SMALL SATELLITES AND NOAA: A TECHNOLOGY STUDY

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Abstract

APL examined technology and space segment options for the polar orbiting spacecraft of the National Oceanic and Atmospheric Administration (NOAA). The principal finding is that the choice of satellite configuration, rather than the particular technology of flight hardware, is the dominant factor that can reduce space segment costs when viewed over a mission life-cycle. For example, the study shows that fewer than half the number of individual instruments-- many of which are quite expensive-- need be purchased and launched over a 15 year period if each of NOAA's polar orbiting satellites were implemented as four small spacecraft rather than one large platform as is now the norm. This result is a direct consequence of NOAA's operational mandate, for which data continuity from certain critical instruments is a mission requirement. These results generalize to any multiple-sensor scenario for which data continuity is a major consideration. It is concluded that a multiple small satellite space segment configuration may be more responsive to NOAA's objectives, but only if the impacts on the ground segment can be shown to be acceptable, which requires further study.

Introduction

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) was commissioned by the National Oceanic and Atmospheric Administration (NOAA), through the National Environmental Satellite, Data, and Information Service (NESDIS), to study the impact of small satellite technology on their operational satellite missions. The study had three parts: a review of NOAA requirements, an analysis of the applicability of small satellite technologies and processes to NOAA programs, and an analysis of the space segment if implemented with multiple small satellites. Following the requirements review, the study focused on the next generation of polar satellites*. The draft final report was scrutinized by a panel of external reviewers drawn from government agencies, industry, and universities. Their feedback was incorporated into the final report submitted by APL to NOAA[1].

NOAA's satellite missions

NOAA is responsible for providing forecast and warning services to protect the American people against physical or economic loss due to changing environmental conditions. In executing this element of its mission, NOAA operates an information service based on meteorological and oceanographic data collected by two satellite systems: GOES (the Geostationary Operational Environmental Satellites) and POES (the Polar-orbiting Operational Environmental Satellites). During the 34 years since weather satellites were first introduced (TIROS-1), the number of instruments aboard and the complexity of these spacecraft have grown significantly. Recent descriptions[2-6] suggest that the large system trend is continuing.

Currently, NOAA maintains two sun-synchronous orbits for the POES series, corresponding to the afternoon (pm) and the morning (am) phasings, respectively. In the year 2001, the morning series is to become the responsibility of the European community.

There are two geostationary positions maintained by GOES satellites: GOES West, over the Pacific Ocean (135°W), and GOES East over the Atlantic Ocean (75°E). Each GOES carries a suite of two primary instruments and four secondary instruments. Each POES carries four primary instruments and six secondary instruments. Both POES and GOES are considered to be "large satellites," approximately 2000 kg, or more than two tons each. The spacecraft must be sized to accommodate their sensors, several of which are rather large, with resources in proportion, including fuel for station keeping and extensive support system redundancy. As a result, both POES and GOES require relatively large launch vehicles.

Smaller, better, cheaper?

APL's study was precipitated as one response by NOAA/NESDIS to the increasing visibility and political appeal of smaller satellites. The original intent was to explore the benefits illustrated by recent well-known examples of state-of-the-art spacecraft and instrument technology on NOAA's platforms. In short, by using "smallsat technology," could a cheaper system be achieved that would be as good or better than the *status quo*, without loss of operational reliability? The answer is that some advantages might be gained, but the impact of technology infusion alone on size and cost of NOAA's spacecraft would be relatively small in comparison to the total system. Small satellites may be exploited in other ways, however.

In the NOAA operational context, "better" must be understood from the end-user's point of view, for which relatively long life, data continuity, and high reliability are essential. This interpretation is quite different from the motivation for recent smallsats which were one-of-a-kind experiments. For the NOAA polar orbiting systems, the small satellite question was generalized to embrace the entire space segment over a mission life-cycle. The study considered alternative system configurations based on several small satellites and compared the resulting space segment implications to the traditional single platform

Table 1. Baseline POES Instrument Payload[6]

Primary payload		
• VIRSR	Visible-Infrared Scanning Radiometer	(Cross-track scanned image, ~ AVHRR)
• MTS	Microwave Temperature Sounder	(Vertical atmospheric profile)
• MHS	Microwave Humidity Sounder	(European contribution)
• IRTS	InfraRed Temperature Sounder	(Atmospheric, alternate ITS)
Secondary payload		
• SEM	Space Environment Monitor	(Charged particle spectrometer)
• LEFI	Local Electric Field Instrument	(Aurora and solar/terrestrial science)
• TOMS	Total Ozone Monitoring System	(Daily two-dimensional mapping)
• SBUV	Solar Backscatter UV Radiometer	(Vertical ozone distribution)
• ARGOS	Data Collection /Location System	(Relay, French contribution)
• S&R	Search and Rescue	(Distress location system, international)

approach. The multiple small satellite solution turned out to be "better" in several regards for the space segment. Overall mission considerations emerged that require further study for the multiple satellite case, including spacecraft operations, data management, and simultaneity of observations

POES

General requirements on the next generation of NOAA's polar orbiting systems include: i) upward compatibility of data products with respect to the currently operational POES satellites, and ii) compatibility with systems operated through the Organization for the Exploitation of European Meteorological Satellites (EUMETSAT) and other international ground facilities. Most of the specific payload and mission requirements follow from these two principles. The POES payload is summarized in Table 1.

Mission requirements stipulate that all four of the primary instruments are "mission critical." Should any one primary instrument fail on orbit, a replacement would have to be put into service as soon as possible, which requires a new launch. The reliability requirement is specified to be 80% for each instrument, for three years of continuous operation. Failure of a single secondary instrument does not necessitate launch of a replacement.

POES on Small Satellites

The study explicitly looked at the consequences of replacing each of NOAA's single polar spacecraft with a set of smaller satellites. The multiple satellite approach taken by APL is a marked departure from otherwise similar studies[4]. It assumes that issues such as station-keeping, mission control, simultaneity, and down-link data formats can be adequately addressed.

Method of analysis

Several space segment scenarios were considered[1] that could support NOAA's objectives for POES. The options were selected to encompass all possibilities, without prejudging their relative merits. Selection methodology is outlined in Figure 1. Following the baseline[6], the next two options are variations within the single spacecraft philosophy. ***Option A*** notes that the baseline

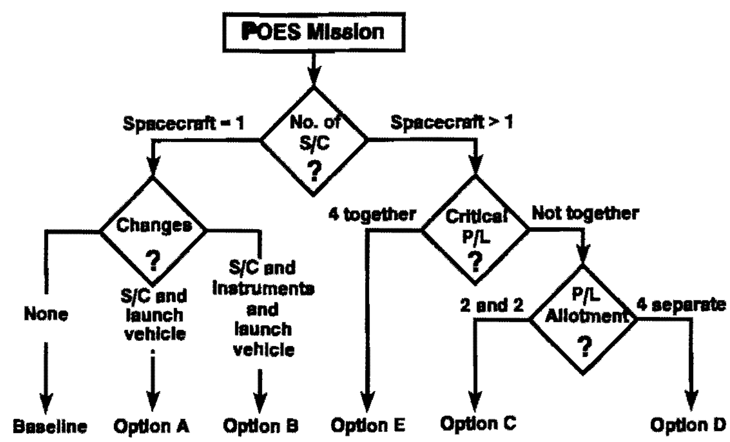

Figure 1. Option selection logic.

payload could be launched on a medium class vehicle, smaller than the baselined Delta II, by reducing the spacecraft bus mass. ***Option B*** assumes that the payload instruments also could be redesigned to minimize their spacecraft resource demands, thus allowing an even smaller satellite implementation and a launch on a correspondingly smaller vehicle.

The remaining three options assume that multiple-spacecraft scenarios are admissible. ***Option C*** divides the four mission critical instruments between two small spacecraft and assigns all six remaining (secondary) instruments to a third small spacecraft. ***Option D*** distributes the four mission critical instruments equally among four small satellites and allocates the remaining instruments according to size, weight, and functional constraints. ***Option E*** retains all four mission critical instruments on one medium sized spacecraft together with the two instruments of opportunity that happen to fit the mass constraints of the smallest suitable launch vehicle. All four space environmental science instruments fit on one small satellite, to be launched by a small vehicle. The resulting scenarios are outlined in Table 2.

Lifetime analysis

Each option was evaluated for expected operational mission lifetime. Assumptions for all options include: probability 0.95 of a successful launch, spacecraft on-orbit reliability of 0.96 for three years, and a probability of survival of 0.80 for three years for each instrument. Consistent with NOAA practice,`replacement would be required upon failure of any mission critical instrument. The study assumed a new launch after failure of any two secondary instruments.

The first question is, How many spacecraft are required to support a NOAA POES life-cycle of 15 years? For those situations in which there are two or more spacecraft per set, the associated question is, How many spacecraft of each kind are required? The spacecraft analysis is summarized in Table 3.

These results have been derived using standard risk and probability of survival analysis techniques. For each launch, survival was calculated through a product of the launch probability distribution and the spacecraft on-orbit probability distribution. A binomial distribution was used for launch success, and a gamma function for the on-orbit probability distribution. The gamma function describes the sequential convolution of exponential distributions that arises under multiple instrument and spacecraft conditions.

Survival probabilities are most impacted by the presence of two or more mission critical instruments on the same platform.

Table 2. Spacecraft and their Payloads According to Option

Payload	Mass (kg)	Power (W)	Baseline	A	B	C_1	C_2	C_3	D_1	D_2	D_3	D_4	E_1	E_2
VIRSR[a]	72	60	X	X	N	X			X				X	
MTS	120	138	X	X	N		X			X			X	
MHS[b]	72	100	X	X	N		X				X		X	
IRTS/ITS	66	72	X	X	N	X						X	X	
SEM	23	21	X	X	N			X				X		X
SBUV	48	24	X	X	N			X	X					X
TOMS	30	25	X	X	N			X				X		X
LEFI	8	10	X	X	N			X				X		X
S&R[b]	75	88	X	X	N			N			N		N	
ARGOS[b]	65	72	X	X	N			N			N		N	
Total power		610	610	610	TBD	112	238	240	84	138	260	128	530	80
Total mass	580		580	580	~300	138	192	249	120	120	212	127	470	166

[a] Implies X-band down-link and recorder X = Instrument from baseline group[6]
[b] Foreign contribution N = New sensor packaging

Table 3. Expected Life-cycle Requirements by Option

Option	Spacecraft required	Expected lifetime
• Single spacecraft (Baseline, A, B)	8	Mean life (each) ~3.2 years.
• Two spacecraft (E)	13	E_1: mean life ~3.2 years (8 required) E_2: mean life ~6.2 years (5 required)
• Three spacecraft (C)	15	C_1, C_2: mean life ~6.2 years (5 required each) C_3: mean life ~6.5 years (5 required)
• Four spacecraft (D)	12	Mean life ~11.4 years each

Summary of Mission Profiles

Each spacecraft launched must include the full complement of instruments appropriate for its configuration. From the discussion above, the payload is known for each launch for all options. Thus, it is possible to construct a framework within which relative space segment procurement costs may be estimated. *The central question is, How many instruments are required, under each option, to meet the NOAA 15 year life-cycle requirements?* The results are summarized in Table 4.

More launches would be required for Option D than for any of the single satellite options, although fewer are required than for the other multiple satellite scenarios (Option C and Option E). Smaller satellites would entail substantially less cost for each launch, however. The difference between the several options of total launch costs over the mission life-cycle was assumed to be relatively small for the purposes of this study.

The dominant factor may be found in the third column of Table 4. There are substantial differences between the options in the number of instruments required for the mission life-cycle. The total number of instruments that must be launched is significantly smaller for the four spacecraft scenario (Option D) than for any of the single satellite scenarios (Baseline, Option A, or Option B).

In the single satellite case, a launch in response to the failure of a primary instrument necessitates putting ten new instruments into orbit, nine of which would not be needed. In the multiple satellite cases, fewer unneeded instruments have to launched. For the POES payload, the primary instruments and most of the secondary instruments are relatively expensive. When instrument cost is a signi-

Table 4. Total 15 Year Life-cycle Space Segment Requirements per Option

Option	Launches	Instruments
Baseline	8	80
A	8	80
B	8	80
C	15	50
D	12	30
E	13	68

There is at least one example of a reliable small ELV from the past. The SCOUT, a relatively crude but dependable 4-stage all-solid vehicle, placed the operational TRANSIT satellites in orbit with 100% success. All of SCOUT's final 25 launches were successful[12] and its overall success rate, encompassing 118 launches over 34 years, was 98.3%.

With the demise of SCOUT, a number of small ELVs are emerging that promise to fill the void. U.S. vehicles launched or about to be launched include the Pegasus and Pegasus-XL, LLV-1, Conestoga, and Taurus. Although none of these has yet demonstrated the reliability POES requires, there is no reason why national resolve, backed up by modern technology, careful engineering, and attention to detail, should not attain SCOUT's enviable record for future launch services.

Conclusions

There have been several persuasive examples of effective small, low-cost, operational spacecraft systems. They have demonstrated many technologies suitable either for small or for large satellites, some of them for the first time in space. They have demonstrated the advantages of developing instruments and integrated payloads for a small spacecraft. They illustrate the benefits of alternative management techniques that were more efficient than those which characterize most large spacecraft programs. For good reasons, such programs have served to energize proactive discussion of small satellites.

But those programs also include examples of relatively short-lived spacecraft. Although designed for limited lifetimes, both Clementine and MSTI-2 encountered fatal difficulties prior to their planned mission completion. A point of diminishing returns is inherent in a drive towards cheaper, smaller, faster. Caution is advised. Whereas savings in a satellite program may be realized through smallsat technology and philosophy, savings must be balanced against technical and program risk.

There have been many small satellites that have flown successfully for decades. In retrospect, the best of these programs have proven that small satellites may be implemented at relatively low cost, and that they are capable of providing many years of reliable operation on orbit. Most of these have been relatively simple spacecraft, but that is precisely the point[13]. On-orbit reliability and therefore data continuity are well served by smaller, simpler spacecraft, each of which have fewer instruments aboard.

The review of small satellite technology in the context of NOAA's mission led naturally to consideration of multiple spacecraft configurations. For several single and multiple spacecraft scenarios, the number of spacecraft and the number of instruments were determined that would be required to satisfy a 15-year life-cycle for the POES mission. Although more spacecraft would need to be launched for a four small satellite solution as opposed to the single satellite options (12 *versus* 8), many fewer instruments would satisfy the life-cycle demand of four small satellites than the single satellite case would require (30 *versus* 80). The instruments are expensive. Under the conservative proviso that the individual spacecraft and launch costs were equivalent in the two cases, then these figures imply that the four spacecraft option would cost substantially less than the cost of the single spacecraft. More may be concluded. Initial assessment shows that the *total* launch and spacecraft costs for the small satellite set would be absolutely less than the corresponding total costs for the large satellites. Furthermore, additional cost savings should result from the extensive hardware commonality across a fleet of small spacecraft, exclusive of the instruments.

From a mission planning point of view, space segment costs are only part of the picture. Additional direct cost considerations may arise in mission control, system operations, and algorithm development. Indirect costs could arise if science objectives were compromised, which would be unacceptable if data integrity could not be maintained within requirements. These issues were not addressed in detail during this study, and deserve deeper analysis.

In summary, it is concluded that a mission design based on effective use of small satellites for the polar orbiter mission may be more responsive to NOAA's objectives than a conventional single satellite approach, and that small satellite options merit further study.

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* The NOAA 1992 O.P,Q Plan[6] is being supplanted by the Presidentially-ordered converged system that will combine the NOAA Polar orbiters with the DMSP satellites. The new system will be known as the National Polar-orbiting Operational Environmental Satellite System (NPOESS), which should be similar in most functional regards to the current POES. NPOESS is intended to begin operations in 2004. Based on documentation available during the fall of 1994, the O,P,Q POES system concept was used as the study baseline.