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Reinventing Disaster Reconnaissance through Space Assets

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ABSTRACT

When a disaster occurs, an aggressive machine of governments, agencies, and volunteers immediately reacts to the event with a lack of information. Currently, agencies rely on unstable communications, perhaps UAV passes (which may be politically limited), or, hours later, space assets. Workers may be dispatched without fully understanding the extent of the damage to roads, buildings, or infrastructure at a risk to the safety of both the afflicted community and their volunteers. Imagine launching a satellite that, within hours, provides clear pictures, communication, sensor readings, and information to volunteers/troops identifying the most afflicted regions

This paper will showcase an example of how responsive space assets could respond to a potential tsunami disaster. It will effectively utilize space assets, propose constellation architecture that can effectively give accurate information within hours and finally look at the performance capability of a satellite covering an affected area. Such architecture must focus on common disaster areas. It is not beneficial to create a responsive asset that covers the whole world when a specific range is required. The orbit must provide repeat coverage that would easily be accessible to the ground support team.

KEYWORDS: low-cost, space assets, Tsunami, Disaster Relief

INTRODUCTION

How can the satellite community aid disasters? When disaster hits, the machine starts running to respond to the human need, the property damage, and safety of the area. Relief workers need pictures to know where the damage is and where to go. They need reliable communications since cell towers may be damaged and flooding the area. Somewhere during the chaos, communication and information is desperately needed. This is where the satellite community can contribute to the disaster relief efforts.

The satellite must be responsive. It does the afflicted communities no good to have a satellite launched 2 months after an event has happened. This timeframe is affected by lead times to integrate spacecraft parts and payloads as well as get through the regulation required to launch. The concept focuses largely on the launch on demand aspect with spacecraft that are built to inventory. Ideally we imagine the spacecraft to be below $5M for spacecraft, launch vehicle, and operations costs for a baseline mission of several months extendable up to 2 years, providing sub-meter resolution. Instead of building assets that last years, this system will last weeks to months to reduce propellant mass below a few km/s and cost. The spacecraft can fly in a low orbit to dispose easily of its services at the end of life.

There are certainly challenges to rapid space asset utilization for disaster relief such as launch vehicle availability; however, providing a low-cost option for disaster relief can significantly change how we utilize space. Existing orbit assets are not always available when and where, you need them. Closing this gap will not only lower the cost to respond to disasters, but save lives.

Different disasters require different sensors and payloads. The bare minimum mission for a satellite will be an image, communication, and secondary sensor information. We first need to define the disasters. A sample of disasters is shown in Table 1. The latitude where these disasters are found determines where to launch a satellite.

Table 1: Defining Disasters

Disaster	*Location*	*Latitude*	*Sensors*
Tsunami	Pacific Ocean Pacific Rim Indonesia to India	60°S — 70°N	Wind Patterns Wave Patterns
Volcano	Ring of Fire around the Pacific Ocean (Pacific Rim)	60°S — 65°N	Thermal Ash/Chemical Analysis
Hurricanes	Gulf of Mexico and West Atlantic Ocean Coast of Australia and East Pacific Ocean	10°N — 50°N 35°S — 45°N	Clouds
Tornadoes	United States to the west tip of Russia East India, Bangladesh, Nepal, East China, Japan, South Korea, Philippines Argentina, Uruguay, South Africa, Australia, New Zealand	23.5°N — 65°N 10°N — 40°N 45°S — 15°S	Wind
Forrest Fire		35°S — 30°N	Thermal Arid Conditions

This paper will focus on Tsunamis as an example of how a satellite can respond to a disaster at a specific latitude range.

The tsunami that hit Japan in 2011 was one of the most recent tragedies in natural disasters. The 8.9 earthquake started at 2:46 PM, with the resulting tsunami hitting shortly after 3pm off the coast of Japan. The resulting waves were over 3 m high and destroyed coastlines in Iwate and Miyagi prefectures within 30 minutes after the earthquake hit. [5] The degree and extent of damage caused by the earthquake and resulting tsunami were enormous, with most of the damage being caused by the tsunami. Estimates of the cost of the damage range well into the tens of billions of US dollars; before-and-after satellite photographs of devastated regions show immense damage to many regions. How could a disaster monitoring system aid the Japanese tsunami? We must first understand how tsunami's are detected and the information communicated.

TSUNAMI ARCHITECTURE

Current systems send information via satellite as shown in Figure 1. A tsunami forms when an earthquake occurs deep within the ocean's floor. [1] The resulting explosion from the earthquake displaces water forming large waves. These waves are monitored with transmitter buoys that signal passing satellites and ultimately send a signal down to an early warning station.[1] In the case of the Japanese tsunami, the resulting waves hit the coast of Japan within 15 minutes of the earthquake because the epicenter of the earthquake was so close to the coast. Tsunami waves can go over 500 miles per hour and generate waves as high as 30 m.[4] The Japanese Tsunami had an earthquake that was settled within the Ring of Fire, which referring back to Table 1, is within that 60°S — 70°N latitude range.

The team must asset the food, clean water, medicine, electricity, and shelter supplies for coming survivors. The team must identify where they can send troops and supplies to the afflicted area. After determining where they can land to send help, they can actually start the effort to gather people. This may consist of sending boats or helicopter rescues to help people stranded in unsafe conditions. As emergency workers continue to come in with supplies and survivors removed to safer locations, logistics issues arise. How can space assets help this situation?

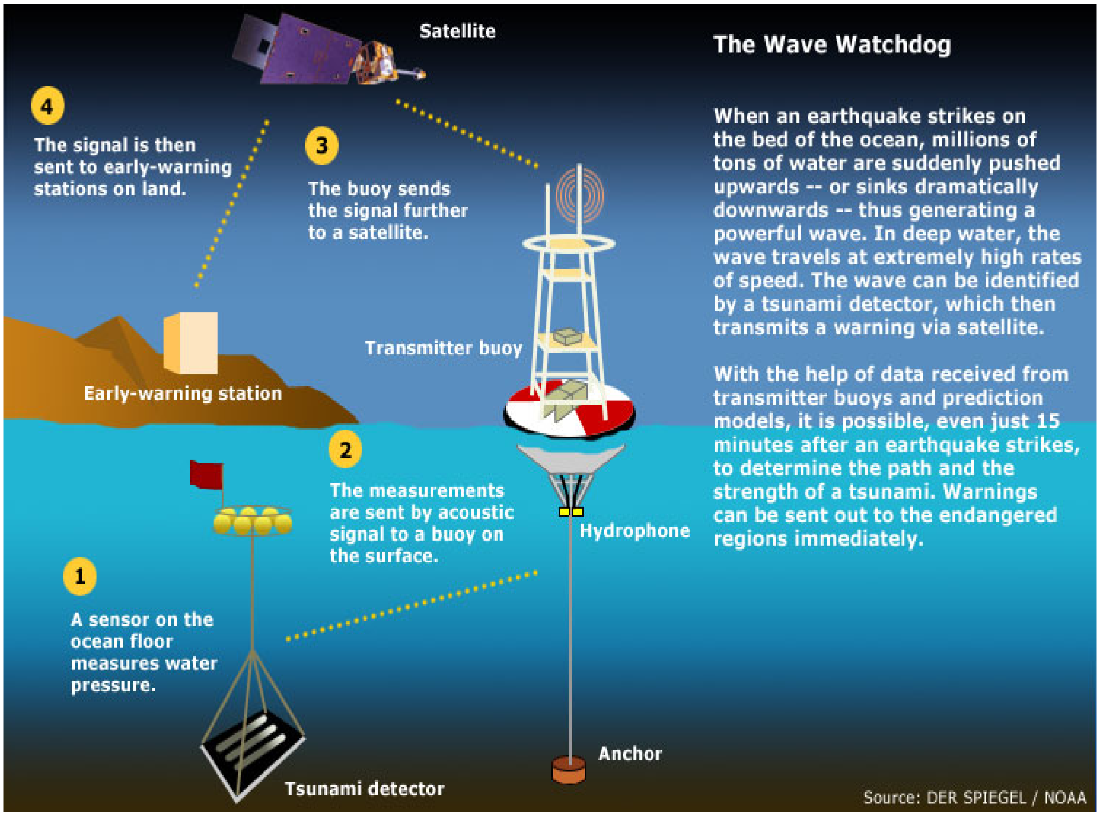

Figure 1: Tsunami detection system

CONSTELLATION REQUIREMENTS

The first thing that space assets can do is give an instant picture of the condition of roads, the location of stranded survivors, or provide intelligence on the best place to send troops. The situation is chaos all around, and having an instant picture after the damage will help the response team adequately address the situation.

This asset is short lived for only weeks to month or at the most a year. Figure 2 shows how resolution changes versus the lifetime of the satellite. Disaster relief would only need a year to two years of lifetime which means that a lower altitude and thus lower resolution is appropriate.

If we assume that we could use a 1 m resolution and have over a one year lifetime and even up to a two year lifetime we can assume a 200 by 400 km orbit. Looking at this, we can see that that translates into a swath width of 1 to 3 degrees. This translates into a about 4,761 square miles of land. Japan is 145,925 square miles in comparison.

Using a private communications satellite to monitor GPS of buoy's [1], means that we can determine if there is a tsunami tidal wave, but not the actual damage. The information does not give any idea on where the volunteers can land or which provinces are in need of the greatest help. A major issue is the fact that places that have working communication systems will be able to call for help and get the fastest response. These places may get the volunteers needed, but are not in the most need of aid when time is crucial. Therefore, a responsive disaster relief system is necessary to identify the right areas that need help and determine the needed aid.

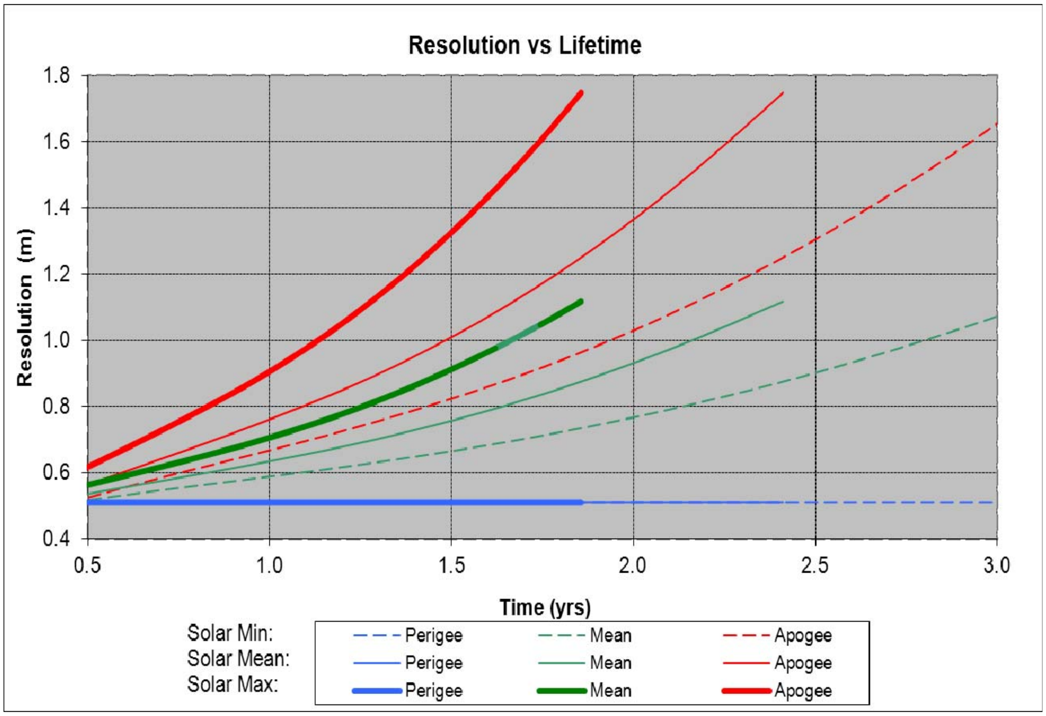

Figure 2: Resolution vs. Lifetime

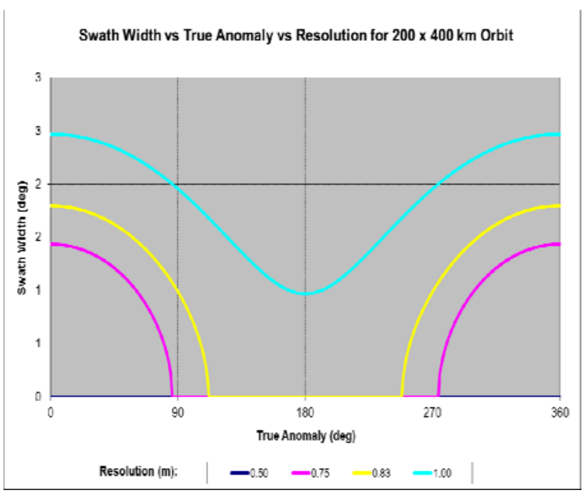

Figure 3: Swath width vs. true anomaly

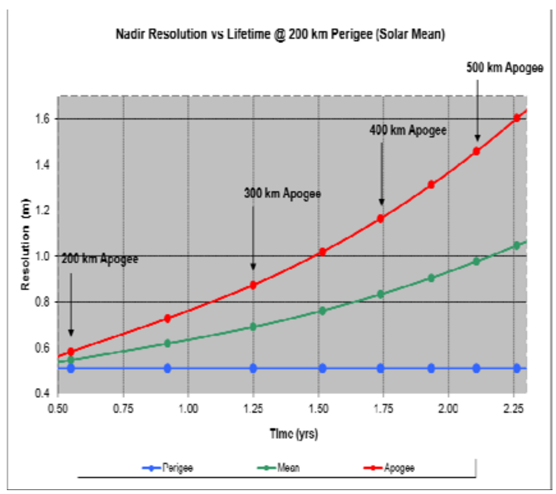

Figure 4: Nadir Resolution vs lifetime.

TIMELINE

A Tsunami can hit an average 6 hours after the earthquake. In the case of Japan, the earthquake was so close that it hit within 15 minutes of the earthquake with most of the damage happening within 30 minutes. Other Pacific areas were issued warnings with waves being felt up to 16 hours away.

Not all, earthquakes cause tsunamis. Tsunami warnings are issued while more information is relayed back through the communication satellites of the buoys in the water. Assuming that a modest 4 hours after the earthquake hits, a satellite is launched, then the volunteer workers would be looking at detailed information 6 hours after a tsunami hits. A flight from Hawaii to Japan for example is approximately 8.5 hours. Therefore if volunteers are sent from Hawaii, a satellite could reasonably be launched and provide detailed information while volunteers where still in the air to determine the best plan of aid. By the time, we deploy volunteers and soldiers we could have initial disaster estimates and know where to land and how to get there.

Images could look for people swept out to sea and determine if there is a safe way to help them. The suggested architecture can take approximately 8 hours to launch a satellite in the air in response to the disaster, which would give approximately 2 hours before a response team arrives. Figure 5 shows a generous timeline assuming a satellite launches when the decision to send volunteers and troops is made. Therefore, while the volunteers are in the air, a satellite image would be waiting for them when they arrive so they can determine the condition of the afflicted area infrastructure and make decisions as to where they would land and which areas they should provide relief to first.

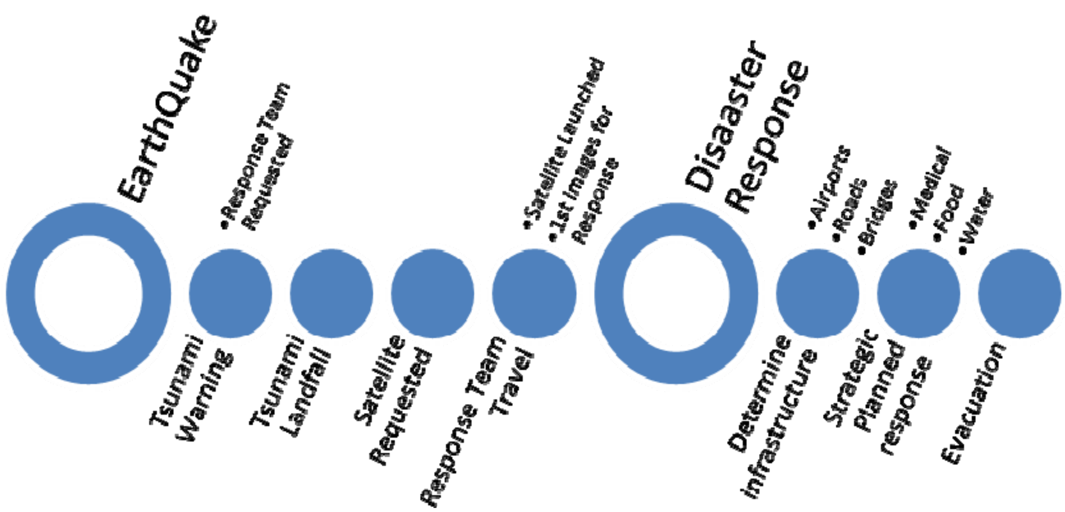

Figure 5: Timeline

The coverage of one satellite with a 65 degree latitude right in the middle of the Tsunami disaster region is given in Figure 6. The chart shows that launching one satellite will give coverage approximately every 90 minutes for the first 6 hours looking at Day 1. This coverage will continue to give daylight coverage until a week from the initial tsunami. Figure 7 shows the resolution that the best successive coverage for the 65-degree latitude is at a 500 or 400 km orbit. For the example given, we use a 200 km X 400 km orbit to show the responsiveness of space architecture to tsunami disasters.

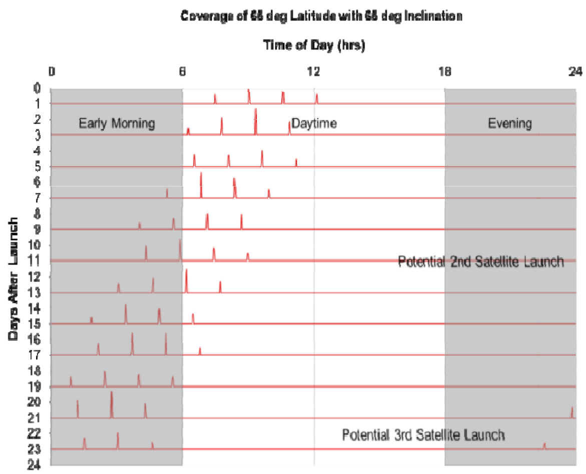

Figure 6: Coverage of one satellite

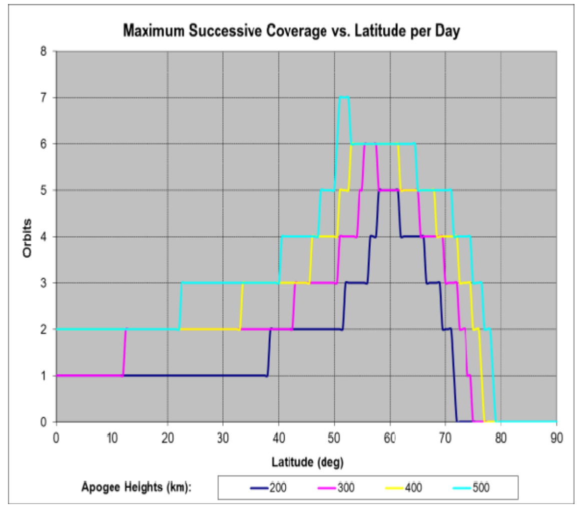

Figure 7: Resolution

If more coverage is needed, a second and third satellite could be launched on day 11 and 23 to give images every 90 minutes during the recovery. Figure 8 shows the coverage of three satellites. If the damage requires an extensive volunteer effort three satellites giving information on what was hit, the state of the roads, and high places for evacuation first. Successive satellites may provide secondary payload analysis as needed for different days (i.e. satellite 1 has a telescope payload, satellite 2 has thermal sensors, and satellite 3 has a lidar sensor, etc.)

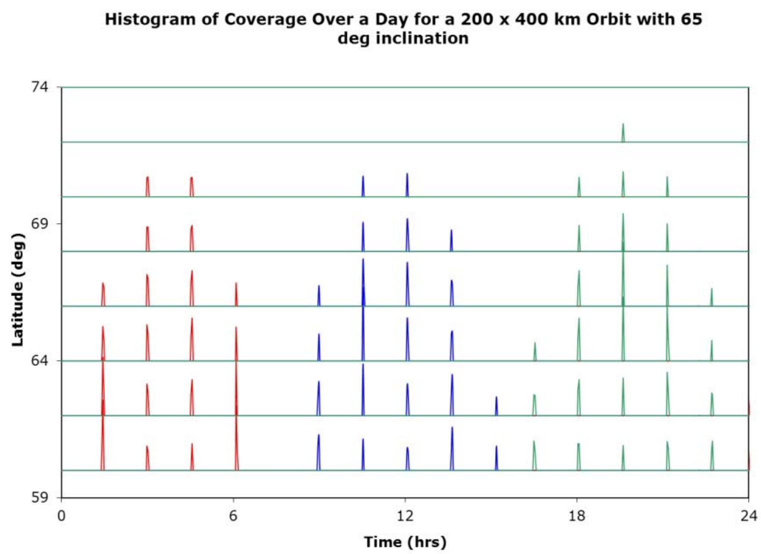

Figure 8: 3-satellite coverage

So far there is a need for images, but no information on the actual satellite architecture. The satellite mission is to provide immediate images about the state of the devastated area. The primary mission is to provide visual assessments of the afflicted area. It should provide direct communication to the volunteer workers with a direct channel from portable antennas. A secondary mission would be to provide some sort of scientific sensor that would give feedback to the infrastructure as needed. These three main objectives are the essential mission of a disaster monitoring satellite. The volunteers in the field must be able to receive accurate information to determine the best course of action and how to save the most lives.

SYSTEM ARCHITECTURE

In order for a system like this to work, it needs to be cost effective. Microcosm has developed NanoEye under an Army Contract. Consider that it is estimated that the Japanese Tsunami could cost about $210 Billion dollars with a loss of life of over 15,000 people, the cost of sending up one satellite that is directly responsive to the disaster would be around $5M.

NanoEye is intended to provide submeter resolution Earth observations from a spacecraft with exceptional orbit and attitude agility. It has 2.5 km/sec of available delta V and is able to move the Field of View by 180 deg in pitch in 3 sec and 180 deg in roll in 6 sec. It also has a baseline X-band downlink of 100 Mbps to a very low cost transportable ground station designed by GATR. The key characteristic of the spacecraft a responsive satellite is that the recurring cost is less than $2 million and all of the hardware is easily accessible where it can be integrated, tested and changed out, if desired to support other missions, even after the spacecraft has been built.

The most important contribution is that it dramatically reduces the cost and time required for the development and fielding of space observation systems or other payloads. The short time and low cost of fielding systems also allows the introduction of new technology much faster and at less cost and risk than would otherwise be possible. The key characteristics of NanoEye are as follows:

- Sub-meter ground resolution using the baseline ITT/Exelis telescope from low orbits
- 2.5 km/sec of available delta V
- 37 W worst-case orbit average power available (can be doubled if needed); bus uses 22 W
- Scan mirror assembly available that can move the field of view in pitch at 60 deg/sec
- Spacecraft roll by up to 30 deg/sec
- X-band data downlink at 100 Mbps to both USN (< $500 per data pass) and easily transportable, low-cost GATR ground terminals
- Attitude knowledge to 0.01 deg and pointing capability to 0.03 deg
- Can accommodate a payload mass of up to approximately 50 kg and 40-50 cm diameter; a larger bus would approximately double size and mass
- Total recurring spacecraft cost, including baseline telescope, of less than $2 million; recurring bus cost less than $1.5 million without the baseline telescope

A secondary benefit is that it represents perhaps the best long-term solution to the ongoing problem of orbital debris. Below approximately 500 km, a debris cloud or uncontrolled spacecraft will decay and re-enter within a few years or within a few weeks. As a result, the debris density at these altitudes is about an order of magnitude less than at traditional higher altitudes in the event that NanoEye is hit by a piece of debris. It will decay and re-enter quickly so as not to create a long-term hazard.

Figure 9 shows the current NanoEye spacecraft. It achieves sub-meter ground resolution from perigee in a 200 x 400 km elliptical orbit and has a very large delta V margin relative to the maximum mission life of approximately 2 years. The optical payload is based on a 9.25-inch diffraction-limited telescope that weighs 3.1 kg, has been built by ITT/Exelis, and has been delivered for a flight on the Kestrel Eye spacecraft. The spacecraft bus components are cubesat electronics provided by Pumpkin and Innoflight, essentially all of which have flown in space and are currently available as off-the-shelf products. The propulsion system, which supports both autonomous orbit control (previously flown and validated on orbit by Microcosm) and rapid attitude maneuvers, is based on 1-lbf thrusters that weigh 5.4 gm each and have been previously built and flown by Aerojet for the LEAP program. The uni-body, all-composite propellant tank and structure is built by Scorpius Space Launch Company (SSLC), and a structural model has been built and vibration tested to 10 g's on an SBIR Phase II contract with the Army SMDC. The real-time X-band data downlink is provided either via the existing Universal Space Network or the GATR portable antenna system being supported by the same Army SMDC contract. Thus, nearly all of the key components have been built and either flown in space or have been space-qualified, such that the performance, mass, and cost are well established.

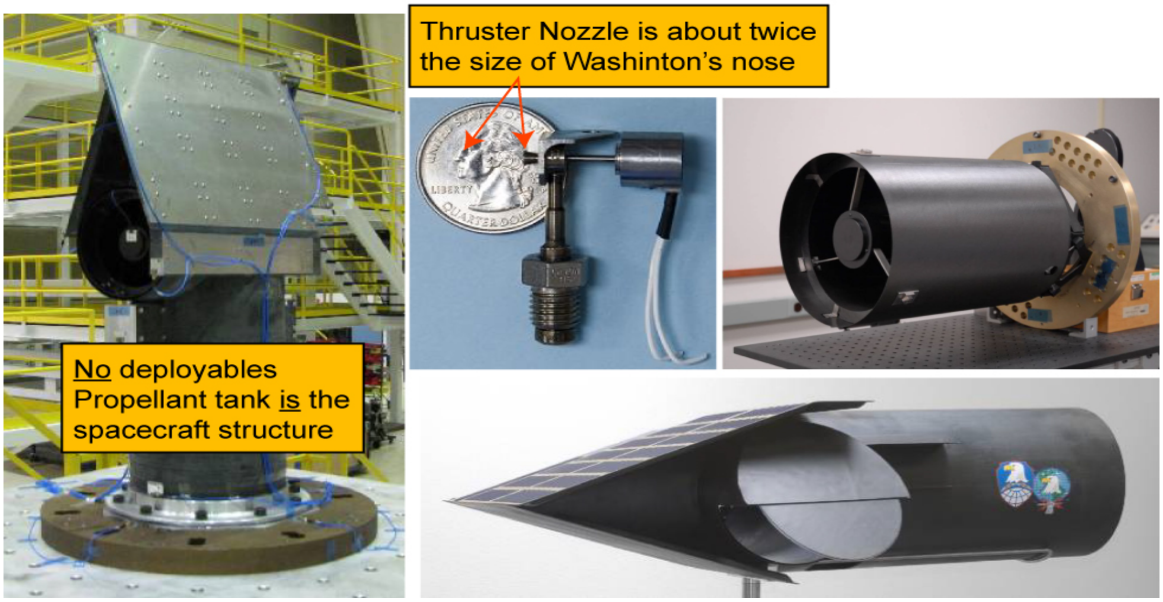

Figure 9: The engineering model of the telescope is shown in the upper right. The structural test model, successfully vibration tested by ITT/Exelis, is shown at left. The Aerojet 1-lbf thruster weighs 5.4 gm and has flown in space on the LEAP program.

In addition to the above, the spacecraft bus is capable of providing large margins in terms of power, mass, delta V, and control authority, such that it can be used for a variety of missions. Low-cost approaches to the ground station and data dissemination are also available, such as the GATR transportable antenna shown in Figure 10. The NanoEye spacecraft bus responds directly to the need to significantly reduce space mission cost in the near term.

Figure 10: GATR Transportable Antenna

The responsive satellite represents a dramatic increase in the state of the art by providing a highly competent spacecraft with a recurring spacecraft cost of less than $2 million. The bus and associated ground system elements are sufficiently flexible and robust to provide overarching low-cost, responsive mission architecture for future disaster satellite systems. The composite spacecraft bus with integral positive expulsion tank is also configurable to other propellant, mission, and payload requirements.

The spacecraft bus provides on demand, rapid response, flexible information to disaster relief volunteers. Specifically, scenarios evaluated during the NanoEye program has led to the conclusion that it is possible to build to inventory to provide on-demand launch capabilities and an anticipated 8 hours from demand to launch.

Spacecraft and launch vehicles built to inventory with launch-on-demand have existed in Russia and the former Soviet Union for over 30 years and are planned to be implemented in China in the near future. For example, in direct response to the Falklands War in 1982, the Soviets launched 29 payloads in 69 days. The United States still does not have this capability, which is the circumstance that this research is intended in part to change. [3]

Providing a specific disaster capability through a multi-faceted spacecraft bus reduces the cost to the military through its plug-and-play CubeSat components. It greatly reduces the cost to $15M total for spacecraft, payload and launch capabilities for three satellites. This cost is based on the assumption that launch is provided by the Mini-Sprite launch vehicle, currently under development by Microcosm. As the technology improves in disaster observations, the satellite is low enough in cost that it can be used to test new payloads and bus subsystems during a mission, while it provides on-demand monitoring capabilities with the prime payload and/or current bus subsystems., The ultimate result is to reduce the on-orbit cost of implementing EO surveillance coverage.

The proposed satellite architecture leapfrogs the Russian capability and fundamentally changes the way business is done in space by reducing, by more than an order of magnitude, both the time and cost required to meet urgent needs. Dramatically reducing the time to put assets in place is certainly achievable by simply funding the build of multiple small low-cost launch vehicles and small low-cost spacecraft and putting them both into inventory for launch-on-demand.

PAYLOADS:

The basic satellite would have an imager and a secondary sensor, most likely a thermal sensor to determine heat signatures of burning fires or human body temperature compared to the ocean, there are other sensors that could aid in disaster relief. Table 2 gives a quick overview of possible sensors that could aid disaster relief.

Table 2: Payload sensors

Name	*Description*
Operational Linescan System (OLS)	A simple three channel imager. It has a visible channel, a near-infrared channel, and a thermal infrared channel (10-13.4 micrometers).
Visible Infrared Imaging Radiometer Suite (VIIRS)	An imager that senses in the visible as well as the infrared.
Advanced Technology Microwave Sounder (ATMS)	A cross-track scanning sounding radiometer with 22 channels combining the capabilities of the earlier AMSU-A1, AMSU-A2, and AMSU-B sensors into a single package with a considerable savings in mass, power, and volume.
Special Sensor Microwave Imager/Sounder (SSMIS)	A conical scanning imaging/sounding radiometer with 21 frequencies ranging from 54 to 183 GHz. It supports a variety of moisture and temperature measurements.
Special Sensor Microwave – Humidity (SSMT-2)	A cross-track scanning sounding radiometer with five channels ranging from 91 to 183 GHz that supports humidity sounding under all-disaster conditions.
Special Sensor Microwave – Temperature (SMM/T)	A cross-track scanning sounding radiometer with seven channels ranging from 50 through 59 GHz and supports atmospheric temperature determination.
Cross-Track Infrared Sounder (CrIS)	A Fourier transform spectrometer using 1305 spectral channels divided into three wavelength ranges: 9.14 – 15.38 µm, 5.71-8.26 µm, and 3.92-4.64 µm and supports water vapor and temperature profiles of the atmosphere.

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PERFORMANCE REQUIREMENTS

One of the advantages of the NanoEye bus is its scanning capability with the Scan Mirror Assembly (SMA). The bus has excellent roll control due to its 1lbf thrusters and pitch motion done by the SMA. A disaster constellation can take advantage of this added agility by scanning the afflicted area. It can image sequential frames at 20frames/sec while collecting a 10km by 10km disaster field mosaic using a tile pattern assembly. The net result is less than 5 seconds to collect the 100 km^2 area with 10-20% overlap. The SMA is 20 times faster than traditional and 5 times faster than originally estimated.

If we assume a country, that is 10 degrees latitude by 10 degrees longitude and scatter targets throughout the country the plot would look something like Figure 11. When viewed from the spacecraft the scattering will show that there are more targets towards the outer edges due to foreshortening. An individual pass may go near the center or off to one side.

If we cut the area into scan segments, with the width of each segment equal to the distance the spacecraft moves in 30 seconds we see that the disaster mosaic will allow us to hit individual targets. The sample dots could show buildings, infrastructure, or groups of civilians. A simulation was run to show the performance of a satellite sampling a disaster event. The results are summarized in Figure 12. The key results are that given one pass of the orbit covers on average 64.4% of the targets in one pass.

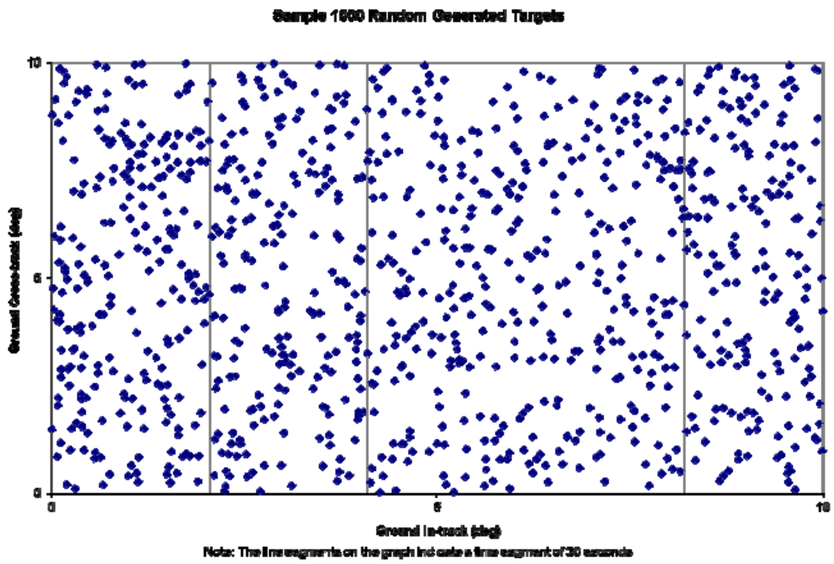

Figure 11: Sample Country Targets

Outcome Parameters	10 Runs 1	10 Runs 2	10 Runs 3	10 Runs 4	10 Runs 5	Average	Units
Incoming Orbit Cross-track	-0.915	0.738	-0.689	-1.027	-0.903	**-0.559**	deg
Number of Targets	1000	1000	1000	1000	1000	**1000**	
Targets Visible from Passing Satellite	618.4	714.2	633.4	619	636.4	**644.3**	
Percent of Targets Visible	61.8%	71.4%	63.3%	61.9%	63.6%	**64.4%**	
Maximum Target/Segment	411.3	421.5	414.5	419.3	422	**417.72**	
Total Visible Targets Imaged	85.5	85.7	88.8	83	79.9	**84.6**	
Total Visible Targets Missed	532.9	628.5	544.6	536	556.5	**559.7**	
Percent of Targets Imaged	22%	18%	17%	19%	18%	**18.6%**	
Percent of Targets Missed	78%	82%	83%	81%	82%	**81.4%**	
Max Targets Imaged	54.7	51.5	58.6	52	52.7	**53.9**	in 1 Interval
Min Targets Imaged	14.1	15	13.9	14.2	12.3	**13.9**	in 1 Interval
Max Time Left Over per Segment	-901.9	-1073.1	-957.4	-905.1	-963.5	**-960.2**	sec
Avg Time Left Over per Segment	-630.0	-759.5	-664.2	-646.0	-654.5	**-670.8**	
Min Time Left Over per Segment	-901.9	-1073.1	-957.4	-905.1	-963.5	**-960.2**	sec
Cross-track Scan Dominate	-260	-307.5	-264.65	-262.25	-269.7	**-272.8**	
Percent of Visible Targets	-291%	-339%	-300%	-303%	-311%	**-309%**	
In-track Scan Dominate	194	219	201	195	195	**201**	
Percent of Visible Targets	221%	246%	227%	229%	231%	**231%**	
Percent of Images Downlinked	100%	100%	100%	100%	100%	**100%**	
Avg Downlink Time Left Over per Segmen	52.9	52.9	52.6	53.1	53.3	**53.0**	
Max Targets Visible Per Pass	1000	1000	1000	1000	1000	**1000**	

Figure 12: Performance Parameters

This type of agility is limited by the downlink system using an S-band antenna at 2Mbps. If we switch to an X-band antenna we would have ample downlink time with time left over to cover the scanned ground from the imaging payload. This would leave room for secondary data from one of the disaster sensors to send down that information automatically.

We know from a random smattering of targets across a "country" 10 by 10 degrees that we will be able to see these targets. Knowing this information will allow for volunteers to make a concentrated effort with their search and rescue teams.

CONCLUSIONS

This paper has presented a low-cost architecture to address disaster relief. The criteria for a relief aid using space assets is that it can be launched when volunteers are dispatched and give them specific information they can use. The architecture is low-cost enough to be satisfied by one satellite, or expanded to a constellation if needed. There are multiple payload possibilities that can contribute to a disaster relief situation. In this paper, we investigated the use of space assets for a tsunami. It showed that reasonably space assets can be dispatched to provide information directly to the ground volunteers using the GATR antenna or other communication means. This low-cost addition to disaster relief aid would enhance the immediate response to natural disasters. Space assets provide a real opportunity to contribute to the response of natural disasters with real-time information. This type of architecture must be looked at to determine how we can best be a part of the conversation and contribute to world disasters.

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