VIKING AND MAILSTAR
TWO SWEDISH SMALL SATELLITE PROJECTS

Mr Sven Grahn
Chief Engineer
Head, System Design Dept
Space Division
Swedish Space Corporation

ABSTRACT

The VIKING Scientific Satellite launched piggyback on Ariane in February 1986 collected magnetospheric data for 444 days. The project was highly successful and of low cost. The key to low cost and high performance lies in a careful formulation of mission requirements. Costly increases often come from secondary or derived requirements, i.e. requirements which optimize performance or scientific return. To squeeze out a few more per cent of science data may perhaps double the cost. The paper describes examples of how such cost traps were avoided in the VIKING project.

MAILSTAR is a low-orbit store-and-forward satellite communications system conceived by the Swedish Space Corporation. Phase B studies have just been completed and show that it is possible to provide a high reliability public telecommunications service by using small satellites. The satellite concept is described as well as different launching concepts, including a piggyback arrangement on the Chinese Long March 2 rocket.

VIKING

Sweden's first satellite, VIKING, was launched on February 22, 1986 as a piggyback payload on the Ariane 1 rocket that orbited the French remote sensing satellite SPOT. The satellite conducted a very successful magnetospheric research mission until May 12, 1987. The VIKING project was managed by the Swedish Space Corporation (SSC) under contract from the Swedish Board for Space Activities, the
government space agency. SSC is a government-owned organization responsible for the execution of Sweden’s space program. The satellite was developed by SAAB Space with Boeing Aerospace as a major subcontractor.

The project aimed at gathering new insights into the formation of Aurora Borealis by making a complete set of plasma physics measurements in the magnetosphere at an altitude of 2 earth radii and on magnetic field lines connected to the auroral oval. Fig. 1 summarizes the key features of the project and Fig. 2 shows the configuration of the satellite.

Fig. 1 Summary of the VIKING Project

<table>
<thead>
<tr>
<th>International:</th>
<th>1986-19 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designator:</td>
<td>February 22, 1986 from Kourou on Ariane V 16 together with the SPOT 1 satellite</td>
</tr>
<tr>
<td>Mass:</td>
<td>Lift-off mass 520 kg, dry mass 286 kg 60 kg science payload</td>
</tr>
<tr>
<td>Initial Orbit:</td>
<td>814-13530 km, 98.6 deg inclination, 261.2 min period</td>
</tr>
<tr>
<td>Size:</td>
<td>Octagonal disk 0.5 meter high, 1.9 meter in diameter.</td>
</tr>
<tr>
<td>Power:</td>
<td>80 Watt solar array power, 114 Watt peak power using a 12 Ah Ni-Cd battery.</td>
</tr>
<tr>
<td>Attitude:</td>
<td>Quarter-orbit magnetic torquing of the 3 rpm cartwheel spin vector. Magnetometer-commutated spin cell for spin rate control.</td>
</tr>
<tr>
<td>Telemetry:</td>
<td>2.5 Watts RF power on 2208.163 MHz at 54.6 kbps (49.6 kbps of science data)</td>
</tr>
<tr>
<td>Telecommand:</td>
<td>S-band uplink on 2033.5 MHz</td>
</tr>
<tr>
<td>Tracking &amp; Ctrl:</td>
<td>ESRANGE, Kiruna, Sweden (67.89 N, 21.11E) Orbital parameters determined from ranging data.</td>
</tr>
<tr>
<td>Science payload:</td>
<td>V1 Electric Field Experiment, Royal Institute of Technology, Stockholm, Sweden V2 Magnetic Field Experiment, Johns Hopkins Univ., USA V3 Energetic Particle Experiment, Institute of Space Physics, Kiruna, Sweden V4 Wave Experiment, Uppsala Ionospheric Observatory, Sweden and the Danish Space Research Institute V5 Auroral Imaging Experiment, University of Calgary, Canada.</td>
</tr>
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The satellite carried four 40 meter long radial wire beams and two 4 meter long axial beams. These beams supported V1 and V4. In addition there were two short stiff radial beams for the V2 and V4 sensors.
Sweden's first own venture into space had high scientific ambitions in the field of geocosmosphysics, traditionally a very strong area of space science in Sweden. The project also had the purpose of building a technology base in Sweden for carrying out the design and operation of space systems. These ambitious goals had to be carried out within a very tight fiscal envelope.

Such constraints made it necessary to make some rather difficult technical and scientific trade-offs. It is the story about these trade-offs and how they eventually led to a very successful mission that the first part of the paper intends to convey.

Defining the Scientific Mission

When a small nation sets out to make its first scientific satellite it is important to choose the scientific objective carefully. If one chooses an objective which requires the satellite to make a long-duration mapping of certain phenomena one arrives at completely different technical trade-offs than with an "exploratory" objective. An "exploratory" mission, in which one wishes to make a concentrated assault on some specific scientific problems, does not require a satellite which lasts for many years. It becomes possible to trade platform reliability and complexity against scientific payload.

The scientists did indeed choose an "exploratory" objective for VIKING and even adopted a "campaign" mode of operating the science instruments. During periods of a few weeks all the investigators gathered at the ground station and ran a continuous scientific seminar. The satellite was used to test the theories that were put forward in the seminar room next to the Operations Center. Such a mission philosophy permitted some rather interesting technical trade-offs.
Adapting to the Launch Opportunity

During the first studies of the VIKING project in 1978 we looked for an orbit that would give maximum access to the altitude region 10,000-15,000 km. The first orbit we studied would have an apogee at about 15,000 km and a perigee at whatever altitude that a piggyback launch opportunity would provide. It was clear from the beginning that we could not afford our own launch vehicle. We had to ride piggyback into space. The inclination that we felt was most useful was 63-65 degrees, which would permit the apogee to be fixed over the northern hemisphere, thereby permitting all the science data gathering to take place within view of our ground station at Kiruna in the northern part of Sweden.

This inclination was studied because we were considering using a Soviet launch vehicle at that time. Many Soviet launches use such inclinations.

So, this kind of orbit seemed ideal. Therefore considerable scepticism was felt by the project team when the use of a piggyback launch opportunity on the planned launch of SPOT by an Ariane rocket was introduced.

The SPOT/Ariane launch would put VIKING into an i=98.7 deg circular orbit at 822 km altitude. By firing an on-board motor the required 15,000 km apogee would be achieved. However, for this orbit the argument of perigee would not be fixed. In fact, it takes two years for the apseline to rotate once around the earth (Fig. 3). This at first seemed quite unsuitable for our mission.

Fig. 3 Rotation of the Apseline of the VIKING Orbit
However, orbit simulations showed that the motion of the apseline offered an opportunity to scan over different regions of the magnetosphere and magnetic latitude. We found that the orbit would permit the study of the interesting regions of the northern polar magnetosphere for about 8 months before the apogee had drifted too far south.

Since the mission was designed to be exploratory, i.e. most scientific questions would "receive an answer" within a few months after launch it was decided to adopt 8 months as the design lifetime of the satellite. We assigned a rather arbitrary number of 80% as the analytical probability for satellite survival during these 8 months.

A piggyback launch usually severely limits the satellite mass and/or volume. This was also the case for VIKING, especially in terms of satellite height. The volume available to us between the Ariane third stage payload adapter and the SPOT satellite was only 0.5 meters high but about 2 meters in diameter (Fig. 4).

![Fig. 4 The VIKING/SPOT Piggyback Arrangement](image)

This naturally put a limitation on solar array area, which more or less dictated the power budget of the satellite. We had adopted a design rule of having only bodyfixed solar panels. Mission analysis showed that the whole science payload could operate for 80 minutes on every orbit. 180 minutes could be achieved on some orbits if idle orbits
were inserted before and after such a long-duration data taking.

The bottom line of the mass budget of the satellite was rather easy to determine. The Ariane 1 had 550 kg of spare capability for the SPOT 1 launch. To get VIKING's apogee up to 15,000 km, and assuming a gross weight of 500 kg, about 230 kg of solid rocket propellant is needed. Thus the dry weight of the satellite had to be roughly 270 kg. (Actually it was 286 kg and the required propellant mass fits very well with the STAR 26 C motor in the Thiokol rocket motor catalogue!)

One could then rather quickly estimate the mass of the structure and essential subsystems and hence arrive at the science payload mass. The mass of the science payload could be traded off against redundancy in the basic subsystems of the satellite. If one did not wish to trade science payload against redundancy the only remaining alternative was to reduce apogee, and thereby compromising the scientific objectives.

Well, the apogee requirement was reduced slightly (it was required to exceed 13,000 km), but the crucial decision was made to fly the mission with a "single-thread" system, i.e. no redundancy in the satellite. This decision was possible because we had adopted an 8 month lifetime and analysis showed that a single-thread system would meet the 80% reliability requirement.

However, reliability calculations do not make the system engineering manager sleep well at night. Only a quality conscious team of manufacturers does. SAAB and Boeing were such a team.

**Suppressing "Nice-To-Have" Requirements**

So, the Ariane piggyback opportunity had led to trade-offs meaning an 8 month design life, a single-thread system and 80 minutes of data-taking per orbit.

This was a good start towards achieving a low-cost high-yield mission. However, what now remained was to combat the tendency to optimize every aspect of the system. This is what the engineer is trained to do. But in this tendency lurks the danger of cost increases which may threaten the project (if it gets too expensive it may be cancelled).

The tendency to make an optimum mission and system design I sometimes call the "secondary requirements trap". Secondary, "derived" or "nice-to-have" requirements are like the octopus' arms in Fig. 5. You have to chop them off as soon as they appear through the door, otherwise they will catch you! Let me give you some examples from the VIKING project!
Defining the "Mission Target". The region of maximum scientific interest (or "mission target") was defined as the altitude range 8,000-15,000 km, 60-80 degrees invariant latitude, local time at the field line footprint=18-24, season=October 1-April 1 (see Fig. 6). The orbital parameters of the VIKING orbit should be optimized to maximize the time spent in this four-dimensional box. The boundary condition was naturally the 98.7 deg, 822 km initial orbit with the ascending node at 2230 local time and a launch date at any time of the year!

The four-dimensional box could be reduced to constraints for two orbital parameters. One of these was a requirement for defining the initial argument of perigee so that the apogee would culminate over the north pole during the time Oct-March. The other requirement derived from the four-dimensional box was to control the local time of the ascending node. In fig. 7 the field-line footprint requirement has been converted into ascending node time.
* Local time of field-line footprint: 1800–2400 hours
* Season: October 1–March 31

**Fig. 6 Four-dimensional "Mission Target"**

Line A describes the orbit provided by Ariane and the mission could start at any point on this line. The line B shows the motion of the local time of the node in the operational orbit of VIKING (822–15,000 km i=98.7). How to maximize the length of B falling within the "Mission Target" marked in fig. 7?

**Fig. 7 VIKING "Mission Target" Expressed in a Date vs. Node Orientation Diagram**
Well-trained and enthusiastic satellite controllers with a mandate to take action when needed are indeed an insurance against premature mission failure!

The "Resource Envelope" Concept - An Example. There was no spare VIKING satellite, only a protoflight model, and no immediate follow-up mission planned. So, why not play it safe and put in as much radiation shielding as possible to make the instruments function as long as possible? Well, that may seem like the clever thing to do, but we adopted a different philosophy. System Engineering decided that there could be no general rule, the scientists had to decide among themselves and sometimes each instrument designer made his own choice.

For example, some instruments would yield significant results after having been in operation only for a few days or weeks while other instruments needed a longer time to "reap the harvest". Of course the whole complement of instruments worked together and should work as a system for a certain minimum time.

As it turned out each instrument designer chose his own way. One designer put in minimum shielding and used the extra mass to have more functional features while another played it safer and put in 5 mm of Al as a shield.

Thus, the allocation of shielding mass between experiments was never something that System Engineering worried about. This was all handled within the group of investigators. System Engineering had given the scientists a "resource envelope" within which they could make their own trade-offs.

The resource envelope contained a total mass, power and data rate for the overall science payload. No margin was given for this envelope. It was an absolute, never-to-be-trespassed boundary! This principle generated a lot of ingenuity in the design and operation of the science payload and contributed to the very efficient mission and it gave a stability to the system design work which contributed to the low cost.

Of course, if you set up such an absolute "envelope" you cannot cheat - System Engineering has to be quite open about the fact that there are margins, but explain that he keeps the margins in his own pocket to hand out to subsystems and payload if really serious problems turn up. This kind of "local self-government" requires mutual trust between scientists and system designers - absolutely!
Where We Did Not Compromise

My description of the trade-offs made in the system design of VIKING may have given the impression that we always had to yield to fiscal pressures and compromise mission safety and scientific return at every technical decision point.

This was definitely not so. We took some calculated risks, I admit, but the really mission-essential requirements were adhered to strictly. For example the satellite was extremely electrostatically clean. We had conductive cover glass on solar cells and conductive thermal control paint and thermal blankets. We even put a slightly conducting "radome" on the log-spiral radio antennas in order to ascertain that the satellite body made good electrical contact with the space plasma. In this way the satellite would cause the minimum disturbance to the plasma environment.

Another scientific requirement that was strictly enforced was that of maintaining a high data rate. This was absolutely essential to transmit wave spectra, auroral images and other data streams. We used as much RF output power as possible without upsetting the DC power budget. When that did not suffice we introduced convolutional encoding (only used by deep space probes at that time) and a Viterbi decoder on the ground. This modification cost nothing in the satellite but maybe a hundred thousand dollars in ground equipment. This bought us a 5.6 dB better link and fulfilled a mission-essential requirement!

The risk of not having redundancy had to be compensated for. Therefore equipment and subsystems qualified and flight proven in other programs were used to the maximum extent. In addition the prime contractor SAAB Space enforced very strict quality assurance procedure for critical subsystems such as the S-band transponder and other parts of the TT&C system.

Finally, I wish to show a visible example of VIKING's "scientific harvest". A UV image of the auroral oval (Fig. 9). VIKING was able to produce such an image every 20 seconds, a vast improvement over earlier satellites.
The obvious answer is to let VIKING stay in the low 822 km orbit until one has reached the region R. Then the motor would be fired and the mission would proceed along a line C with the same slope as B. The point along the orbit where the motor would fire controls the argument of perigee and by using this strategy full control over the orientation of the orbit would be achieved for an arbitrary launch date.

The drawbacks with this strategy are that you have to keep the rocket motor in storage in space for a long time and the risk of mission loss is increased. You cannot roll out booms and remove sensor covers before motor ignition and therefore there would be a long period of no scientific data. Also, it would be necessary to have stored-command capability and deployed antenna booms which could withstand the high-g rocket impulse. In addition, the thermal control system would have had to be designed for two cases, the spin vector in the orbital plane and perpendicular to the orbital plane. The simple thermal concept with a "cold" and a "hot" side of the satellite would not have been possible.

This scheme was never adopted for one very simple reason - the risk of losing the mission while waiting for motor ignition during months was not worth taking. It was better to get some data quickly even if the orbit orientation was not optimum. So, we decided to fire the motor on the third orbit by timer control and there would be no communication with the satellite from lift-off until after the motor had fired and antenna booms could be safely deployed. (Thus, the mission proceeded along line B in Fig. 7.) We also deleted the requirement for stored commands. With the apogee over the north pole we had plenty of contact time on every orbit and only real-time control was used.

The decision to fire the motor immediately was essentially made by the scientists. I concocted the optimized strategy and presented it to the scientists to see how die-hard the requirements for an optimum orbit was! I got my answer. We then used only a varying argument of perigee to maximize the time within the four-dimensional box. Another boundary condition was added to the mission design; but a very wise and cost-saving condition! Another octopus’ arm chopped off!

Protecting the Power System. The thing we feared most in the operation of the satellite was to destroy the battery. Solar panel power was only half of the peak load with all experiments turned on. Protecting the battery became a real obsession with the Flight Operations crew. Since we only had one ground station, losing contact with the satellite while there was full power load on the bus would be dangerous.

Such an unfortunate situation could appear either as a result of an operator error; forgetting to switch off the
payload and transmitter before LOS, or because of a failure in the command up-link transmitter.

Therefore the satellite had an amp-hour meter which monitored the state-of-charge (SOC) of the battery and switched off non-essential loads in case the SOC dropped too low. Therefore we did not need to invest in a redundant uplink transmitter on hot standby. This saved a not insignificant sum in the project.

This all sounded safe, but as the mission proceeded the amp-hour meter could not be used as intended and we were left with no automatic protection against discharging the battery! And, as stated by Murphy's Law, we had a failure in the 1 kW uplink transmitter!

The uplink transmitter power suddenly started dropping during a middle-of-the-night pass when the satellite was operating at maximum power drain. Within a few minutes the transmitter power had dropped to zero. What saved the mission? Certainly not any automatic device - we had none left to rely upon! No, it was the satellite ground controller who, all alone in the dead of the night, took all the right decisions in a matter of seconds before losing all uplink power. She switched off all non-essential loads before contact was lost and saved the mission.

Fig. 8 The VIKING Operations Center
MAILSTAR

Since 1984 the Swedish Space Corporation has been studying a commercial low-orbit store-and-forward communications system based on the use of small satellites. The market for the system is Swedish industry and trading companies operating in the Third World. These studies have been supported by the Swedish Board for Space Activities and a company established to commercialize the concept, the Mailstar Co.

The Mailstar Company is owned by the Swedish Telecommunications Administration, SAAB Space, Ericsson Radio and the Swedish Space Corporation. Phase B has been completed.

Network Principle

The system is based on a network structure as in Fig. 10. A base station handles all traffic between users. A remote terminal drops a message in the satellite "Mailbox". The base station reads the memory on each passage over the base station and relay messages to destinations in Sweden via
the terrestrial network. Messages to other remote terminals and messages from Sweden to remote terminals are uploaded to the "Mailbox" computer memory. The base station also uplink a "polling list" which the satellite uses to control traffic with remote terminals. Thus the satellite exercises system control.

![MAILSTAR - NETWORK STRUCTURE](image)

Fig. 10 MAILSTAR Network Principle

The use of a high-latitude base station is very advantageous for serving the whole world from a polar orbit. As seen in Fig. 11, 70% of all orbits in one day pass within "view" of a base station assumed to be placed at Kiruna Sweden.

Two kinds of remote terminals have been studied, a 64 kbps model with a 0.7 meter steerable dish and a 2 kbps model with a fixed omni antenna. The remote terminal is built around a personal computer.

Traffic Capacity

Traffic simulations show that with two satellites in orbit, each having a 64 kbps link and an 80 Mbit memory 200-300 Mbyte can be transferred in and out of Sweden per day. This assumes that there are 130 remote terminals transmitting short messages. Of these terminals 40% are assumed to be located in each of Latin America and Asia while 10% are located in each of Africa and Oceania.
Fig. 11 MAILSTAR Contact Times. One Satellite in a
h=822 km, i=98.7 deg Orbit.

The average delay between transmission and reception of a
message is around 2.5 hours while 95% of all messages have
reached their destinations within 7 hours.

The high data rate has been determined to be able to handle
areas of high user density where up to 75 terminals may be
within view of the satellite.

Satellite Design

The characteristics of the space segment are summarized in
Fig. 12, and the configuration and size is shown in Fig.13.

The Mailstar project has been conceived as a purely commer-
cial enterprise. Thus, high capacity, low cost and high
reliability have been design drivers. These considerations
led to a coherent set of trade-offs. Some of the trade-offs
related to the satellite design and their influence on
ground terminal design are "walked through" below.
THE MAILSTAR SPACE SEGMENT
SUMMARY

Launch Vehicle: Ariane, Scout or CZ-2
Satellite mass: 123 kg
Orbit:
- h=622 km, i=98.7 deg (Ariane, Scout)
- h=1200 km, i=63 deg (CZ-2)
System Life: The system consists of two satellites. Each is fully redundant and has an 80% probability of surviving 5 years.
Size: Truncated octagonal prism 0.8 meters high and 0.7 meter in diameter.
Power: 45 Watts DC power required continuously.
Altitude: Nadir-pointing by 18 meter long gravity-gradient boom.
Radio links: Uplink in the 1626-1645 MHz band.
Dowlink in the 1530-1544 MHz band at 1 Watt RF power.

Tracking & Ctrl: ESRANGE, Kiruna, Sweden (67.89 N, 21.11E)
Orbital parameters determined from base station antenna az/az data.

Fig. 12 MAILSTAR Space Segment Summary

Fig. 13 MAILSTAR Satellite Configuration and Size
Piggyback Again. It was clear from the feasibility study phase that the space segment would dominate overall costs. Therefore we tried very hard to make the satellites as small and cheap to launch as possible. We aimed at small satellites that could be launched piggyback. To find regularly available launch opportunities is essential to run a commercial space system. At the moment this is not easy for any commercial space system operator. To find regularly occurring piggyback launches is even harder!

Therefore the satellite has been designed to fit several launch vehicles. The basic launch vehicle adapter ring of the satellite is compatible with SCOUT. Using SCOUT is not a piggyback launch, but if there are no piggyback launches available one may be forced to buy a dedicated launch. Right now, the cheapest dedicated launcher is the SCOUT.

To fit the Ariane and CZ-2 launch vehicles special adapters have been designed. For Ariane a 1194 mm diameter tube structure like the VIKING central tube houses the satellite during launch. The main satellite, a SPOT or other remote sensing satellite is placed on top of this tube. After separating the main satellite the tube with Mailstar is separated from the third stage and the Mailstar satellite is then ejected from the tube.

Fig 14. CZ-2 Piggyback Arrangement
For the CZ-2 a "propulsive adapter" called the Orbital Transfer Module has been designed (Fig. 14). This is in essence a conical adapter structure with rocket motors for giving a two-impulse Hohmann transfer from the initial 175-400 km orbit to a h=1200 km circular orbit.

Satellite Size and the Allocation of System Gain. It is reasonably safe to assume that the smaller the satellite is, the lower are the launch costs. However, the smaller the satellite, the smaller the solar panel area is available. Lack of solar panel area limits the DC power available and essentially sets an upper limit for the RF output power of the downlink transmitter serving the customers. Market studies show that up to 64 kbps data rate is needed to serve the customers. With satellite output power, antenna gain (essentially an antenna with hemispheric coverage) and data rate more or less fixed the gain of the ground user terminal could easily be determined. For the L-band frequencies chosen, it turned out that a dish with about 0.75 meter diameter is needed to achieve the system gain necessary to support 64 kbps. Thus, satellite size dictates ground antenna diameter.

However, the satellite moves across the sky, so this antenna has to be steerable. A monopulse tracking system is costly even in mass production, so the design of the remote user terminal is based on knowledge of the satellite orbit. The terminal receives orbital data from the satellite. This data is transmitted as part of protocol headers. The terminal calculates azimuth and elevation and sends commands to step-motors driving the antenna dish. Thus, the antenna is steered by "dead reckoning". Studies show that orbital parameters need only be updated every fortnight. A total pointing error of the remote terminal antenna of 5-7 degrees has been allocated in the link budget. The orbit computation error contribution to this total error has been set at 2 degrees. Remaining errors are mainly alignment errors in setting up the antenna azimuth turntable.

On-Board Redundancy. The space segment costs increase with redundancy, but so does system life. Studies showed that it was highly cost-effective to have each satellite fully redundant, i.e. all subsystems except the mass memory for message storage have been assumed to be redundant. So, in contrast to VIKING which completely lacked on-board redundancy, this small satellite project ended up with a fully redundant system design.

Project Status

The system has been fully costed and independent market surveys have been made. Competitive tariffs have been set and a normal business analysis has been made to determine
return-on-investment, financial risk exposure and other viability indicators. The analysis shows that the system can earn a handsome profit as a purely commercial system without subsidies of any sort. However, similar services can be provided through geostationary satellites promising a higher profit and lower risk exposure for the system operator.

However, a significant part of the prospective customers prefer an independent and self-contained communications system like Mailstar over a geostationary system requiring several hops for global traffic. The inherent resistance to jamming and eavesdropping of the Mailstar system is also an attractive feature. Therefore the system is being re-evaluated to serve such "closed user groups".

Some technical concept changes may be necessary and it is probable that the system must share the space segment with other missions. Hopefully, by the time this conference convenes again we shall be able to report on the new definition of the system.

CONCLUSION

The recent experience in operating and designing small satellites in Sweden has demonstrated that such vehicles are highly useful for sophisticated science missions and that they also are commercially profitable in the field of store-and-forward communications.

ACKNOWLEDGEMENTS

I am indebted to Mr Per Zetterquist, the VIKING Project Manager during the definition and early development phases, under whose guidance I had the privilege of serving as System Engineering Manager. Our colleagues at SAAB Space and Boeing Aerospace were inspiring partners in the design of the VIKING system.

Mr Anders Ekman at SSC managed the Phase A and B studies of MAILSTAR which were performed mainly by SAAB Space and Ericsson Radio.

REFERENCES

TECHNICAL SESSION II
SMALL SATELLITES - SUBSYSTEMS

Session Chairman - Mr. Benjamin Cox, UNISYS

1. "Bare Bones Propulsion for Small, Low-Cost Satellites"
   - Richard L. Daniels, AMSAT

   - Ali Siahpush and Andrew Sexton, Globesat, Inc.

3. "Microcomputers for the Space Environment"
   - James K. Elwell, QSI, Corporation

   - Ralph M. Sullivan, Johns Hopkins University

5. "A Survey of Recent APL Spacecraft Power Systems"
   - Gregg A. Herbert, Johns Hopkins University

6. "Comparison of Recent APL Satellite Subsystem Weights for Future Weight Estimation Purposes"
   - Kevin Heffernan, Johns Hopkins University