on an "as required basis", the operations staff being redeployed to other tasks during non-active satellite periods, thus cutting down significantly the running operations costs even for satellites producing many hundreds of Mbits/day. Similarly for low-cost satellites producing kbits rather than Mbits of data, it is now possible to receive data using rooftop antennas and command/receive using desktop PCs.

4.4.3 Reliability versus cost

For larger missions, it has always been normal practice to maximise the reliability of the ground system despite the associated increase in cost. This is not unreasonable for man-rated missions, but is almost always an unnecessary expense for most other missions. There is a very sizeable potential reduction in cost to be obtained by accepting just a small reduction in system reliability. It is proposed here that it should be agreed "up-front" that a small percentage (perhaps 5%) of satellite passes can be lost through ground system outage. This may (though not necessarily) lead to some data loss, but even so a data loss of a few percent is not usually significant. By agreeing to this reduction in reliability, the level of hardware (and perhaps software) redundancy required in the ground system can be reduced, and hence the cost is lower. Likewise, if the number of passes required per day to support the mission operation can be reduced through a slightly less than optimal coverage program, the cost of operations also falls.

4.4.4 Data availability

There is no doubt that for all missions it is essential to be able to process some subsets of the data in Real-Time and/or Near Real-Time. However, the less data that has to be processed in this manner the simpler the immediate ground system complexity becomes. For the majority of small satellite missions, it should only be necessary to process instrument/bus health data as a matter of urgency, thus decoupling the task of satellite "operations" from that of off-line data processing.

4.4.5 Data transfer

There are basically two different methods of transferring data from the operations part of the ground system to the user or data processing centres. The first (and most expensive) is via one of the many space or terrestrial data links. This is the common route for most satellite data and gets the data to the end user very quickly. However, it is more often the case that although the end user likes to have this data "as quickly as possible" it is not often an absolute necessity. In this case the alternative route via mailed magnetic tapes/optical disks can be just as satisfactory; possibly some (small) percentage of the data can still be transmitted via a lower band (and lower cost) data link; it is important to try to avoid the exclusive dedicated use of these links as this too adds to the cost.

4.4.6 Data access

There are as many different philosophies regarding methods of data access as there are concerning designs of satellites. Generally however, the most cost efficient and practical method is the concept of a Centralised Data Handling Facility which is accessible by users over local data networks. This concentrates the pipeline data processing in one place, whilst allowing the individual users both to develop their own specialised software and to make full use of centrally developed software.

4.4.7 The special case of satellite constellations

Constellations of small satellites in low Earth Orbits are currently under consideration, mainly for commercial communications purposes.

The operations control centre has all conventional control centre functions, but with some important extensions, such as implementation of the initial satellite phasing and phase keeping within prefixed tolerances.

The telemetry and command station is conceived traditionally with the important task of tracking each satellite in turn. In fact the constellation should be designed to exhibit an observation repetition cycle (time symmetry) where both traffic data and observed orbital arc distribution are satisfactory for every satellite to keep all services at standard level.

The Communication Mission Centre will not only include the user resources assignment and communication, but also the delicate function of monitoring actual utilisation of the resources.

The Communication Master Station is devoted to communicate operational plans to users, whereas the satellites have to relay also their status information and the user resources utilisation to the Operation Control Centre and the Communication Mission Centre.

The major and, at the same time, critical aspects lie in managing a true multisatellite configuration, planning and monitoring resources for users which may be much different to each other.

5. TYPICAL MISSIONS

There are five types of mission that show promise for Developing Countries. These include Imaging, Polar orbiter, Plasma Physics Space Science Constellation, Technology Demonstration and Store-and-Forward communications.

A brief discussion of these five missions follows.

5.1 Imaging

The basic sensor is a Charge Coupled Device sensitive in the visible spectrum. This device is employed as an imaging camera. Appropriate lenses are commercially available. A filter wheel is placed in front of the camera to enable spectral wavelengths within the CCD sensitivity range to be samples. Rutherford Appleton Laboratory have outlined a simple imaging experiment which sampled the 1μ spectrum with an array of 600 x 400 pixels at a resolution of 11 km (visible to near IR).

The choice of orbital inclination and altitude depends on the geographical location of the interested country and the region to be observed. For example, countries located in the equatorial regions would be observed on every pass from a spacecraft in an equatorial orbit. A polar orbit would be the choice for countries at high geographic latitudes; mid-latitude countries could consider alternate inclinations. Tables 9 and 10 provided hereafter outline a possible baseline system, some enhancements to the baseline, and an alternate system.

5.2 Polar orbiter

The polar orbit presents the opportunity for worldwide imaging (weather, forestry and crop surveys, etc.) auroral studies, magnetospheric physics, etc. A spacecraft in this orbit should be a versatile platform that could evolve technologically as a Developing Country's capabilities mature. This spacecraft could ultimately perform quite complex missions. There is a near-polar orbit that is Sun synchronous in which illumination conditions range from 100% to about 60%, depending on the time of day of launch.

Table 10 depicts some possible spacecraft designs for this orbiter.

5.3 Space science (plasma physics) constellation

Collaborative science can be performed by multiple spacecraft deployed by a single launch vehicle or multiple launches. Different combinations of inclinations and altitudes provide time coherent sampling of the natural environment. The AMPTE program, which is well published in open literature, is an excellent example of this type of activity. This could be a multinational effort with shared costs; the benefits could be very important. It is a chance for nations to cooperate, understand and work with cultural differences and achieve significant results. The spacecraft alternatives described in Tables 1 and 2 in section 2.1 are equally applicable here with the addition of propulsion to vary the orbit parameters. Existing worldwide ground stations could be employed to support such a mission.

5.4 Technology demonstrations

This type of mission serves to introduce new or enhanced capabilities. The technology spacecraft should possess extensive telemetry for performance evaluation and diagnostics. New technology and subsystems can receive extensive evaluation on orbit before being committed to operational use. Some possible technology experiment examples follow:

- surface coatings,
- solar cells and cover slides,
- spacecraft component parts,
- new mechanisms (deployable booms, antenna, ejectable covers),
- batteries,
- materials (composites, etc.),

and, of course, major new spacecraft subsystems. Many different spacecraft configurations can be used as test beds, with configurations shown in Tables 9 and 10. Once again, mission parameters can be varied depending on what is being tested. At 1 500 km altitude, the Earth's radiation belts become a major player in spacecraft component performance. Solar cell performance over a given lifetime is a consideration. Some surface coatings change their properties in the presence of UV from the Sun. Surfaces erode in the ram-direction due to the presence of atomic oxygen in very low orbits. These are a few examples of technology studies required to assure long life in orbit.

5.5 Store-and-forward communications mission

A simple but effective means of communications, especially to remote areas, is by means of store and forward. This is accomplished by uploading messages to a spacecraft which stores them in its memory. Solid-state memory technology has progressed to the point where reasonable capacity and cost make this a challenging competitor with tape recorders. As the satellite traverses its orbital track, the message is "dumped" via an RF system to an appropriate receiving station within the satellite's RF footprint on the earth. A "bent pipe" capability could be utilised for communicating between two remote stations that have the spacecraft in RF view simultaneously. "Bent pipe" is a real-time system where the satellite acts as an amplifier and relay station.

Again, there are many optional spacecraft configurations that are suitable for this type of mission. The spacecraft designer should always remember that the simpler the system, the better, the more reliable and the least costly it is.

Table 9: Example Space Configurations for an Imaging Mission

IMAGING	BASELINE SYSTEM	INCREASED CAPABILITY	ALTERNATIVE (SYSTEMS)	BASELINE PERFORMANCE	INCREASED PERFORMANCE EXPECTATION	ALTERNATIVE SYSTEM PERFORMANCE EXPECTATION
ORBIT & ALTITUDE	DEPENDENT ON GROUND COVERAGE REQUIRED					
POWER	SOLAR CELLS & NICKEL CADMIUM BATTERIES	ORIENTED SOLAR ARRAY		ADEQUATE	MORE POWER LESS SURFACE AREA LESS WEIGHT	
ATTITUDE CONTROL	ELECTROMAGNET FOR CAPTURE, GRAVITY GRADIENT FOR OPERATIONS. HYSTERESIS DAMPING	MOMENTUM WHEEL FOR YAW STABILITY HYSTERESIS DAMPING	3-AXIS REACTION WHEELS. MAGNETIC TORQ. MOMENT. DUMP	<10° OFF LOCAL VERTICAL	1° - 3° OFF TO LOCAL VERTICAL	0.01° BUT REQUIRES INCR. POWER
ATTITUDE DETECTION	MAGNETOMETER & DIGITAL SOLAR ATTITUDE DETECT	HORIZON SENSORS DSADS		1 MIN. DSAD 1 DEG MAGNETOMETER	1 MIN DSAD 0.1 DEG HORIZ.	
STRUCTURE	ALUMINIUM & ALUM. HONEYCOMB			HIGH STRENGTH TO WEIGHT RATIO		
THERMAL CONTROL	PASSIVE; SURFACE COATINGS. MULTI-LAYER INSUL.	ACTIVE; LOUVERS		PAINTS & MLI ARE ADEQUATE	MINIMISE THERMAL EXCURSIONS	
TELEMETRY	S-BAND, DIGITAL. HOUSEKEEPING & DATA TELLTALES	SOLID STATE MEM. OR TAPE RECORDER PERMITS REMOTE SENSING		ACCEPTABLE	RECORD MORE DATA (COST INCR.)	
COMMAND	S-BAND DIGITAL. RELAY CMDS FOR PWR TRANSFER DATA COMMANDS	COMMAND MEMORY DELAYED EXECUTION OF STORED CMDS		ACCEPTABLE	WORLDWIDE OPERATIONS	
ANTENNA	OMNI-DIRECT BEFORE CAPTURE. DIRECTIONAL AFTER CAPTURE FOR OPERATIONS			ACCEPTABLE		
PROPULSION	NOT REQUIRED			NOT REQUIRED		
INSTRU-MENTS	CCD WIDE < FOV	INFRA RED SENSORS. ADD NARROW FOV VISIBLE		MINIMUM REQUIRED	HIGHER RESOLUTION BROADER OBSERVING SPECTRUM	
DATA RECOVERY	REAL TIME	REAL TIME & MEMORY READOUT		REQUIRES STATION IN VICINITY OF DOWNLINK	EXTENDED SYSTEM UTILISATION	
GROUND STATIONS	WITHIN LINE OF SIGHT OF AREA BEING OBSERVED	ONE REQUIRED FOR CMD & TM MGMT		ADEQUATE	CENTRAL LOCATION FOR DATA ACQUISIT. & CONTROL	
TRACKING	BEACON - FOR ORBIT DETERMINATION & STATION ALERTS	MAY REQUIRE MULTIPLE SITES		ADEQUATE	IMPROVED POSITION ACCURACY	

Table 10: Example Configurations for a Polar Orbiter

POLAR Sun-SYNCH.	**BASELINE SYSTEM**	**INCREASED CAPABILITY**	**ALTERNATIVE SYSTEM**	**BASELINE PERFORMANCE**	**INCREASED PERFORMANCE EXPECTATION**	**ALTERNATIVE SYSTEM PERFORMANCE EXPECTATION**
ORBIT & ALTITUDE	$i \approx 99^\circ$ CIRCULAR					
POWER	SOLAR ONLY MODE SOLAR BATTERY ORIENTED ARRAY	SHUNT REGULATOR & DISSIPATIVE FOR DUMPING EXCESS POWER	SOLAR PANELS OR BODY MOUNTED CELLS-ORIENTATION DEPENDENT	ADEQUATE	BETTER INTERNAL TEMPERATURE CONTROL	MAY PRESENT SOME DESIGN PROBLEMS
ATTITUDE CONTROL	GRAV. GRADIENT MOMENTUM WHEEL FOR YAW ASSIST. HYSTERESIS DAMP ELECTROMAGNET FOR CAPTURE		SPIN STABILISED	1-3°		0.1° DYNAMIC BALANCE REQUIRED
ATTITUDE DETECTION	DIGITAL SOLAR ATTITUDE DETECT & MAGNETOMETER	HORIZON SENSORS AND DSADS		1 MIN. DSAD 1 DEG MAGNETOMETER	1 MIN DSAD 1 DEG HORIZ. SENS.	
STRUCTURE	ALUMINIUM & ALUM. HONEYCOMB		MAXIMUM USE OF NON-MAGNETIC/ HYSTERESIS MATL TO MAINTAIN SPIN	ACCEPTABLE		MAINTAIN SPIN WITHOUT REACTION JETS
THERMAL CONTROL	PASSIVE; SURFACE COATINGS. MULTI-LAYER INSULATION	POSSIBLE CONDUCTIVE PATH TO EXTERNAL RADIATORS		a/e CONTROL BY PASSIVE SURFACE COATINGS & MLI	MORE OPERATIONAL FLEXIBILITY	
TELEMETRY	S-BAND, DIGITAL HOUSEKEEPING & DATA TELLTALES	ADD MEMORY - SOLID STATE OR TAPE RECORDER		ACCEPTABLE	COMPLETE ORBITAL DATA ACQUISITION	
COMMAND	S-BAND DIGITAL RELAY CMDS, FOR PWR TRANSFER DATA COMMANDS	CMD SYS. MEMORY PERMITS DELAYED EXECUTION OF STORED COMMANDS		ACCEPTABLE	MORE OPERATIONAL FLEXIBILITY CAN DUTY CYCLE IF REQUIRED	
ANTENNA	OMNI-DIRECT BEFORE CAPTURE. DIRECTIONAL AFTER CAPTURE FOR OPERATIONS		MULTIPLE <u>OR</u> SPIN AXIS LOCATED	ACCEPTABLE		MAY EXPERIENCE FARADAY MODULATION. NON-ORIENTED MAY INCREASE RF POWER
PROPULSION	REQUIRED IF EQUATOR CROSSING TIME IS TO BE MAINTAINED			NOT REQUIRED		
INSTRUMENTS	UV IMAGERS ELECTR. & PROTON DETECTORS MAGNETOMETER		PERMITS SCANNING & SECTORING	PLATFORM CAN ACCOMMODATE A VARIETY OF SENSORS		GREATER SCIENCE YIELD FROM INSTRUMENTS
DATA RECOVERY	REAL-TIME FOR HIGH LATITUDE STATIONS	MEMORY STORE & DUMP		LOW LATITUDE STATIONS PASSES IN GRPS OF 3 = TWELVE HRS CRTS	WORLDWIDE SAMPLING	
GROUND STATIONS	SINGLE SITE FOR COMMAND & CONTROL MULTIPLE FOR TM	MEMORY ADDITION MAKES SINGLE SITE OPERATIONS POSSIBLE		ACCEPTABLE	ECONOMICAL	
TRACKING	BEACON - FOR ORBIT DETERMINATION & STATION KEEPING					

6. CONCLUSIONS

6.1 General

The feasibility of space flight and the validity of its achievements can no longer be questioned, but only a fraction of the world is involved in these activities. Small satellites offer the prospect of extending the opportunity to participate in space activities to countries and individuals throughout the world. In so doing, they provide the chance for local industry to improve its technology base. The development of this industrial infrastructure is accomplished by the accumulation of internal expertise and the acquisition of organisational and management skills. This should contribute to the overall development of the country, resulting in better communications and education, improved health, emergency rescue and disaster relief, and optimum control of the country's resources, especially its agricultural output.

Unless there is an existing communications infrastructure, satellite systems are the only truly cost effective means for information gathering and dissemination. Satellite-based audio-visual media are the best answer to the illiteracy problem, offering interactive processes, immediacy, visual power, and simultaneous delivery to the entire country. Satellite remote sensing can provide operational data for the monitoring and management of both land and ocean resources, including information on weather, droughts, floods, vegetation, forestry, soil conditions and water resources. The appropriate use of satellites needs to become an integral part of each country's overall planning in accordance with their priorities and their technical and financial capabilities.

Although each country has its own unique problems to solve, there are a number of ways to help move toward space activities, for instance centre space activities around the local university; provide the university with training courses in space science and engineering; obtain technical assistance from foreign universities and research institutions; and inaugurate no-exchange-of-funds co-operative agreements with established space agencies (for example, for launches; for tracking, command and data acquisition support; for use of test facilities; for training; and/or for sharing of data).

6.2 What to do next

Advice on proceeding with a small satellite project can be obtained from a number of sources. Major Space agencies and their technical divisions are generally open to requests for information (eg. on launch opportunities) and to suggestions of co-operative projects (eg. in scientific fields). Within more limited domains, a similar situation may be encountered by addressing universities with a record of space activities.

As this report shows, the International Academy of Astronautics is ready to act to stimulate the development of small satellite systems. In the present report, management advice and technical information on the major elements of such a system have been collected to provide initial guidance.

On a more basic, technical plain, the potential for student exchanges and collaborative educational projects with universities already established in the field must be mentioned. In addition, major aerospace professional organisations, like the AIAA, periodically schedule courses both on such system aspects, as well as on more detailed technical issues. Finally, several books on satellite systems aspects have recently appeared that can be useful to provide the necessary background to managers, project scientists and engineers. Some of these books are included in the list given in Appendix 7.1.

6.3 Recommendations

In view of both of the benefits and of the technical and economic feasibility of small satellite missions, the following recommendation are made:

- Governments and the research institutions of all countries, but in particular of the developing countries, are urged to study, undertake, and support small satellite programs for research, educational, and applications (eg. remote sensing, communications) purposes, in accordance with their current technical and financial capabilities;
- the industrialised countries should take the lead in gathering and disseminating information on the significance and importance of astronautics, beginning with, but not limited to, small satellite systems;
- the developing nations should undertake to accede to, and to increase, such information;
- given the attractiveness of space activities, particular encouragement should be given by the industrialised countries to projects that provide education motivation, with special attention to spacecraft realised mainly for engineering purposes in a University environment;
- established space agencies should consider the option of implementing technical assistance programmes to promote development of space capabilities at foreign universities and research institutions; such programs could be aimed at dispensing technical advice, or providing external reviews;
- co-operative agreements need to be encouraged that support the development of new national satellite programs without exchange of funds, eg. by having the supporting agency provide the flight opportunity, supply a part of the payload, allow the use of testing facilities, or make available existing ground stations for data collection or TT&C purposes;
- an indirect way to provide support for third party programs is for established agencies to develop or procure, as part of their own small-satellite program, low-cost components that the manufacturer can easily export;
- launch opportunities for small scientific and civilian applications satellites should be made available by the operators of launch systems at reasonable economic conditions;

- adequate consideration should be given to the desire of countries developing small satellites but not possessing national launch systems, to be associated in some form with the preparation of launch systems, eg. by hosting an airborne system, providing components or upper stages;

- raw data from Earth observation satellites should be made available on a non-discriminatory basis for research and civilian applications, to all countries;

- remote sensing data utilisation training programs should be intensified, to enable more effective use of these data, and by this way the identification of both specific national needs and benefits;

- studies should be made to support investments in ground stations, which can today exploit inexpensive commercial microcomputers, to enable local use of satellite data, eg, to prevent droughts by proper management of watershed resources;

7. APPENDICES

7.1 References

Michael D. Griffin & James R. French (1991). Space Vehicle Design. AIAA Education Series, Washington.

James R. Wertz & Wiley J. Larson, Eds. (1990). Space Mission Analysis and Design. Kluwer Academic Publishers, Dordrecht.

Peter Forescue & John Stark, Eds. (1991). Space Systems Engineering. Wiley Press.

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