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ORS Mission Utility and Measures of Effectiveness

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Abstract

This paper briefly summarizes the traditional space system mission utility analysis process in order to establish a framework for utility analysis for Operationally Responsive Space (ORS). We then define both general and specific ORS Measures of Effectiveness (MoEs) in the following broad categories:

- Cost
- Responsiveness
- Coverage
- Data Quality or Quantity
- Risk
- Flexibility
- Goal-Oriented

These are adjusted somewhat with respect to the traditional utility categories of performance, cost, risk, and schedule to reflect the fact that ORS missions are not duplicative of traditional missions, but complementary to them.

ORS mission utility is particularly challenging in part because traditional missions typically have a constant, long-term purpose (e.g., provide 0.25 meter resolution images of any point on the Earth's surface within 48 hours), whereas ORS missions, by their very nature, are intended to respond to dynamic world events (e.g., provide appropriate coverage of hurricane Katrina or the recent flare-up in Kenya). This makes utility measures inherently more challenging. Nonetheless, demonstrating and quantifying mission utility is key to funding ORS missions in an environment of severely constrained budgets and is critical to the future success of ORS.

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1. Introduction to Mission Utility Analysis

This section summarizes the background and need for Mission Utility analysis. For a detailed discussion of this process for traditional space missions see Wertz [1999].

In looking at the ability of a space mission to achieve its requirements and objectives, there are two broad types of measures:

A ***Performance Assessment*** measures how well the system meets its quantitative goals and requirements. This is engineering oriented — i.e., what is the maximum resolution or what is the area search rate that can be achieved.

In contrast, ***Mission Utility*** is a quantitative expression of how well the system meets its overall mission objectives. It is user oriented — i.e. how many lives are saved, how will it affect the outcome of the battle or war, or what is the average annual savings if this system were to be implemented?

There are two distinct objectives of mission utility analysis:

- Provide feedback for the mission design
- Provide quantitative information for the decision-making community.

Utility analysis addresses the basic questions for decision making, such as whether it is better to develop a particular ORS-Sat or to simply put the money into buying more UAVs.

Although it is equally true of all types of missions, the Warfighter Panel at RS5 taught us an important lesson for ORS: The space system doesn't matter. What matters is what it can do for the warfighter or the victim. They are not really interested in the "how" of space missions, just as I don't really care about how far apart cell phone towers have to be. If I have cell phone coverage when I need it, I'm happy with the service. Otherwise I'm not. The warfigher doesn't really need another piece of equipment that will serve mostly as something to put under the wheels of the truck when it gets stuck.

Ultimately, ORS is not about launch systems or spacecraft. It's about what we can do to help the warfighter, or the cop in New Orleans, at low cost, by tomorrow morning or, better, this afternoon. That's what Mission Utility is intended to measure.

2. Mission Utility Analysis for ORS

One of the current elements of the ongoing Operationally Responsive Space (ORS) debate is whether and to what extent Responsive Space systems have sufficient utility to warrant the funding required to implement them. Traditionally, ***Measures of Effectives*** (MoEs) or ***Figures of Merit*** (FoMs) have been used to quantify the performance, which can then be compared to the cost of implementation. There have been some initial attempts to do this for ORS with both confusing and misleading results, as discussed in the next section.

ORS Mission Utility is particularly challenging. Traditional missions typically have a constant, long-term purpose. For example, we may want to provide 0.25 meter resolution imagery anywhere on the Earth within 48 hours. We then set about designing a space system to achieve this.

In contrast, ORS missions are intended to respond to changing world events. For example, we want to provide appropriate coverage of the war in Iraq <u>or</u> to re-establish communications that have been wiped out by a storm in Africa. This makes it difficult to assess Mission Utility. How do we measure the potential usefulness of a system in meeting warfigher or victim needs that result from unknown future events?

While this ambiguity in goals is challenging, it isn't unique. Ultimately, what is the objective of the Hubble Space Telescope? The real goal is to discover things about the Universe that have never been discovered. This makes it even more challenging than ORS to measure mission utility.

While we may not be able to specify what is needed for ORS missions with precision, we can certainly estimate what types of systems will likely have high utility and what impact they can have on potential outcomes. We do know that unanticipated events will occur. So the real question for ORS is, Will we be as prepared as possible for the next hurricane, tsunami, or biological, chemical, nuclear, or non-nuclear attack on a major world city? The process of demonstrating and quantifying mission utility in these circumstances is key both to funding ORS missions in a severely constrained budget environment and to funding the <u>right</u> ORS missions.

3. Lessons Learned: MoEs that Don't Work

I was involved some time ago with designing a small constellation of satellites that needed frequent, but not continuous, coverage. We decided to use the *Average Gap Duration* (AGD) as our primary MoE and created a small program to calculate various gap statistics.

We initially created a 4-satellite constellation that had an AGD of approximately 60 minutes, which we believed was a bit longer than would work well for this application.

We next tried a 6-satellite constellation, which we re-optimized to provide the best coverage possible. Having done this, we ran our statistics program and found that the AGD was now about 90 minutes. It seemed to us unlikely that our customer would be delighted with paying for two more satellites to go from an average gap of 60 minutes to an average gap of 90 minutes!

Our first assumption was that we had made a mistake in our calculations, but we reviewed them with some care and found that they were indeed correct. Here is what had happened:

- With 4 satellites, we had many gaps, some long and some short
- With 6 satellites, the coverage was much better and filled in nearly all of the short gaps — what was left was a small number of long gaps that resulted in the increase in the average gap duration.

What had occurred was not an error in the computations, but a more fundamental error in our choice of MoE. Consider, for example, a system that has a single gap of 4 hours duration and a second system that has a gap of 4 hours plus 10 gaps of 1 hour each. The second system will have an average gap of only 1.3 hours, but is clearly not 3 times better than the first system.

MoEs should be, and often are, the basis for making fundamental system decisions. The wrong MoEs can be very misleading and can lead to fundamentally incorrect decisions.

A less blatant, but similar result has occurred for ORS. At RS5, a paper was presented for which the major MoE was chosen as the cost per hour of coverage [Tomme, 2006, 2007]. The basic numerical results were:

- SIGINT $43,000/hour
- Communications $61,000/hour
- Imagery $429,000/hour

These large values led the author to conclude that ORS was too expensive to be worthwhile.

The basic problem with this analysis is that this isn't the right MoE. Consider the example of a 35 mm camera bought for $100 and used to take one critical photograph of the terrain or enemy positions. At an exposure time of 1/125 sec, <u>the cost of taking that photograph is $45 million /observation hour. Clearly, this is an extravagant waste of taxpayers money!</u> The military should never be allowed to buy cameras.

Of course, one might argue that the camera will be used for many more photographs than the one critical photo. We could take thousands of photos and, therefore, reduce the cost per observation hour to some more reasonable number. But, in the end, our goal isn't to take as many photos as possible, but to get the one photo that we really need. In many respects, the real purpose of ORS is to avoid having to take thousands of photos, and to try to put as few resources as possible into getting the one, or a few, photos that provide the information that the end user really needs.

What matters for ORS isn't the cost/hour, but the cost of the system and what it lets us achieve that we couldn't otherwise achieve. Our real question is whether it's worth $20 million (the cost /mission used in the reference paper) to

- Find Osama bin Laden and pinpoint his location <u>now</u>
- Find victims of a hurricane, tsunami, or enemy ambush in time to rescue them
- Fill in for a destroyed satellite that was watching Chinese military maneuvers on the Tibetan border
- Provide secure supplementary communications for a Special Forces team in central Africa

The goal of ORS is specifically <u>not</u> to blanket the Earth with coverage. <u>It is to get the right data to the right people, when they need it</u>.

4. Selecting MoEs for ORS?

There are four basic requirements for choosing the right MoEs [Wertz, 1999]:

- Clearly related to mission objectives
- Quantifiable (but not necessarily easily)
- Understandable by and meaningful to decision-makers
- Sensitive to the system design

Note that the most important measures of what we want to do — save lives, win battles, reduce losses — can not be quantified with precision. Nonetheless, we want to be able at least to estimate these values, just as we estimate the lives and property saved in justifying firefighting budgets in any large city.

Traditionally, MoEs fall into 4 broad categories:

- Performance
- Cost
- Risk
- Schedule

In order to find MoEs appropriate for ORS we want to adjust these categories to reflect the goals of ORS that are intended to be complementary, not duplicative, of traditional missions. While there may be many ways to do this, I believe a reasonable breakdown of ORS utility categories is as follows:

- Cost
- Responsiveness
- Coverage
- Data Quality or Quantity

- Risk
- Flexibility
- Goal-Oriented MoEs

As we will see below, the last category is the one that is both the most important and the most difficult to quantify.

5. The ORS MoEs

Clearly, the choice of specific MoEs will depend on the mission and the definitions of some may also be mission-dependent. Nonetheless, I believe the list below includes the most likely MoEs for most ORS missions.

5.1 Cost

ORS missions are typically intended to fulfill a specific function, such as provide imagery, communications, or weather data for a well-defined area or activity. Therefore, mission cost is likely to be more important than the cost per unit. There are two mission costs that are important:

Non-Recurring Engineering (NRE) = Development Cost. This is the full cost of developing the initial system, excluding the actual manufacturing of the first unit. In cost modeling, the cost of building the first unit is called the ***Theoretical First Unit*** (TFU) cost.

Recurring Cost per Mission. This is the ongoing cost of building and launching subsequent flights of identical units. It includes:

- Launch
- Spacecraft bus
- Payload
- Operations (typically normalized to 1 year)

When multiple units are built, the cost per unit is normally represented by a ***learning curve***, which is a decreasing exponential representing the idea that building two of anything is less than twice as expensive as building one. (See, for example, Wertz [1999] for formulas for modeling NRE, recurring costs, and learning curves for multiple units.)

For ORS, we assume that most operational systems will include a non-recurring development phase, then a recurring phase in which multiple units are built and launched, or built and stored for later launch-on-demand. For ORS systems both costs and manufacturing procedures for communications constellations such as ORBCOMM, Iridium, or Globalstar are more relevant than the cost of building one-of-a-kind spacecraft (See, for example, Molnau, et al. [1999], Burgess [1996], Brunschwyler, et al. [1996], or Champlin [1993].) For a discussion of the cost of maintaining systems for later launch-on-demand, see Wertz [2004].

Two other cost MoEs are potentially relevant, but typically will not be as meaningful:

Cost per Year. This MoE will not be meaningful if the goal is to achieve a particular objective, such as support of a particular military or rescue mission.

Cost per Unit of Performance. In this MoE, "performance" should be one of the goal-oriented MoEs, rather than one of the technical measures for the reasons discussed in Section 3 above. The cost per data bit is a bad idea in most cases — it's results we want, not data volume.

5.2 Responsiveness

This is, of course, the fundamental objective of ORS and, therefore, should be a major MoE. The principal distinction here will be between Tier 1 and 2 responsiveness, which are concerned with how quickly we can provide data to the end user, and Tier 3 which is concerned with how rapidly systems can be developed. (For definitions of Tiers 1, 2, and 3, see the DoD ORS Report to Congress [2007].)

Tier 1 and 2 Responsiveness MoEs are discussed in detail with formulas and examples in Wertz [2005]. The most relevant of these MoEs for the mission as a whole are:

Total Response Time (TRT). This is the time from when a new request for data is made until the data is given to the requestor or end user. (For example, an unforecast tsunami hits Southern CA and the LAX Westin. The TRT is the time from when a request for the data needed for rescue is made by someone with the appropriate authority until it is delivered to those who can use it.)

For Tier 2, the TRT is given by:

> ***Total Response Time (Tier 2)*** = Preparation Time + Weather Delay + Launch Window Delay + Insertion Time + Orbit Response Time + Data Return Time.

where the various terms are defined by Wertz [2005]. For Tier 1, TRT will be given by:

> ***Total Response Time (Tier 1)*** = Preparation and Command Time + Orbit Maneuver Time (if applicable) + Orbit Response Time + Data Return Time.

The assumption is often made that the TRT for Tier 1 will necessarily be less than that for Tier 2, but that is not necessarily the case. Tier 1 systems are typically deployed in Sun synchronous orbits so as to cover nearly the whole world, since there is no way of knowing where future events of interest will occur. Therefore, a single satellite may well have a revisit to a particular location of once every 1–3 days (depending primarily on the altitude, swath width, and whether we are interested only in daylight observations). A Tier 2 system will most likely be launched into either a Fast Access Orbit or Repeat Coverage Orbit in order to provide both more rapid and more frequent observations of the specific location of interest [Wertz, 2005]. Thus, in the example mission in Section 7, the TRT for a Tier 2 system will be approximately 11 hours, which may or may not be longer than what would be needed for a Tier 1 asset.

Other potentially important measures of Tier 1 and Tier 2 responsiveness are:

Mean Revisit Time. This is the mean time between revisits to the target. Depending on the application, we may be interested in the mean revisit over an entire day, or during daylight or during hours of defined coverage. The ***Mean Response Time*** is similar, but includes both request and response delay times. The Mean Response Time is more useful in that it is more meaningful to the end user. As discussed by Wertz [1999], the Mean Response Time would not only be more meaningful to the end user ("Mr. President, with this system, the average time from when you request the data until it is handed to you will be x.x hours."), but it avoids the major pitfall described in the first example in Section 3. This is the major reason that the Mean Response Time was initially created as an MoE.

Time Late (TL). The TL measures how "stale" the data is when it is delivered to the end user. Since the actual communications time from low Earth orbit to a local user will typically be much less than 50 msec, the TL will most often be dominated by communications delays associated with having to store, process, or interpret the data for the end user. (The policeman rowing through the streets of New Orleans is most likely not interested in the raw data from a satellite. He wants to know the street address where people are trapped on a roof.)

Tier 3 Responsiveness MoEs will be the following:

Development or Build Time. There are two times of interest here. The ***Development Time*** is the time required to develop and build a first unit of a particular type of spacecraft such that it is ready to be put into storage for launch-on-demand. In addition, there is the idea of what is often called the "***6-day spacecraft***" in which all of the various parts and subassemblies exist in storage and a spacecraft is built-on-demand and then launched. In this case, the ***Build Time*** would be the time required to define, assemble, and test a spacecraft to meet a particular demand.

Technology Insertion Time. If a new sensor or capability is developed, it may not be necessary to build an entire space system from scratch in order to implement it. For example, assume that an observation spacecraft has been built and is in storage awaiting launch-on-demand. It may well be feasible to upgrade the sensor or focal plane array on these existing assets in storage in order to insert the new technology. This becomes much more likely if the spacecraft are built according to Plug-and-Play standards. (See, for example, Graven et al. [2006, 2007, 2008] and Hansen et al. [2007].) Thus, the time required to insert a new technology may be extremely short, relative to the traditional approach of having to fund, define, develop, build, and test an entire new space system. The capacity to rapidly take advantage of new technology is one of the major potential advantages of Responsive Space and can serve as an important mechanism for rapidly leveraging newly created technology to benefit the warfighter.

5.3 Coverage

Coverage is strongly related to responsiveness in that the more often an area is seen, the shorter the response time will be in getting the desired data to the end user. Therefore, coverage MoEs are, to a degree, interchangeable with responsiveness MoEs.

Orbit Response Time (ORT). This is the time from arrival in orbit until the first observation of the target. For some systems this could include time required for check-out, calibration, and outgassing of the spacecraft. For a well-designed responsive spacecraft that is ready to go when it reaches orbit, the ORT is the time from launch until the first pass over the target. For the Fast Access Orbit, this will typically be between 0.5 and 2 orbits (i.e., 45 to 180 minutes). For most other orbits, the mean ORT will typically be 6 to 12 hours, depending on whether a daylight pass is required. (See Wertz [2005].)

The ORT depends only on the orbit parameters and the geometrical relationship between the launch site and the target, and not on the time of day. (Once the spacecraft has been launched, the orbit follows a well-defined path with respect to the surface of the Earth.) Thus, the only impact of the time of day at which the spacecraft is launched is to change the time of day of the observation of the target. For responsive Earth observations, the launch window delay discussed above serves only to adjust the time of day of the target observations. For subsequent days, assuming a prograde responsive orbit, the observation time will move earlier by about 30 minutes per day due to both the motion of the Earth in its orbit and, more importantly, the rotation of the orbit plane due to the Earth's oblateness. (See, for example, Wertz [2001].)

Observations per Day. Depending on the mission, this may be per satellite or for the system as a whole, if there are multiple satellites. Similarly, we may wish to count the entire number of observations per day or only those that occur during daylight.

As shown in Figure 1, the number of observations per day per satellite will depend primarily on the orbit inclination, altitude, and minimum working elevation angle. For detailed computations, see Wertz [2008]. The broad conclusion from this data is that a prograde Repeat Coverage Orbit provides 3 to 10 times as many observations per day as does the traditional Sun synchronous orbit.

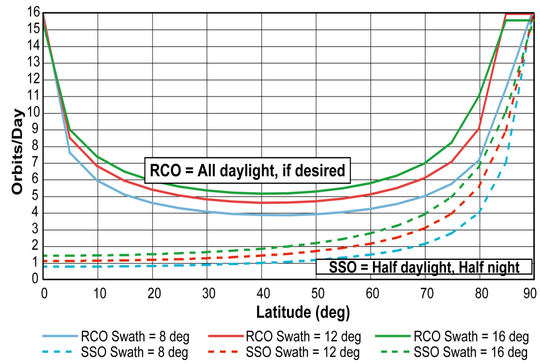

Figure 1. Orbits/Day of Coverage vs. Latitude for Repeat Coverage Orbit (RCO) and Sun Synchronous Orbit (SSO). (from Wertz [2008].)

Number of Spacecraft. This is the number of spacecraft required to achieve a given level of coverage or frequency of observations. In a well-designed responsive system, this will be a number that can change as the needs evolve. Thus, a single satellite would normally provide the initial observations and assessment. As circumstances evolve, the decision can be made later either to increase the frequency of observations (for example, from once every 90 minutes to once every 45 minutes by launching another satellite 180 deg out of phase in the same orbit) or extend the span of observations to include a larger fraction of the day.

5.4 Data Quality or Quantity

Resolution at Nadir. For imaging missions, the basic measure of the image quality is the resolution at nadir [Wertz, 1999]. An alternative measure often used by image analysts and scientists is the ***National Imagery Interpretability Ratings Scale*** (NIIRS) which goes from 0 (worst) to 9 (best) and is based on the ability to interpret the resulting images. (See Fiete [1999].)

A major advantage of Responsive Space systems in terms of data quality is the ability of the system to fly lower because it is not trying to cover the entire world and does not need a 10 or 15 year life. Ultimately, as shown in Figure 2, altitude is a remarkably low cost substitute for aperture. The 2.4 meter diameter Hubble Space Telescope looking down from 800 km will have essentially the same resolution as an 0.7 meter aperture instrument flying at 250 km. However, Hubble initially cost about $2.5 billion in today's dollars, whereas an 0.7 meter diameter instrument will cost several million dollars.

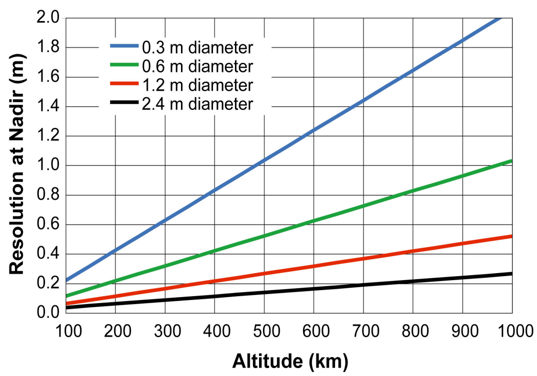

Figure 2. Resolution at Nadir as a Function of Aperture and Altitude. (from Wertz [2008].)

Bandwidth or ***Number of Simultaneous Users.*** For a communications mission such as Blue Force Tracking or Supplementary Communications, the basic measure of performance is either the bandwidth or the number of simultaneous users. In today's space systems, there is an ever increasing demand for more bandwidth as information transfer becomes more and more important. Initially, we are likely to need only latitude and longitude and simple commanding in the field. As systems and processes become more sophisticated, the amount of data needed grows, such as a new requirement for secure cellular communications. Of course, modern cell phones nearly all have cameras such that there will be enormous value in transmitting images and, in due course, color images with high resolution. Thus, it will be important for Responsive Space Communications to provide continuously increasing data rates.

5.5 Risk

Because Responsive Space systems are much lower cost than traditional missions, we expect that they should be able to tolerate a higher level of risk. In addition, launch-on-demand implies that there is more than one system available for immediate or nearly immediate launch, thus further mitigating the consequences of a launch failure. Nonetheless, today's space systems are dramatically risk averse and that mindset will not easily change. Thus, risk will continue to be an important MoE, even if the amount of acceptable risk is larger than for traditional missions.

Probability of Successful Deployment. This takes into account both the probability of a successful launch and the probability that the space system will work successfully on orbit. Historically, both launch systems and spacecraft have worked better after any problems have been resolved with the first few to be launched. Launch vehicles have a long-term probability of success of about 90% and are likely to be the dominant factor in the probability of successful deployment.

Probability of a Successful Mission. This MoE takes into account the potential for executing a back-up launch if either the launch vehicle or spacecraft fails on the first launch. Given the potential for a back-up launch, the probability of a successful mission should be very high. However, when a failure occurs, launches have historically been stopped for anywhere from several months to a year or more in order to investigate the failure. There has not yet been enough experience with ORS missions to determine whether this paradigm will continue or whether, like missiles or airplane attacks, several opportunities will be permitted in the hope of ensuring mission success.

Ability to Reconstitute Assets. A key purpose of ORS systems is to allow the potential to reconstitute assets that have been destroyed or otherwise failed on orbit. The Chinese ASAT test has made it clear that American space assets are vulnerable to enemy attack. Note that "reconstituting assets" does not necessarily, or even usually, mean a replacement of identical capability on-orbit. Generally, the assumption is that ORS assets used to replace traditional National assets will be significantly less capable and shorter lived. However, this is made up in part by allowing them to be focused on a particular region or event of interest and having some capability on orbit is better than no capability.

5.6 Flexibility

Orbit Agility. Because of the very high delta V requirements to change orbits, most spacecraft will do orbit maintenance from time to time, but otherwise remain in a fixed orbit for most of their operational life. (It takes more delta V to change a spacecraft from a polar orbit to an equatorial orbit than it does to launch it into orbit in the first place. Under ordinary circumstances it is effectively impossible to turn a spacecraft around and fly it the other way, as can be easily done with aircraft.) However, Col. Robert Newberry has introduced the concept of ***Agile Spacecraft*** to refer to a spacecraft that can make modest changes in orbit parameters to meet specific mission needs.

An example of the mission utility of orbit agility comes from the discussion above of the dependence of resolution on altitude. At 200 km, a spacecraft would normally have an operational lifetime of only a few days. However, consider a spacecraft in a 400 km circular orbit with a nominal lifetime of 1–2 years and a resolution at nadir of 0.8 meters. For a delta V expenditure of 60 m/s, the spacecraft can be put into a 200 km x 400 km elliptical orbit with a resolution of 0.4 meters at perigee, thus providing twice the nominal resolution over a particular area of interest. When finished, the spacecraft can be returned to a higher perigee or, if near the end of life, brought down in a positive deorbit.

Observations Time Flexibility. A subset of spacecraft agility is the ability to adjust the timing of observations over an area of interest. This is most easily done by making a small change in altitude, which changes the period and, therefore, the arrival time and azimuth over the target. This can be used for several purposes:

- To keep the enemy off balance such that the satellite does not arrive where or when it is expected
- To adjust the arrival conditions to provide a better view, such as bringing the target nearer to nadir as the satellite flies over
- To adjust the arrival time to correspond to a planned event, such as a planned attack or the arrival of another satellite for simultaneous or adjacent viewing

The delta V required to adjust the arrival conditions will be inversely proportional to the time allotted to make the adjustment. In low-Earth orbit, every 13.7 m/s of delta V will change the mean altitude by 24.4 km and the period by 30 sec. Integrated over a day, this change can be substantial. For example, assume we see a particular location once per day. A 13.7 m/s delta V will shift the next day's pass (15 orbits later) by 7.5 minutes either sooner or later.

Multi-Mission Utility. This refers to the potential to use the same asset for more than one mission. A typical responsive space mission will cover a specific location on Earth which the satellite may see only a few times per day. This means that the same satellite could potentially work in some other part of the world without interfering with its primary mission.

Similarly, if the primary mission lasts a few weeks or months, there may be the potential for using the space asset for the next major world event, or simply to supplement other space assets. If the spacecraft is sufficiently agile, then it may be able to change the orbit to a degree to allow optimal coverage of a latitude other than that for which it was launched. (An inclination change requires a delta V of approximately 130 m/s per deg of change. This implies that inclination changes will be both modest and infrequent.)

5.7 Goal-Oriented MoEs (GO-MoEs)

Most of the MoEs above are measures of technical performance. They are engineering parameters that describe how well the system works. But our real objective in any operational space mission, irrespective of whether it is an ORS mission, is to do something for the end user or for the people who have put up the money to fund the system. These broad objectives are represented by the ***Goal-Oriented MoEs* (GO-MoEs*)***. Quantifying these is typically challenging and most likely cannot be done with precision. Nonetheless, these are the MoEs that are the most important in terms of providing feedback to the system designer or deciding whether to build the system in the first place.

For example, suppose we are considering whether to use a newer, lighter-weight, more efficient, but more expensive solar array for an ORS surveillance satellite. If a careful analysis shows no impact on the GO-MoEs, then the right answer is to stay with the option that is lower cost. We only want to spend extra money on those features that will have a positive impact on the end objectives of the mission.

How can the choice of solar array affect the number of lives saved or outcome of the battle? There are several possible ways:

- The lighter solar array can reduce the spacecraft mass, allowing more propellant, increasing the agility, and, therefore, allowing better coverage.
- The more efficient solar array will be smaller, therefore reducing the drag, allowing the spacecraft to fly lower, and improving the resolution.
- The more efficient solar array can also provide more power to either improve the communications link or allow the system to operate either longer or in a different theater on the same orbit.

These are all technical performance measures, but it is relatively easy to see how these can potentially affect the GO-MoEs and, therefore, have a positive impact on the overall mission. Irrespective of the merits or demerits of better solar arrays, the point is that what we really want to measure is the impact of potential system changes on the end user, the victim, or the organization that has funded the system.

There are 4 basic sub-categories of GO-MoEs:

- **Measures of Success**
- **Impact on Outcome**
- **Measures of Utility**
- **Level of Preparedness**

Each of these is discussed below.

Measures of Success. For a great many ORS missions the Measures of Success are the ***Number of Lives Saved*** and the ***Money or Property Saved***. While these are exceptionally difficult to quantify, they are really what many of the ORS missions are all about.For the warfighter, the real measure of how much the system helps will be its ability to reduce both combatant and civilian casualties and to save money and property that would otherwise be destroyed or consumed. Much the same applies to using ORS for natural disasters. Could we have saved lives or reduced the amount of damage by having better surveillance or communications after hurricane Katrina or the SE Asia tsunami?

Impact on Outcome. If an ORS mission was launched in response to a particular event or a newly identified need, did it have an impact on the outcome of that event? Could it have a major impact on the outcome of future events? For example, if the Chinese choose to destroy one or more American satellites in advance of a major military activity, could the presence of ORS-developed gapfiller satellites prevent an invasion of Tibet, Taiwan, or Korea? Perhaps even more important, could the known presence of the ORS gapfiller capability prevented the attack on the American surveillance satellites in the first place?

For natural disasters, could we change the fundamental outcome by having ORS systems available? Hurricane Katrina is a particularly good example here. Its difficult to envision a location in which space surveillance or supplementary communications would be less needed than in CONUS, where the communications infrastructure and aircraft availability is as good or better than anywhere in the world. But somehow Katrina managed to immobilize a large portion of that ground and air infrastructure. Planes that were flying were needed for other tasks and not available for damage assessment. Much of the communications infrastructure was destroyed. The first photos published in *Aviation Week* of the aftermath of the hurricane were taken by NigeriaSat, part of the Surrey small satellite Disaster Monitoring Constellation.

It is, of course, possible that some American satellites had, or could have had, rapid high quality images of New Orleans and workable communications channels. But, if that was the case, they weren't available to the policeman in the street or those who were trying to coordinate disaster relief. This re-emphasizes the basic character of ORS Mission Utility — ***It isn't the data or the processes that exist that matter, it's what gets to the warfighter, the end user, or the victim or what is used for their benefit that matters. To have utility, the data has to get to the people who need it in time for them to make use of it.***

Measures of Utility. Strongly related to the Measures of Success and Impact on Outcome are the ***Measures of Utility***. Specifically, how will the mission impact our ability to:

- Predict
- Protect
- Respond
- Retaliate
- Restore
- Rescue
- Contain
- Limit Collateral Damage

Of these, the one that is least related to the prior discussion is the ability to predict, since we typically think of ORS missions being launched in response to world events. A predictive mission that has substantial utility is a Wind Lidar that can directly measure winds at various altitudes [Wertz, et al., 2004]. This is critical to all of the military services as well as many natural or man-made disasters. For example, where will the winds take a volcano plume or airborne chemicals from a civil disaster?

In the same season as Katrina, Hurricane Rita entered the Gulf of Mexico and it was uncertain for some time what path Rita would follow. This made preparation both difficult and expensive. Figure 3 shows the coverage of an ORS Wind Lidar system in a single day over the region of the Gulf.. This type of wind data would significantly improve the capacity to predict the track of the storm and, therefore, make better, safer, and more economical preparations.

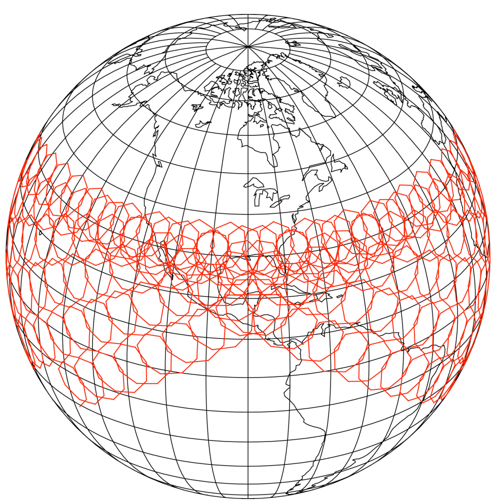

Figure 3. Wind Lidar Data Over the Gulf of Mexico in One Day. 6 successive orbits provide data every 90 minutes for 9 hours, allowing much better prediction of the path of storms or toxic clouds. (from Wertz [2008].)

Level of Preparedness. How ready are we to respond to unforeseen world events or changing conditions on the battlefield or in the war on terror? In one sense, we are, by definition, unprepared for events that are unforeseen. However, just because we don't know the nature of the event, does not mean that we can't be prepared for it. Irrespective of the nature of the problem or event, the types of services that we need are largely the same — surveillance to understand what has happened, communications to work with those who have been impacted, and data such as winds or successive images to predict how the situation will evolve. In a sense, ORS provides a new tool to be able to respond to changing world events, specifically when we don't know the nature of those events.

6. Evaluating MoEs

Some of the MoEs are straightforward to evaluate while others, typically those that are more useful, are far more challenging. Specifically, the technical performance measures — such as response time, resolution, data rates, or coverage — can be evaluated analytically or with simple numerical methods. Cost and risk parameters are harder to know with certainty, but can be modeled with well known methods and models, although the fact that they are well-known does not necessarily make them correct, particularly when the paradigm under which the ORS systems are built differs dramatically from the traditional space mission methods and processes. Both Wertz [1999] and the references cited in each of the sections above provide more extended discussions of the evaluation of technical performance MoEs, cost, and risk. Coverage evaluation methods are covered in detail by Wertz [2001].

By far the most challenging to evaluate, and the most important, are the GO-MoEs. In most cases, the only realistic way to estimate these is either via simulations or scenario evaluations.

For simulations, there is an important distinction for the evaluation of MoEs. ***System Simulations*** tend to concentrate primarily on technical parameters of the system itself — i.e., power, communications bandwidth, coverage, resolution, and similar parameters. In contrast, ***Mission Simulations*** model these parameters at more of a top level and provide more detailed models of "outside parameters" that may dramatically affect the outcome, but have little to do with the system itself, such as weather or the evolution of ground events. Thus, we may spend a great deal of time optimizing coverage patterns to minimize gaps, when in reality, gaps in coverage may well be dominated by weather patterns over the target area.

One of the major characteristics of a good mission simulation is that it should provide good animation or other visible output that creates a more intuitive feel for what is causing the results. Recall the problems discussed in Section 3 resulting from an excessive reliance on statistical results. Statistics can, at times, be very valuable, but they rely on the idea that the underlying data has a Gaussian or random distribution. Neither orbit patterns nor weather are Gaussian. Therefore, in addition to statistical results, we want analytic values, animations, simple approximations, and scenario evaluations to gain a "feel" for what is occurring so as not be misled by purely numerical simulations.

Finally, we also want ***scenario evaluations*** in which we look at the impact of the ORS system on specific real or projected events. These can be done by a combination of simulations of the event, analysis techniques, and discussion with experts in that particular field. The evaluation of what might have been achieved in past real events is one of the most effective methods of evaluating mission utility.

7. Example: The Hawaii Disaster of 2010

In late October 2010, an earthquake and resulting tsunami struck Japan with damage to all of the major airports and most homes, businesses, and infrastructure. Communications were badly disrupted and it was difficult to assess the damage or to find people that needed help, needed to be moved, had been washed out to sea, or were in imminent danger due to potential aftershocks.

By order of the President, HawaiiSat was launched from KSC 10 hours after the Earthquake hit to provide both visible and IR images. The satellite carried an 0.5 meter diameter imager. Following a 4 deg inclination change at the equator, the satellite was placed in a 250 km altitude circular orbit at an inclination of 24.5 deg. The ground swath of HawaiiSat's first 5 orbits are shown in Figure 4. The first images of the damage at a low elevation angle were returned on the first orbit about 80 minutes after launch. The second pass, 90 minutes later, flew almost directly over the islands and gave very good images of the damage and allowed the first estimate of the drift rate and direction of debris floating at sea by comparison with images from the first orbit. The next two orbits provided images at shallow angles for the big island and more nearly overhead for the rest of the islands. The fifth orbit again passed nearly overhead, 6 hours after the first orbit. 5 or 6 orbits of imaging occurred on subsequent days, moving about 35 minutes earlier per day.

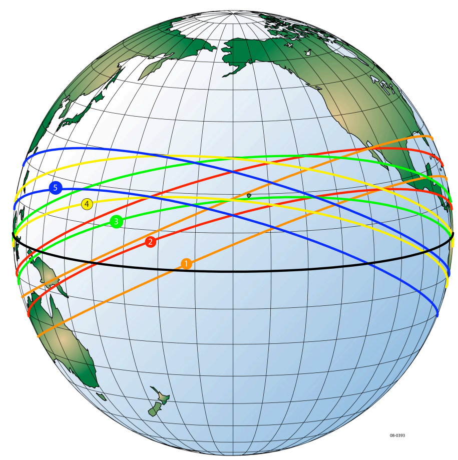

Figure 4. Swath of the First 5 Orbits for the Hypothetical HawaiiSat Mission. Hawaii will be visible on 5 or 6 orbits/day with the observation times moving approximately 35 minutes earlier per day.

The spacecraft parameter and cost estimates for the above system are based on the Frequent Revisit Surveillance mission discussed by Wertz [2006] and Cox, et al. [2005, 2006]. Based on these parameters, the HawaiiSat MoEs are:

- **Cost**
  - NRE — $40 M
  - Recurring cost/mission — $17.3 M
- **Responsiveness**
  - Total Response Time — 11.3 hr
  - Mean Revisit Time — 85 min for 6 to 7.5 hrs
  - Time Late — 5 min
- **Coverage**
  - Orbit Response Time — 80 min
  - Observations/Day — 5 to 6
  - Number of Spacecraft — 1

- **Data Quality**
  - Nadir Resolution 0.3 m
- **Risk**
  - Prob. of Succ. Deployment 90%
  - Prob. of Succ. Mission 99%
- **Flexibility** TBD
- **GO-MoEs**
  - Need a mission simulation and discussion with emergency response personnel to evaluate these critical measures

While we don't yet have all of the numbers we need, it seems clear that ORS provides a new capability to Respond, Restore, Rescue, Contain, and Limit Collateral Damage. With ORS, we will be prepared to save lives and property.

8. Conclusions

Just as they are for traditional missions, Mission Utility and MoEs are critical to the success of ORS missions, both in the process of making design decisions and in demonstrating utility vs. cost in what will remain a very constrained budget environment. While the technical performance measures are relatively easy to quantify, it is the Goal-Oriented MoEs (GO-MoEs) that are important in evaluating how well ORS missions meet their broad objectives. These will typically need to be evaluated by a simulation, mission assessment, or both.

The choice of an ORS mission is likely to depend not only on the nature of the world event to which it is responding, but also on outside circumstances that may dictate how best to respond. For example, for either disaster relief or battlefield monitoring, visible light surveillance will provide high resolution, broad coverage, and rapid, relatively easy interpretation. However, if nighttime coverage is critical, we may choose to change to IR or visible/IR combined. If there are heavy clouds forecast for the next several days, then a synthetic aperture radar (SAR) mission is likely to be the most effective.

Finally, the key issue for ORS mission utility is that it isn't the existence of data or processes that matters, it's what gets to the warfighter, the end user, or the victim or what is used for their benefit that matters. To have utility, the data has to get to the people who need it in time for them to make use of it, typically under circumstances that are far less than ideal.

If we can do this, then ORS will have a clear role to play in future space missions.

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