

ORS Responsive Systems Architecture Design and Indicated Directions for the 1st Spacecraft and Payload Missions

Kirk Stewart
Kirk D. Stewart, Ph.D, PE
PO Box 44, Niwot, CO 80544; (303) 530-3505
drkdstewart@comcast.net

ABSTRACT

Operationally Responsive Space (ORS) is an important DoD initiative to identify and build missions to use small satellites and significantly decrease costs. Efforts over the past two years have focused on establishing spacecraft standards and developing technologies. With the recent formation of a DoD program office to develop and conduct responsive war fighting support operations with small satellites, the DoD and industry need to examine the architectures and program development paths that achieve those goals.

This paper examines an important way of potentially using the small satellites and standards defined by the ORS/JWS Industry Systems Engineering Team (ISET) and the benefits that would result. Working from one of the essential ORS objectives, the need for responsive contact with ORS LEO missions, the author develops a new mission application for ORS satellites and defines the system architecture, identifies some main requirements, and suggests a preliminary design. The system discussed promotes responsive launch, efficient operations, and low-cost system systems development from which all small satellites and missions would benefit.

The proposed mission application greatly enhances LEO missions and their value by the use of a small group of communications satellites. The analyses in the paper identify trades on the mission, applicable orbits, and operations; recommend a system configuration; suggest satellite configurations consistent with the developed ORS standards; and discuss additional benefits this mission would yield. The results provide compelling arguments and implications for the definition of the overall ORS systems architecture, the procurement of at least five satellites for the first block buy, and the ground support and launch segments to be developed for ORS.

INTRODUCTION

Program Background

Certain recent DoD space efforts are focused on the use of small satellites to support the war fighter in tactical theaters. One effort is referred to as Operationally Responsive Space (ORS) Joint War-fighter Support (JWS) and has resulted in the establishment of a formal Joint ORS Core Office at Kirtland AFB, in May, 2007.

In ORS, emphasis is being placed on small satellites which can be responsively launched and support the tactical theaters of operations with one year missions. Phase III of that effort, managed by the Naval Research Laboratory (NRL), and their Industry Systems Engineering Team (ISET) studied potential missions and created standards for the spacecraft bus, payload and launchers. The TacSat-4 and TacSat-3 programs are related efforts which test the application of such standards to design and build typical ORS spacecraft.

A variety of missions were defined and studied for their requirements and payload needs. A goal was to create similar spacecraft buses, designed to a common standard and using standardized interfaces, which would support a substantial proportion (roughly 80%) of the missions. A secondary objective of standards was to be applicable to the economic production of other, non-DoD spacecraft and further enhance small satellite affordability.

While the above efforts dealt with many program business and hardware issues within the context of traditional existing and certain desired capabilities, the author believes that the ORS is at the stage where it could be further enhanced by consideration of certain broader perspective and system architectural approaches. These approaches could be so beneficial as to pay for themselves.

This paper proposes and discusses a potential approach for improving the operational responsiveness of (primarily) LEO missions by using a small number of communications satellites in a specific arrangement.

The number of satellites to be employed could be the same as the size of the program's anticipated block buys. Due to the mission, its focus, and the spacecraft requirements, it would be a logical first buy and use of ORS standards and operational concepts.

ORS Spacecraft Capabilities

The direction resulting from the ISET committee deliberations was to focus on LEO and HEO missions and a single spacecraft bus standard. Levels of desired capabilities were selected to attempt to cover 80% of the missions ORS would attempt to support. Current key required vehicle capabilities are shown in Table 1.

Table 1: ORS Spacecraft Capabilities

ORS Requirement Category	Capability	Comments
SV Launch Mass	400 kg	Falcon 1 & Minotaur IV Launch Vehicles Volumes and I/Fs
Bus Wet Mass	200 kg	Approx. 50 kg fuel
Allowed Payload Mass	175 kg	PDG Defines Volumes
Provided PL Power (Avg.)	200 watts	PDG for other power use and options
Provided PL Power (Max.)	700 watts	PDG defines Various Services
Eclipse Energy to PL	350 w-hr	PDG for Options
PL Power Dissipation into Bus	60 watts	PL may provide additional radiators
SV Position (GPS)	90 m (3 σ)	Better in LEO
Payload Attitude Knowledge from Bus	0.0167 deg (3 σ)	To match assigned number
SV Pointing Control	0.05 deg (3 σ)	When not maneuvering
Slew Rate (Max.)	2 deg/sec	ADCS has degraded capabilities > 1 deg/sec
SV Propulsion ΔV	300 m/s	Potential for modular propulsion capabilities
S-band Uplink	2 kbps	SGLS and USB Compatible
S-band (SCN compatible) Downlink	0.5 to 2 Mbps	Leo Higher, HEO lower
Tactical Downlinks	Up to 274 Mbps	Eventual Spiral (future) Development Capability
Bus Design Life	1 year	Better in non-ORS use?

Data source: ORS GBS and PDG Specifications, Rev 2.

Payload and Launch Capabilities

The spacecraft bus defined by the standards is intended to carry 175 kg of payload mass and provide the power and support shown above. The ORS spacecraft are expected to evolve with technology to incorporate future capabilities, such as the bus provision of Common Data Link (CDL) tactical communications.

The program includes the goal of responsive launch. The possible launch vehicles are driven by the total spacecraft mass and volume and the orbits to be attained. The ISET studied potential launch vehicles and narrowed in on the SpaceX Falcon I and RSLP Minotaur IV systems. Subsequent TacSat-4 program decisions have chosen to develop an upgraded Minotaur which may become the focal vehicle for HEO missions.

MAXIMUM UTILITY ORS MISSIONS

The operational concepts for ORS missions have the satellites supporting the theater needs during a single pass over the area. This means being tasked, taking data, and sending it to users in a timely manner. These operations involve uplinks, ground and on-board collection planning, attitude maneuvering, payload operations, and high rate downlinks. LEO missions will be particularly stressed.

The TacSat-3 mission typifies this problem and illustrates the limits to serving the war fighter under the current system architecture concepts. If all of the above activities are attempted during the limited area engagement time, the satellite is much more limited in its abilities to be responsively tasked, cover the theater, and get data back down. Current operational concepts plan to use ground stations in-theater and elsewhere around the world (e.g., the AFSCN) to task the satellite and retrieve data when the in-theater operations are not suitably aligned.

This approach requires out-of-theater ground stations to be scheduled well in advance to de-conflict supports if handling multiple satellites. Those ground assets will be limited in their ability to upload last minute tasking.

Similar problems occur on the responsive data recovery side. If the orientation of the satellite for data collection, its limitations on re-orienting to a downlink site, or its data rates can not get the data to the war fighter in-theater, the data must be recovered soon thereafter at a worldwide ground site. By this time, the data may have lost some timeliness for the war fighter.

These limitations on tasking and data recovery degrade the assets' value to the tactical theater. *A better solution is required.*

The ISET supporting ORS Phase III considered one solution. That was to require each standard bus to have cross-link capabilities, and be able to access any other ORS bird to relay communications and data. They would then still use worldwide ground stations at fixed sites to complete the information transfers. This would require a large number of operating satellites and the addition of very high rate communications links to

each. The crosslink equipment was deemed to be too large of an additional payload (and detrimental to the primary capability) for a standard ORS bus.

The ability to command and retrieve large amounts of data without large delays is still an attractive idea for LEO ORS missions. The solution proposed herein takes a systems look at overall architecture of ORS to develop concepts to provide wider flexibility and responsiveness.

THE RELAY COMMUNICATIONS SATELLITES SOLUTION

If the fleet or any ORS spacecraft in orbit had more frequent access to a communications relay satellite, it could be tasked right up to the time needed to start any re-pointing for in-theater mission work. Then, as soon as it was done with its operation pass, it could transmit the data via the same system. This timeliness of tasking and data retrieval is the number one reason for such a system. (There are also other benefits which will be mentioned after the system is described.) HEO satellites could also use the system while at lower altitudes.

ORBIT RING DESIGN AND DEFINITION

The proposed ORS/JWS Communications Support Satellite System (OCS³) is fairly simple. It would consist of a single plane of equatorial satellites spaced to communicate with the ones ahead and behind. This inclination is selected because most of the ORS spacecraft, missions, and theaters are envisioned to be at low or middle latitudes and low inclination orbits allow for larger launch mass. With proper altitude selection the system can provide continuous coverage of many LEO orbits and frequent contact opportunities per orbit over all latitudes.

Each LEO satellite would access the communications ring through a communication link located on the zenith face of the vehicle. The OCS³ system would use crosslinks to pass communications around the plane to a satellite over a US or master downlink gate site. All ORS satellite operations could be conducted from this central, secure location. Data analysis and mission planning could be conducted using virtual mission operations support centers. Tasking results could be returned to the war fighter in a timely fashion via existing military communications systems including satellites and the military internet.

The system could be initially populated with a minimum number of satellites and kept in readiness. Later it could be quickly augmented to provide extra coverage. Launching and operating the system would provide tremendous training and readiness for the time when other ORS missions need to be performed.

Communications Systems Architecture

The communications capability of each OCS³ satellite would be bi-directional up and down. Communications with other OCS³ satellites could be simpler. Communications traffic with companion satellites would always be in a single direction around the ring. For instance, one could always transmit to the satellite following and receive from the satellite ahead. Data would be passed around the ring until it reaches the gateway to the operational satellite or the master ground gateway.

Commands, maintenance operations, or tasking would go up from the U.S. site, go westward around the ring to the gateway for the operational satellite, and from there down to it. Data would come up to the gateway, go again westward, and be sent down by the satellite over the master station. There, data would be processed, analyzed, and routed through existing military communications systems back to the war fighter. Tasking could be sent up at any time to the satellites approaching or in the theater. Thus, the ultimate in responsiveness is achieved and the requirements for worldwide ground stations and highly trained personnel in the field are reduced.

The required antennas and RF equipment for the system would be straightforward. The forward looking antenna would only receive and the aft antenna would only transmit. For high rate communications over the distances that will be proposed, the beam width of the antennas could be fairly narrow for power efficiency. In a system's minimum number-per-ring ("basic-N") configuration, signals would just clear the Earth's atmosphere. As the number of satellites in the ring is increased, companions would be closer and higher off of the horizon. Crosslink beams might be in the neighborhood of 10 degrees and pointed about 10 degrees below local horizontal.

Communications up and down could use S-band or higher frequencies. Links between the ORS³ satellites and the operational satellites will not have the usual atmospheric losses and the master site can employ larger antennas and power for solid link margins.

Operationally, the OCS³ satellites will have longer contact windows with both the LEO satellites and the master station and can pass greater volumes of data.

Both the up and down links and the crosslinks can be less aggressive versions of the eventually desired Common Data Link (CDL) capabilities and provide potential path for spiral development of CDL systems.

Selection of Orbit and Number of Satellites

For OPCS³ system and its orbit include several basic features:

- A single plane of satellites.
- The satellites should be in a circular orbit to maintain simple positional relationships.
- The initial (basic-N) number of satellites should provide useful immediate capabilities.
- A full number of satellites would provide near complete, full time coverage of a substantial portion of the Earth's latitudes.
- The OCS³ orbit should be one obtainable with the intended small launch vehicles common to the rest of the ORS program.
- The communication system should be at sufficient altitude for broad applicability to other ORS spacecraft and missions.

Naturally, the OCS³ would use the ORS bus, payload, and launch vehicle specifications for their development. Since there will only be one type of mission payload, OCS³ could be the best first ORS mission application.

OCS³ Mission Altitude Selection

The first step in this analysis was to determine the number of satellites required to populate a single orbit plane at various altitudes such that the satellites would always "see" each other. The horizon used was 100km above the hard Earth to avoid signal losses through the atmosphere. This also creates a beneficial overlap of the coverage areas and determines the latitudes for continuous coverage. Figure 1 shows the altitude of the satellites in the communications system ring as a function of the minimum number of satellites.

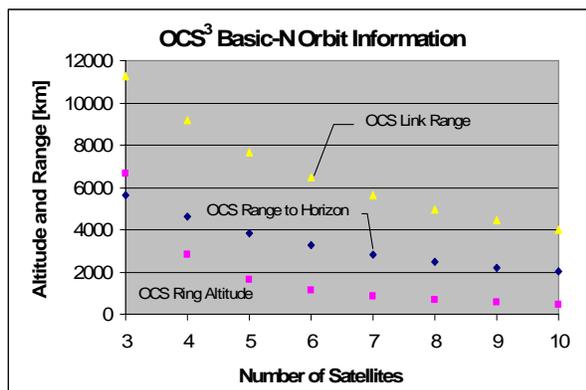


Figure 1: Satellite Altitude and Cross-link Range by Minimum Number (basic-N) in System

Altitudes above 8,000 km were not considered due to decreasing mass-to-orbit launch capabilities. Reaching OCS³ orbits requires additional propulsion for apogee

kick. (Added delta-V for OCS³ can be provided within the ORS mass allocations.) Higher altitudes also expose the satellites to higher radiation levels.

A surprisingly low number of satellites can provide full coverage of equatorial and mid-latitude areas. The typical altitudes required ("Ring Altitude" in the figure) are less than the apogees of HEO missions. Thus, OCS³ would not serve HEO applications around their apogees.

Since low system populations appear feasible and additional satellites have associated cost, we will tend to focus on configurations where the initial minimum number of satellites is five or less.

Geographic Coverage

The next consideration is the ground coverage envelope of OCS³. Due to the use of an Earth radius of 6,478 km to account for atmosphere, the ground coverage areas of the satellites overlap at the equator and up to a full time coverage latitude (north and south). Since the ORS LEO satellites fly at higher than 350 km altitude, the real overlap is even greater. For this analysis it was assumed that an operational LEO satellite talks only to a communication satellite if it is above the operational satellite's local horizon. This provides additional conservatism regarding overlap. Under these circumstances, the continuous coverage latitude for all basic-N populations is always approximately plus and minus 11 degrees.

Figure 2 shows the maximum Earth latitude covered by OCS³ satellites at various orbit altitudes identified by the basic-N number for the ring. Satellites flying above higher ground latitudes will have brief periods of no available contact. But, all satellites will be reachable most of the time and only have the possible short lack-of-contact availability twice an orbit.

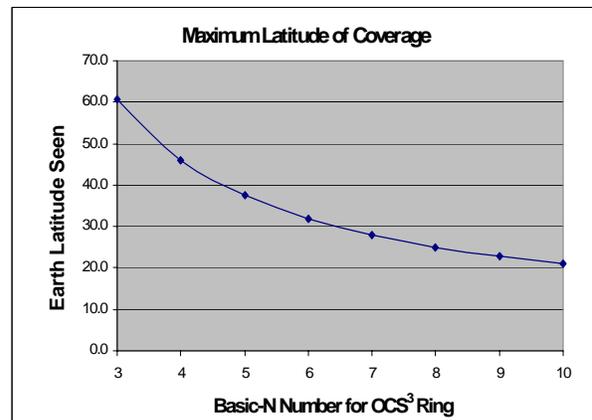


Figure 2: Maximum Ground Latitude Coverage

Figure 3 shows how the minimum full-latitude coverage increases (from the original 11 degrees) as satellites are added to and equally spaced in a system. In the figure, the dots in each column (in ascending order) represent from 1 to 5 satellites added in the system at that basic altitude. The first satellite added has great impact, but further additions increase the coverage little.

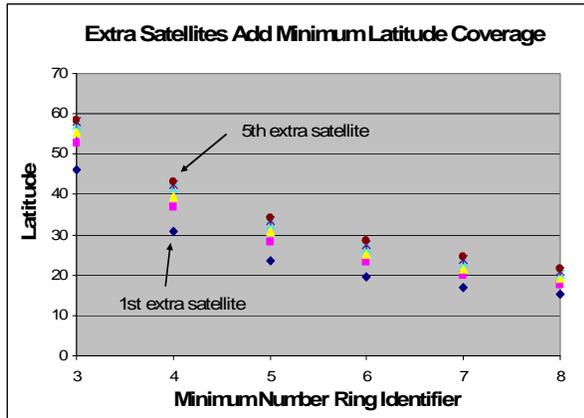


Figure 3: Increased Latitude Coverage with Extra Satellites

Launch Capabilities

Finally, let's see what the launch capabilities are. Here assessments become complex and deserving of a much more detailed analysis. However, some enlightenment can be derived from simplified calculations and comparisons to ISET launch capability conclusions.

The ISET studied Minotaur capabilities for 63.4 degree inclined orbits, mostly for a launch out of Vandenberg AFB. The nominal mission profile was to have the Minotaur inject its payload into a 185 x 8,250 km orbit, and for that payload to use part of the 300 meter/sec capabilities of the standard bus to raise the perigee to around 525 km for the final orbit.

From low, but not equatorial, latitude launch site, the plane change to a zero inclination orbit can require significant delta-V. Optimal propulsion approaches split the plane change between the perigee and apogee burns, so a more sophisticated analysis is needed in final trade-offs to determine launch capability. It appears that Minotaur launches out of Cape Canaveral could be slightly handicapped. The most attractive launch site for this project might be Kwajalein where the plane change is much less, and possibly unnecessary.

The TacSat-4 program is developing and procuring an up-upgraded Minotaur with a large STAR-48 upper stage. It will inject TacSat-4 into an orbit with an apogee near

12,000 km. This could be an attractive launch vehicle for OCS³, but ISET data is not available.

If we assume the Minotaur can put 400 kg into an elliptical orbit, the delta-V to circularize at various altitudes from the 185 perigee can be easily calculated. The apogee delta-V, the payload mass fraction and estimated space vehicle initial mission mass are indicated in the next figure. In all cases, they are plotted by the basic-N number of satellites per Figure 1.

In Figure 4, the assumption is that 400 kg total (wet) mass was inserted into an 8250 x 185 km elliptical orbit by the launch vehicle. The apogees are 6,622 km for the basic-3 ring and 2,783 km for the basic-4. Some form of the Minotaur should have appropriate performance potential for the communications system orbits being considered.

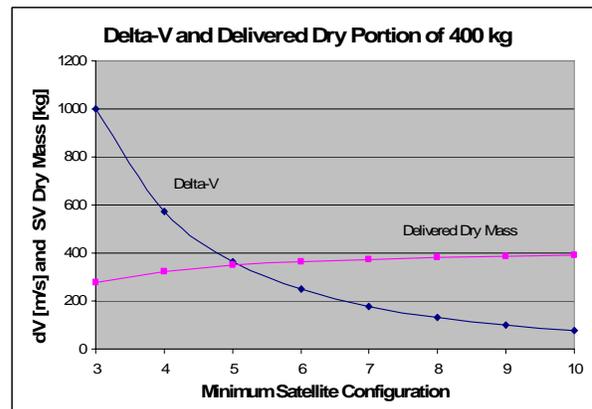


Figure 4: Delta-V Required at Apogee and Delivered Dry Mass (assumes 400 kg initial)

Summary of Orbit Selection

With the decreasing altitude of the more numerous populated rings, the maximum latitude decreases quickly. For +/-45 degree coverage, the system needs the altitude of the basic-4 configuration. A fifth satellite at that altitude provides full time minimum coverage over +/-30 degrees. Higher basic population number systems suffer from lower altitudes and probably only the basic-5 with a couple extra satellites is worth considering. The basic-3 with an extra satellite may be worth considering if the altitudes can be achieved with the selected launch vehicle and added propulsion and radiation is not excessive.

The basic-4 system architecture with augmentation to 5 satellites for critical war fighting operations appears to be an attractive configuration for system design. Further study of this architecture and suitability with the ORS infrastructure is highly recommended.

APPLICATION OF THE ORS BUS STANDARDS

An objective of the ORS program is to use standards and common bus elements to create flexible and affordable spacecraft. This proposed communications system, then, should be an application of that philosophy.

The payload for this application appears to be well within the defined ORS Phase III payload parameters. An estimate for the payload might be on the order of 100 kg. That is well under the ORS identified payload mass of 175 kg and allows for potentially larger propulsion delta-V. The configuration of the payload would include two fixed antennas for the cross-links and one steered, nadir oriented, main up/down link antenna.

The system selection of a circular, equatorial orbit means the spacecraft can operate as a simple nadir pointer pitching at a constant rate and with solar arrays deployed normal to the orbit plane. They will not interfere with the mission operations and can use single axis drives. It should be easy to perform the communications mission with payload power allocation of less than 200 watts.

This application would have no bus requirements for CDL or other bus provided high-rate downlinks. The simple constant pitch attitude system could allow reductions in reaction wheel mass; the control electromagnets would be removed for lack of efficacy (weak geo-magnetic field); there would be minimal data storage requirements; and, the constant payload power dissipation could simplify thermal design.

With these simplifications, mass reductions for the structure, power, and attitude control systems should be obtainable and allow for an up-scaled propulsion system to provide the extra delta-V for attaining the selected satellite's orbit.

The resulting potential vehicle also revitalizes the possibility of supporting certain high delta-V missions that were dropped in early ISET considerations. The bus and payload (the total dry mass) for this communications mission could be around 250 kg, with the remaining 150 kg under the standards capabilities used for launch performance or apogee kick and on-orbit maneuvering of the OCS³ satellite.

The communications mission suggested above would require a five to eight satellite initial buy. It could also provide a smaller, possibly simpler, standard bus attractive to other users. This would be a benefit for the ORS program.

COSTS AND BENEFITS

The initial build of this system should be at least five satellites. With the target ORS procurement cost of \$5-10M (some recurring cost will be assumed by the standards program) the satellites might be \$50M, the payloads \$30M, and another \$10M might be necessary for the augmented propulsion. The launch vehicles for the project may be more costly. However, the entire program might be in the \$140M ballpark.

This effort would be a low risk and ideal initial application and test of ORS/JWS concepts. It would provide an early application of operational concepts and systems prior to the time when critical LEO missions need to be performed. It also provides early launch and ongoing operations readiness for those missions. The OCS³ mission could also be an attractive one for foreign participation and Consolidated ORS (CORS) consideration.

Ground stations, mission control centers and other support items are already required for the program, so there are no additional costs there. The reduction in fixed or mobile ground stations will be a tremendous cost savings to ORS. Also, the training and readiness that will be needed for ORS missions and that is provided by the building, launching, and operating the suggested OCS³ communication system could more than offset the cost of the program.

CONCLUSION

The use of a dedicated OCS³ communications system to support operational ORS space missions is a system architectural approach that should become a fundamental piece of the ORS war fighter support architecture for a truly effective, responsive, and low-cost national or consolidated ORS capability.

The enhancement of other missions, the reduced ground segment costs, and the training and readiness derived make this proposed mission a compelling and logical one with net cost savings for the ORS program.

COMMENTS AND ACKNOWLEDGEMENTS

The analysis in this paper is the private work of the author and was not supported by public or contract funds. The sources used are publicly released information and available from the ORS program. The information used in this paper includes the Phase III System Readiness Review and ORS program standards developed by the ISET and NRL.

The author wishes to acknowledge that ideas for ORS communications capabilities have been expressed by various members of the ISET, notably Mr. Bob Smith

of General Dynamics. These ideas stimulated the author's desire to further explore and define this means of using a single plane of satellites for ORS.

Thanks to Dr. Allan Mense of Raytheon for comments and input on the radiation environments and concerns at various studied altitudes.

ORS SPECIFICATION REFERENCES

1. NCST_IDS_SB001_PDG_ISET_R2_28Feb07,
Payload Developers Guide for ORS, Rev 2.
2. NCST_IDS_SB002_LVIS_ISET_R2_28Feb07,
Launch Vehicle Interface Specification for ORS,
Rev 2.
3. NCST_S_SB001_GBS_ISET_R2_28Feb07,
General Bus Specification for ORS, Rev 2.