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ABSTRACT

On December 16, 2006, Tacsat-2 launched from Wallops Island, Virginia atop a Minotaur rocket to become the first Operationally Responsive Space (ORS) Satellite. Some of the objectives of this program were rapid development and rapid deployment of the spacecraft as well as a low mission cost. For example, the spacecraft bus was delivered in 12 months from the start of the contract. Following the completion of its mission, Tacsat-2 was recognized by Aviation Week and Space Technology Magazine with its Small Company Product Breakthrough Award. Since this initial success, ORS has grown into a much larger national effort that hopes to revolutionize space missions by using plug and play spacecraft components with a rapid call-up "space wing" that can replenish, augment and reconstitute national space capabilities.

Sierra Nevada Corporation (SNC) Space Systems a new entity created through the acquisition of MicroSat Systems and SpaceDev by SNC, is building on the success of the TacSat-2 (TS2) program and folding that experience into the ORBCOMM Generation 2 augmentation program (OG2). As outlined by ORBCOMM, the current order for 18 OG2 satellites with a possible option for 30 more will enhance the currently flying constellation of 27 low-orbiting satellites that provide global two-way messaging service. As stated publicly by ORBCOMM officials on December 4, 2007 ORBCOMM expects to pay about $6.3 million for each of the 18 satellites and to launch them between 2010 and 2012.

The fact that many of these same cost and schedule requirements resemble many of the same goals of ORS is not a coincidence. SNC is using lessons learned from ORS concepts that have resulted in similarities between the two endeavors. The interplay between ORS and OG2 is resulting in intentional benefits to the ORS endeavor and the recent ORS office award of the Multi-Mission Space Vehicle (MMSV) Phase II contract to SNC further enhances these synergies. The MMSV program will form the basis for a modular tool-kit of spacecraft busses and payloads that will enable the rapid deployment of low-cost space vehicles to meet time critical ORS needs.

In this paper, similarities between the OG-2 single payload, low cost, launch-on-demand mission and ORS objectives are examined and the implications of the OG-2 program on future ORS missions are projected.

KEYWORDS: ORBCOMM, ORS, SNC, Tacsat-2

INTRODUCTION

Operationally Responsive Space (ORS) faces the challenge of developing end-to-end enablers required to meet the nation's critical need for highly responsive space capabilities and to execute rapid end-to-end capability efforts to meet urgent operational needs of the Joint Force Commanders (JFC's). To develop these capabilities ORS is using both tactical satellites (Tacsats) that will help develop the necessary technologies and operational satellites (ORSSats) that will satisfy operational needs.

Tacsat-2 (TS2), as the first Tacsat launched, offers some initial ORS lessons learned that can help the program to progress. However, what is significant about SNC's approach to ORS is the leveraging of its commercial efforts for the ORBCOMM Generation 2 (OG2) program to also further the state-of-the-art. Both of these programs are introduced and then compared for joint lessons learned. Finally, how these approaches will influence ORS in the future is discussed.

The TacSat 2 Program

On December 16, 2006, Tacsat-2 (TS2) launched from Wallops Island, Virginia atop a Minotaur I rocket to become the first ORS Satellite. The one year mission made several notable accomplishments. First, TS2 was launched in only 36 months despite both an orbit and launch vehicle change during System Integration and Test. Second, it demonstrated command uplink and image downlink to a mobile tactical ground unit, collected color and panchromatic images from space with less than 1 m resolution, and providing a unique ELINT sensor demonstration from space. Third, it demonstrated a variety of advanced on-board autonomy such as an ability to command the spacecraft via the Internet, on-board autonomous orbit maintenance software used to determine orbital parameters and to plan thruster firings, and an on-board autonomous task planning and execution capability.

This mission was enabled by a capable spacecraft as pictured in Figure 1. The TS2 spacecraft supported fourteen successful payloads/experiments on one 361 kg spacecraft for a 58% payload mass fraction. It also used several key subsystem technologies including the first U.S. Hall Effect thruster flown in space (providing new data on in-situ performance), a low power transceiver demonstration, and a thin-film solar array deployment demonstration.

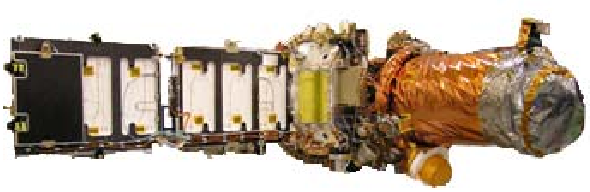

Figure 1. TacSat-2 Spacecraft.

The ORBCOMM Program

ORBCOMM is a publicly traded company that provides worldwide, machine-to-machine data transfer to and from subscriber units and a ground system. Using the internet, subscribers can monitor a wide variety of parameters collected by the units. As outlined by ORBCOMM, the current order for 18 satellites with a possible option for 30 more is a proactive approach to replacing the currently flying constellation of 27 low-orbiting satellites that provide the two-way messaging service. In May 2008 ORBCOMM awarded a contract for OG2 spacecraft to SNC. As stated publicly by ORBCOMM officials on December 4, 2007 ORBCOMM expects to pay about $6.3 million for each of the 18 OG2 satellites and to launch them between 2010 and 2012.

The OG2 spacecraft will increase subscriber performance with an initial seeding of 18 OG2 spacecraft into the existing constellation. The target orbit is LEO 600 to 750 km, at approximately 45 degrees inclination. SNC is the prime contractor with support of ITT and Boeing. SNC Space Systems (previously known as MicroSat Systems Inc. and SpaceDev) is designing, testing, and producing the spacecraft in Colorado. The payload is a software defined radio built by ArgonST that provides subscriber communications with the ground stations, Automated Information System (AIS) maritime tracking, and spacecraft bus command and telemetry. The spacecraft is shown in Figure 2.

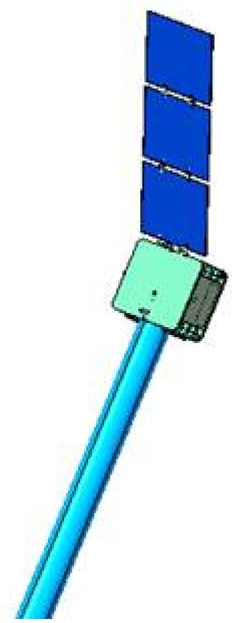

Figure 2. ORBCOMM Spacecraft.

INTERPLAY OF ORS AND OG2

OG2 Program Timeline vs. TacSat-2

Both TacSat-2 (TS2) and ORBCOMM Generation 2 (OG2) programs were formulated for low cost and rapid design/build/test cycles. Notably, TS2 was a cost-plus contract where OG2 is fixed price. The bus and payload costs of the two programs were significantly different due to the overall complexity and greater performance of TS2 as contrasted to the economy of scale of the OG2 production line. However, there is a similarity between the two when the sophisticated and powerful OG2 payload is considered.

Several of the programmatic approaches used by SNC for TacSat-2[1] were applied to the OG2 program and are summarized in Table 1. The aggressive timeline of the TS2 program provided the basis for the OG2 program plan. The engineering execution of the OG2 program is more formal than TS2 owing to the lower risk posture of OG2 caused by the exigencies of a publicly traded customer and a longer mission. The time expended for formality is balanced with the less complex design of OG2 to yield a schedule matching TS2.

Examination of the program timelines shows much similarity from start through launch. Intuitively there is an expectation that the similarity between the one TS2 and the multiple OG2 spacecraft design, build and test cycles would deviate as launch approaches. That expectation is further supported considering the fact that OG2 required the ordering of nearly all of the spacecraft electronic components two months after contract award where TS2 started with some of the avionics already in hand. However, the matched pacing of the two programs from program start to integration and test is primarily due to the less complex spacecraft design of OG2 requiring fewer engineering hours.

In order to achieve the OG2 initial launch date, six spacecraft must be built and tested for potential simultaneous launch. That challenge will be met through the transfer of SNC production experience from other product areas in the corporation that have large production runs including sophisticated configuration management systems. At 24 months into the TS2 program a significant number of the 14 experiments had been integrated and tested. The comparison contrasts that integration effort with the difficulty building six identical, single payload spacecraft.

Table 1. Programmatic Comparison.

Characteristic	TS2 (from contract award)	OG2 (from contract award)	Comments
Date of PDR	N/A	4 months from Contract Award (actual)	TS2 design was heavily derived from TechSat 21 so no PDR was held
Date of CDR	6 months (actual)	7 months (actual)	
Delivery of Bus to I&T	12 months (actual)	11 months (planned)	
Delivery of Payload to I&T	14 to 19 months (actual)	13 months (planned)	TS2 had 14 payloads/experim ents
Spacecraft Environmental Testing	18 months (actual)	16 months (planned)	
First Launch	36 months (actual)	26 months (planned)	OG2 requires six spacecraft on first launch.
End of Production	36 months (actual)	35 months (planned)	
End of Mission	3 years from contract award (actual)	7 years from contract award (minimum requirement)	

These considerations were used to formulate the SNC OG2 proposed schedule. OG2 completed CDR in December of 2008 and is on its way to the first flight unit. To date, the application of the TS2 responsive timeline to the OG2 program has been successful.

OG2 and TS2 Bus Characteristic Comparison

Although the OG2 spacecraft does not resemble TS2 externally there are some similarities in several key design characteristics as shown in Table 2. Bus Dry Mass, power generation capability, battery capacity, three-axis attitude control and delta-v capability are all similar characteristics. There is also a significant re-use of flight software from TS2 in the OG2 spacecraft.

However, there are also several key differences. The communications mission of OG2 leads to less stringent pointing requirements and computing processing capability than the more stringent imaging mission of TS2. Also although the delta v requirements are similar, OG2 is driven to the less costly liquid propellant solution for propulsion needs.

Table 2. TS2 and OG2 Bus Comparisons

Characteristic	TS2	OG2	Comments
Bus Dry Mass (kg)	153	111	
Payload Mass (kg)	214	40	
Launch Mass – Wet (kg)	373	165	TS2 had 14 payloads / experiments
Power Generation (W)	675	670	TS2 fixed array, OG2 gimbaled array
Battery Capacity (A-hr)	30	30	
Attitude Control	3-Axis	3-Axis	
Pointing Accuracy (degrees)	< 0.05 (actual)	2.5	
Pointing Control (degrees)	< 0.03 (actual) [2]	2.5	
Delta – V Capability (m/s)	70	140	TS2 used electric while OG2 uses mono-propellant propulsion
Processors	165 MIPS	2 x 20 MIPS	
Communications Link	S-Band	VHF	
Launch Vehicle	Minotaur I	Falcon 1e and Minotaur IV Classes	TS2 also had Falcon design requirements

ORS INFLUENCE ON OG2 DESIGN

With the lessons learned from the design, build and operation of TS2 as well as their on-going work in ORS, SNC has refined its approach to spacecraft design. One key item that both ORS and OG2 share is a requirement for modularity - ORS for flexibility in spacecraft configuration for the mission at hand and OG2 for ease of mass production. So while looking different physically, the influence of modularity can be seen in the OG2 design.

The OG2 bus structure is designed in a longeron and panel type arrangement so that production of the structure is faster, the sides are lightweight and removable, and the bus components can be isolated on one bottom deck with the payload components on the top deck. Figure 3 shows those design features.

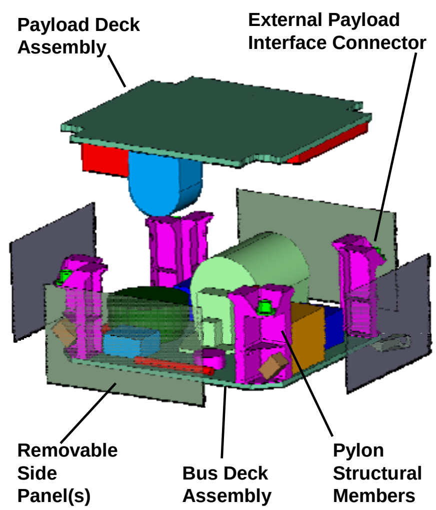

Figure 3. OG2 Bus Modular Features

This arrangement allows the payload and bus to be assembled and tested in parallel with each other and brought together later in the integration and test flow. That same approach has been applied to the propulsion subsystem which is assembled on a flight plate, tested at the supplier, and delivered to the production line. Figure 4 shows the modular design and interface with the bus. SNC required minimized and centralized electrical interfaces to the propulsion subsystem for speed of assembly and the supplier created a subsystem with mechanical and electrical features that enable a plug and play type interface that is extensible to other spacecraft.

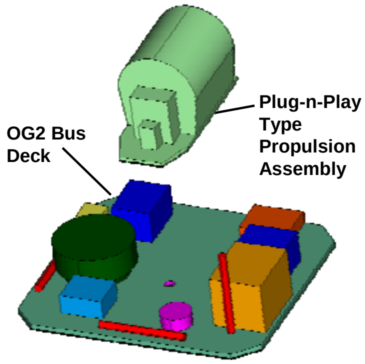

Figure 4. OG2 Propulsion Subsystem Modularity.

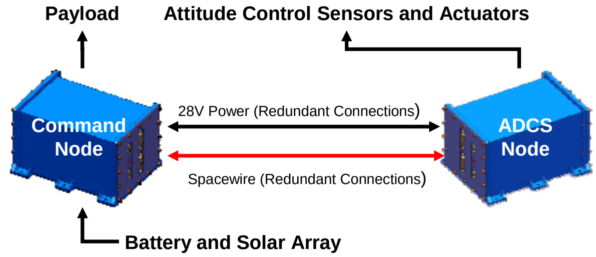

Figure 5. OG2 PnP IPDR Avionics Architecture

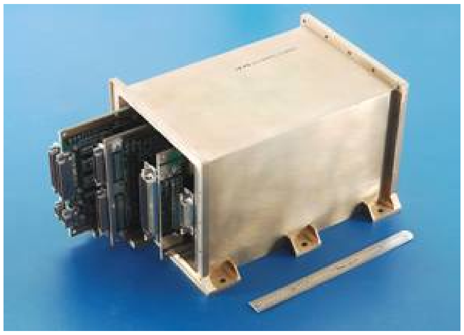

Figure 6. OG2 PnP IPDR Avionics Node

The Plug-n-Play (PnP) emphasis of ORS has been an ongoing effort at SNC. In response to the PnP objective of ORS SNC has created a networked avionics architecture called the Intelligent Power and Data Ring (IPDR). IPDR consists of a ring topology of identical, modular nodes interconnected via standardized harnessing. Each node function can be specified independently by the end-user through real-time, software/firmware uploads. Spacecraft system capability and price can thus be tailored through the addition, or removal, of nodes. IPDR is engineered to be fully compatible with a variety of legacy and AFRL PnP SPA-S interface protocols. The ring network implements a SpaceWire core to support high-speed data transfer around the ring, and any user-programmable protocol (including heritage interfaces) from the ring out to peripheral devices. Generation 1 IPDR experiments are to fly on TacSat-3 and TacSat-4.

A second generation IPDR has been developed using significant internal funding for use on OG2 and provides new flexibility in the packaging of the bus components. Considerable cost savings were achieved on OG2 through the use of ground and flight software from the previous SNC spacecraft Techsat 21, TacSat-2 and DSX. The challenge was to re-use heritage flight software for OG2 in conjunction with new avionics. For Techsat 21 and TacSat-2 high performance integrated avionics allowed the bus housekeeping functions to be centralized in a single avionics unit. In order to capitalize on the cost benefits of the IPDR for OG2, the functions of Command and Data Handling and Power had to be separated from the Attitude Determination and Control functions in order to fit in the moderate performance IPDR nodes. Figure 5 indicates the resulting architecture and distribution of functions between IPDR nodes and Figure 6 shows an IPDR node unit. The networked avionics architecture has enabled easy reassignment of component interfaces between the nodes during the design phase.

OG2 CONTRIBUTIONS TO ORS

While the OG2 mission is specifically targeted to a non-ORS commercial communications mission, its formulation and construction during the unique period of the national ORS concept maturation has resulted in both intentional and unintentional contributions to ORS development. The majority of the benefits accrue to ORS Tier 2 - replenishment, augmentation and reconstitution using existing technologies. The benefits to the ORS effort are discussed in the following paragraphs.

Creation of new sources of low cost flight proven subsystem components. The scale of OG2 acquisition (potentially 48 spacecraft) encourages smaller, low cost component suppliers to invest in conversion and upgrade of hardware previously flown on a more experimental basis to the requirements of a five year mission. Other suppliers whose primary business was closely related decided to stretch into offering a component or system. In one case aircraft equipment that has been flown in space on higher risk missions is being ruggedized and qualified by a supplier for space use. Some of the more widely known U.S. and foreign component suppliers were not able and/or willing to reach the price points of the technically diversified companies who incorporated their unique capabilities to develop low cost solutions. The competition was stiff. This same effect has enticed SNC and their partners to invest in the streamlined design, test, and production infrastructure necessary for the completion of the program.

Standardization of components by market forces. Due to the large OG2 order, SNC was able to specify different component electrical interfaces than some suppliers used in their standard offering. In some cases this was done with future US applications in mind so that those components now conform to more common U.S. microsatellite design. Suppliers were willing to implement those changes at a very competitive price because of the obvious advantages of dilution of Non-recurring Engineering cost.

Demonstration of streamlined design, assembly, test methodologies at the component and system level. The approach of the OG2 program to utilize single-string spacecraft and achieve system availability to subscribers through the number of spacecraft was also a significant factor in SNC's ability to utilize less well known suppliers. Flexibility in the application of industry design and test standards was important to achieving the demanding cost and schedule requirements. Suppliers were encouraged to propose and justify methods of design verification that they believed were lower cost and/or faster. This approach enabled the purchase of non-U.S. components that were built to acceptable non-US standards while adhering to the constraints of the International Traffic in Arms Regulations. As a result of this approach, and with successful flight validation, these components and verification methods will become available to the ORS community.

Lessons learned from the ORBCOMM Generation 1 manufacturing process in 1997 have been incorporated into the planning of the manufacturing for OG2 [3]. There are differences however in the SNC implementation. Enterprise resource planning systems will be used to control all aspects of manufacturing and are already in place. A separate production team has been formed and will participate in the build and test of the first two spacecraft followed by responsibility for production of the remaining 16 spacecraft. Most importantly, the influence and needs of ORS are present now where they were not during the Generation 1 effort. In this case, test scripting approaches developed on TacSat-2 and DSX are the starting point for OG2 bus and systems level testing. Flight validation of the streamlined SNC testing approach required to manufacture and test this number of spacecraft at the system level will also make those methodologies available to the ORS community.

Immediate and longer term availability of a flexible, medium performance microsatellite platform at a very low cost for ORS use. The Generation 1 ORBCOMM program resulted in a successful spacecraft bus design by Orbital Sciences that was built and sold to other users, with the presumed cost savings from the investment in the ORBCOMM Generation 1 spacecraft design. In fact, TacSat-1 was an Orbital Sciences MicroStar bus whose direct heritage was the Generation 1 ORBCOMM spacecraft. TacSat-1 was to be launched in 2004 and was eventually cancelled in 2007 due to lack of a launch vehicle. With that history in mind, SNC has inserted design features into OG2 that are beneficial to a wider application of the spacecraft bus but not necessarily required for the OG2 mission. Among those features is the ability to mount the spacecraft bus to the launch vehicle strongback with the solar panels facing inward in order to free the opposing face of the structure for accommodating other types of payloads. Of course, the plug and play type infrastructure in the IPDR avionics set enables the lower cost integration of payloads for other users. Easy removal of the modular propulsion subsystem gives other users the options to gain additional volume inside the spacecraft bus for payloads.

Flexibility for rapid response from a variety of launch ranges and with a variety of launchers. Consideration of other uses of the OG2 elements extends to the launch system design as well. Figure 7 shows the OG2 Strongback structure and arrangement in a Minotaur IV fairing. The Strongback remains connected to the upper stage of the launch vehicle after the spacecraft have been released. The spacecraft and Strongback have been designed to fly on a variety of launchers – Minotaur IV, Falcon 1e, and PSLV. This flexibility was required by ORBCOMM to maximize launch opportunities. The resulting benefits are the implementation of a tenant of ORS to have the flexibility for rapid response from a variety of launch ranges and with a variety of launchers.

A useful feature for ORS use is the modularity of the Strongback allowing the launch of two, four, or six spacecraft by adding or subtracting the two-spacecraft modules that make up the Strongback.

The Strongback has also been designed to hold an optional microsatellite of any type that will fit on the top with the addition of an optional plate. The structural design features necessary to support the additional spacecraft are removable so that unnecessary mass is not carried to orbit.

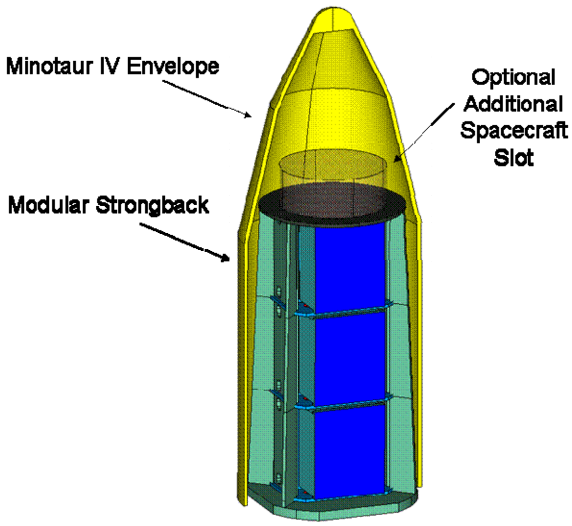

Figure 7. OG2 Modular Strongback

SNC has also designed a multiplexer and separation sequencer unit that minimizes the interface demands of a multi-spacecraft launch on the launch vehicle. A battery on the Strongback provides the energy to initiate spacecraft separation without requiring power from the launch vehicle.

Experience with "space wing" operations and rapid launch. The SNC production plan for OG2 will result in multiple spacecraft ready for launch. Anywhere from 3-18 spacecraft could be in storage at one time. Similarly to ORS, the spacecraft must be stored in a ready state with a minimum of maintenance required. The launch campaign is formulated based on the shipment of a set of spacecraft already attached to the Strongback to the launch site in a single container. The Strongback is removed from the container, automated health and status checks are performed, and the Strongback is placed on the launch vehicle for encapsulation and launch.

The OG2 spacecraft launch Electrical Ground Support Equipment (EGSE) is designed to perform automated testing on as many as six spacecraft simultaneously. Those tests must be highly automated to reduce the launch preparation timeline and require fewer staff at the launch site. A ground data system is under construction that will enable ready call-up of the configuration of any spacecraft on the ground or in flight. That ground system will also allow real-time remote monitoring of tests at the launch site by spacecraft engineers. These plans are driven by the fixed price format of this contract but in the case of ORS would minimize the government infrastructure required to maintain readiness.

All of these plans and features have a direct relationship to ORS concepts and the lessons learned in the design and execution of the OG2 storage and launch plan will be used in the formulation of future ORS systems. The MMSV contract recently awarded will give SNC the opportunity to influence ORS directly in the months ahead.

CONCLUSION

The OG2 program is synergistic to the ORS effort in a variety of programmatic, technical, and operational ways. The need to augment an existing commercial spacecraft constellation rapidly, with low cost, identical spacecraft is a direct execution of ORS concepts. The simultaneous development of the OG2 spacecraft with ORS is a unique confluence of timing, technologies and expertise resulting in efficient and rapid exchange of benefits between both endeavors. The OG2 spacecraft bus and Strongback have been designed with features for ORS application. Immediate and tangible benefits are available for the ORS community in the form of new sources of low cost, modular spacecraft bus components.

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