NASA's Marshall Space Flight Center Recent Studies and Technology Developments in the Area of SSA/Orbital Debris

Bruce M. Wiegmann
NASA Marshall Space Flight Center
Huntsville, AL

ABSTRACT

NASA's Marshall Space Flight Center (MSFC) has been investigating the various aspects of the growing orbital debris problem since early 2009. Data shows that debris ranging in size from 5 mm to 10 cm presents the greatest threat to operational spacecraft today. Therefore, MSFC has focused its efforts on small orbital debris mitigation. Using off-the-shelf analysis packages, including ESA's MASTER software, analysts at MSFC have begun to characterize the small debris environment in LEO to support several spacecraft concept studies and hardware test programs addressing the characterization, mitigation, and ultimate removal, if necessary, of small debris.

The Small Orbital Debris Active Removal (SODAR) architectural study investigated the overall effectiveness of removing small orbital debris from LEO using a low power, space-based laser. The Small Orbital Debris Detection, Acquisition, and Tracking (SODDAT) conceptual technology demonstration spacecraft was developed to address the challenges of in-situ small orbital debris environment classification including debris observability and instrument requirements for small debris observation.

Work is underway at MSFC in the areas of hardware and testing. By combining off the shelf digital video technology, telescope lenses, and advanced video image Field Programmable Gate Array (FPGA) processing, MSFC is building a breadboard of a space based, passive orbital tracking camera that can detect and track faint objects (including small debris, satellites, rocket bodies, and NEOs) at ranges of tens to hundreds of kilometers and speeds in excess of 15 km/sec.

MSFC is also sponsoring the development of a one-of-a-kind Dynamic Star Field Simulator (DSFS) with a high resolution large monochrome display and a custom collimator capable of projecting realistic star images with simple orbital debris spots (down to star magnitude 11-12) into a passive orbital detection and tracking system with simulated real-time angular motions of the vehicle mounted sensor. The DSFS can be expanded for multiple sensors (including advanced star trackers), real-time vehicle pointing inputs, and more complex orbital debris images. This system is also adaptable to other sensor optics, missions, and installed sensor testing.

MSFC's Flight Robotics Laboratory is investigating various test capabilities to evaluate proximity range sensors and state estimation and to test short range sensors and capture mechanisms for capturing tumbling non-cooperative satellites.

1. INTRODUCTION

The region of space between 200 km and 2,000 km altitude known as Low Earth Orbit (LEO) is a global natural resource that must be conserved. Over the past 55 years, humanity has become increasing dependent on LEO as a home for satellites that perform a myriad of functions that affect the daily lives of people across the globe. LEO satellites provide weather information and support natural resource monitoring. Communications satellites facilitate a global communications network. Scientists use specialized satellites to learn about the ever-changing climate of the Earth, the nature of gravity and relativity, and about our planet's place in space and time. National security interests operate spacecraft to gather intelligence and provide war fighters with critical information in battlefield conditions. Furthermore, all signs point to an increase in LEO operations with the emergence of the small satellite market and the initiation of serious efforts to mount human expeditions beyond LEO.

As many within the community know, our use of this resource has been clouded by our lack of forethought and understanding of just how the choices made in LEO impact our future ability to make use of this resource. Already,

debris from exploding rocket bodies and fragmented spacecraft pose an increased threat to operational spacecraft throughout LEO. While technical measures such as the passivation of rocket bodies and conservation measures such as the 25-year rule have reduced the debris production of objects launched over the past few decades, compliance with these guidelines has yet to be fully realized. As a result, many studies have shown that a business as usual approach to orbital debris mitigation will allow the debris population in LEO to continue to increase, thereby increasing the risk to operational satellites. Many within the community point to these dangerous trends and conclude that action must be taken to stem the growth of the debris population.

The population of LEO objects is divided between operational spacecraft and debris objects. Typically, debris is categorized as small (<0.5 cm), medium (0.5 – 10 cm), or large (> 10 cm). This classification captures both the observability and potential threat of the debris object. Small debris can typically be shielded against, presenting very little impact to operational spacecraft. Large debris, including spent rocket bodies and non-operational spacecraft, can be tracked and cataloged and currently makes up approximately 76% of the over 11,000 unclassified objects tracked in LEO by the Joint Space Operations Center (JSpOC). A collision with a large debris object is typically catastrophic, destroying both objects as was the case in the 2009 collision between the Iridium 33 and Cosmos 2251 satellites. Debris classified as medium in size in not readily tracked by ground assets but poses a lethal threat to operational satellites. The estimates for medium debris populations in LEO range from 300,000 to 600,000 unique particles but much of this data results from simulations due to very limited observational data sets.

Throughout the life of a spacecraft, there are several opportunities to create debris of all shapes and sizes. Large debris is typically created at major events in the life of a spacecraft. The upper stage that is used to put a satellite in orbit can remain in orbit after the satellite has been delivered. The satellites themselves will only operate for a finite period of time. Once their mission is complete, they will also become space debris. Both of these categories of space debris are subject to guidelines for disposal. In LEO, the overarching guideline is the 25-year rule which states that, after their mission is complete, objects should be placed in orbits that will allow for them to naturally re-enter the Earth's atmosphere within 25 years of the end of their life.

By far, the largest source of space debris is fragmentation, or the break-up of satellites and rocket bodies in orbit. To date, there have been 203 known breakups of orbiting objects. The majority of these have occurred due to explosions. The fragmentation of a 5 to 10 ton satellite can produce 3,000 – 5,000 debris objects bigger than 10 cm and 150,000 – 250,000 debris objects between 1 and 10 cm^2. There are several reasons for orbiting objects to explode. Propellant tanks and batteries can be heated by the sun in orbit and the remaining contents of these tanks will evaporate, increasing the pressure until they explode. These pressure vessels can also explode if struck by a small micrometeoroid or piece of debris. It is estimated that as much as 70% of all fragmentations are caused by explosions. Fragmentation can also be intentional, like the Chinese ASAT test that destroyed the Fengyun-1C spacecraft in 2007. It is estimated that 29% of the fragmentation events in orbit were deliberate. The remaining 1% of fragmentation events was collisions between orbiting objects.[3]

While collisions make up a small percentage of fragmentation events today, several factors lead experts to predict that collision fragments will make up 50% of all objects in LEO within 50 years.[4] First, many spacecraft and rocket bodies now undergo a process known as passivation as part of their end-of-life operations. This includes depressurizing all storage tanks to avoid explosions. Second, the space community expects a general decline in the number of intentional fragmentation events (ASAT tests) due to increased pressure to avoid the creation of orbital debris. Finally, it is expected that as the population of orbiting assets increases, so too will the probability of on-orbit collisions.

How crowded is LEO and where is all the debris?

There are currently 22,000 objects being tracked in Earth orbit by JSpOC. 16,000 of these are publicly acknowledged; the remaining 6,000 are classified. In addition there are estimated to be 600,000 untracked objects in Earth's orbit. These objects tend to be grouped into three orbit categories: Low Earth Orbit (LEO) extending from 200 km to 2000 km altitude, Geo-Synchronous Orbit (GEO) at approximately 35,800 km altitude, and Medium Earth Orbit (MEO) which lies between LEO and GEO. Roughly 73% of all tracked objects in Earth orbit are located in LEO. While GEO is home to many communications satellites that have a high value, only about 5% of the tracked objects reside there. For this reason, the primary focus of orbital debris investigations occurs within the LEO region.

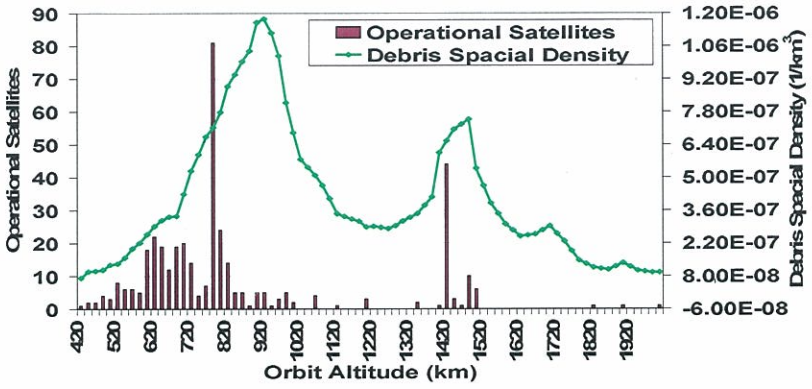

Fig. 1 OD Flux and Operational Satellites vs. Altitude

Fig. 1 shows that even within LEO there are distinct regions of higher population. The figure also shows the number of active satellites and overlays on that the curve of debris special density at those altitudes. This chart clearly shows the convergence of high satellite populations with large populations of orbital debris. The peak between 750 and 800 km is of particular interest as this orbit houses the Iridium satellite constellation and contains most of the debris from the Iridium-Cosmos collision and the Fengyun-1C ASAT test. For those working to mitigate the threat of orbital debris these regions have become the focal point for research.

What is the main threat from orbital debris?

While large events such as the Iridium-Cosmos collision have brought new attention to the issue of orbital debris, the primary near-term threat to orbiting assets comes from the medium sized debris in Low Earth Orbit[5]. The reason is a combination of the aspects already discussed. LEO has the highest concentration of both active satellites and debris, thus increasing the probability of objects colliding. Satellites cannot be effectively shielded against medium debris collisions like they can for small debris. Also, because the medium debris cannot be tracked from the ground, we cannot perform collision avoidance maneuvers like we can when two large objects are predicted to collide. Medium debris is large enough to do significant damage but too small to be seen. Combining those characteristics with a convergence of high populations of both debris and active satellites makes the medium orbital debris population in LEO the most threatening at this time.

2. THE SMALL ORBITAL DEBRIS ACTIVE REMOVAL ARCHITECTURE STUDY

In 2011, MSFC Advanced Concepts Office (ACO) and Dr. Richard Fork, a renowned pulsed laser expert at the University of Alabama in Huntsville (UAH), had a series of strategic meetings that focused on: What are the orbital debris removal benefits, if any, which could be obtained from a LEO spacecraft, integrated with a low powered pulsed laser. Before the ACO would do a conceptual study of such a spacecraft, we determined that it would be better to conduct an overall Small Orbital Debris Active Removal (SODAR) architecture study. The goals of this study were to 1) Determine if such a system would be feasible architecturally by 2) Determining the fewest number of LEO spacecraft required to remove 50% of the small orbital debris flux within the key operational spacecraft orbital altitude bands within the shortest allotted time period.

The study assumed that a space qualified low power laser would have been developed at the time of this mission for another mission application and that this laser could be integrated upon a LEO spacecraft. The study only focused on the feasibility of using a laser to remove 1-10 cm OD from LEO. It did not address the sensitive nature of the use of lasers in LEO and the assembled team fully acknowledges this aspect is beyond NASA engineers and will be addressed in future years, if warranted, by the USA Department of State.

The overall Figure of Merit (FOM) utilized was the goal of a 50% reduction in LEO orbital debris flux of OD objects of 1 cm to 10 cm in size within a five to ten year operational period. The ESA's MASTER 2005 data base was utilized to determine the areas of highest small debris to medium flux for initial mission design purposes and the altitude of 800 km at an 83° inclination was chosen as the initial reference orbit as this region had the highest flux density of 1 to 10 cm OD.

It was assumed that the pulsed laser would fire as many times as necessary within an allocated time span of 0.2 sec to 2 sec (corresponds to axial distances of 3 km to 30 km away) to produce the required de-orbiting Delta V (see Table 1) necessary to de-orbit the orbital debris object within one orbital revolution from various altitudes immediately following the period of laser interaction with debris object.

Table 1De-Orbiting ΔV Required vs. OD Altitude

Total De-orbiting ΔV Required to De-orbit LEO Debris			
Altitude (km)	Orbital Velocity (km/s)	De-orbit ΔV (m/s, to 50 km)	% ΔV Required to De-orbit
1400	7.159	349	4.9%
1200	7.252	304	4.2%
1000	7.350	257	3.5%
800	7.452	208	2.8%
600	7.558	157	2.1%
400	7.669	102	1.3%

The study concluded the following:

1) Four spacecraft would be necessary to eliminate ~50% of the small orbital debris within the critical LEO operational zones over a 5-10 year period
2) Laser must be designed to engage objects in the "ram" direction (@ relative velocity ~15km/sec) as over 99% of orbital debris is from a head-on direction and be capable of delivering a total de-orbiting ΔV pulse within 1 sec to 2 sec (15 km – 25 km)
3) Effectiveness of overall system is dependent on:
   - Effective laser range
   - Laser duty cycle (and/or debris availability)
   - Engagement efficiency (tracking capability, clearinghouse approval, etc.)
   - Operational spacecraft-years (# of spacecraft * operational years per spacecraft)
4) Debris removal effectiveness decreases as orbital debris population (flux) decreases
5) Advances in today's pulsed laser technologies are required
6) The capability to detect & precisely track small orbital debris up to 100 km away from the LEO spacecraft, is the first technology challenge that must be successfully demonstrated

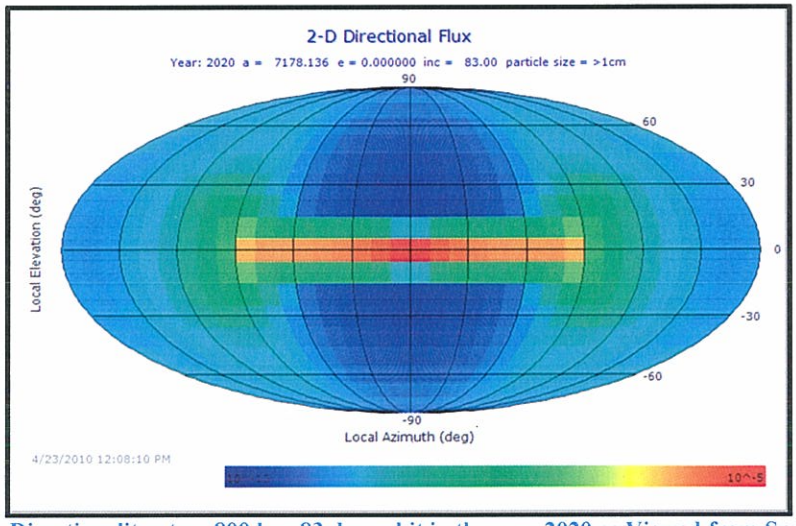

Fig. 2 Small OD Flux Directionality at an 800 km, 83 deg orbit in the year 2020 as Viewed from Spacecraft Looking into Ram Direction (data source: NASA ORDEM 2010 pre-release)

3. THE SMALL ORBITAL DEBRIS DETECTION, ACQUISITION, & TRACKING (SODDAT) SPACECRAFT STUDY

The MSFC Engineering Directorate's Advanced Concepts Office (ACO) conceptually designed a SODDAT satellite in 2011. The SODDAT satellite would be launched into an orbit that had a high amount of small to medium sized OD flux (800 km orbit at an 83-degree orbital inclination) for a three-year design mission (with capability up to five years). SODDAT would use a trio of three gimbal-mounted optical telescopes to detect glint from debris. If the debris trajectory moves toward the satellite for more than 1.5 seconds, the spacecraft's laser range finder, mounted on the gimbal with the telescopes, would activate and track the object while the telescopes rotate to keep the object in sight during the transit. Data from encounters would be transmitted to ground stations periodically depending on the amount of activity and the amount of image processing done by the spacecraft.

In the study's final design state, SODDAT was sized and priced to be an "Explorer Class" mission (~$150 million). This price includes the spacecraft, instruments, launch, and testing and verification. The spacecraft's mission life is assumed to be approximately three years based on the life of the electronics and LADAR equipment.

The 800 km orbit was selected to maximize the number of potential debris encounters (high flux) and the mission payoff as there are many active satellites at that altitude. Debris impacts in the 800 km orbit would have a closing velocity of ~16 km/s. The area of detection zone determines how many objects SODDAT can expect to see. The formula for determining encounters is:

Objects / Time = Flux * Area[1]

Based on the current debris model, SODDAT should be expected to have 0.6 orbital debris encounters per day (this is directly proportional to the optical Field of View (FOV) employed). But, again, until the spacecraft is deployed, this is only a mathematical estimate. The true purpose of SODDAT will be to ground NASA's orbital debris models in hard data.

The SODDAT instruments will concentrate on debris in a retrograde orbit (i.e., coming toward the spacecraft) as shown in Fig. 3. The Field Of View (FOV) for the debris detector will be 2° X 2°. Debris objects will have trajectories that converge toward the center of the FOV. The star field in the background will move at a predictable 3.6° angle through the FOV. The instruments aboard SODDAT are expected to detect objects as small as 1 cm with an albedo of 0.1 from distances of up to 100 km. If an object comes within 10-25 km of the spacecraft, the LADAR will activate and begin tracking the incoming object.

[1] Where area = the cross-section a spacecraft presents edge-on to the direction of flight.

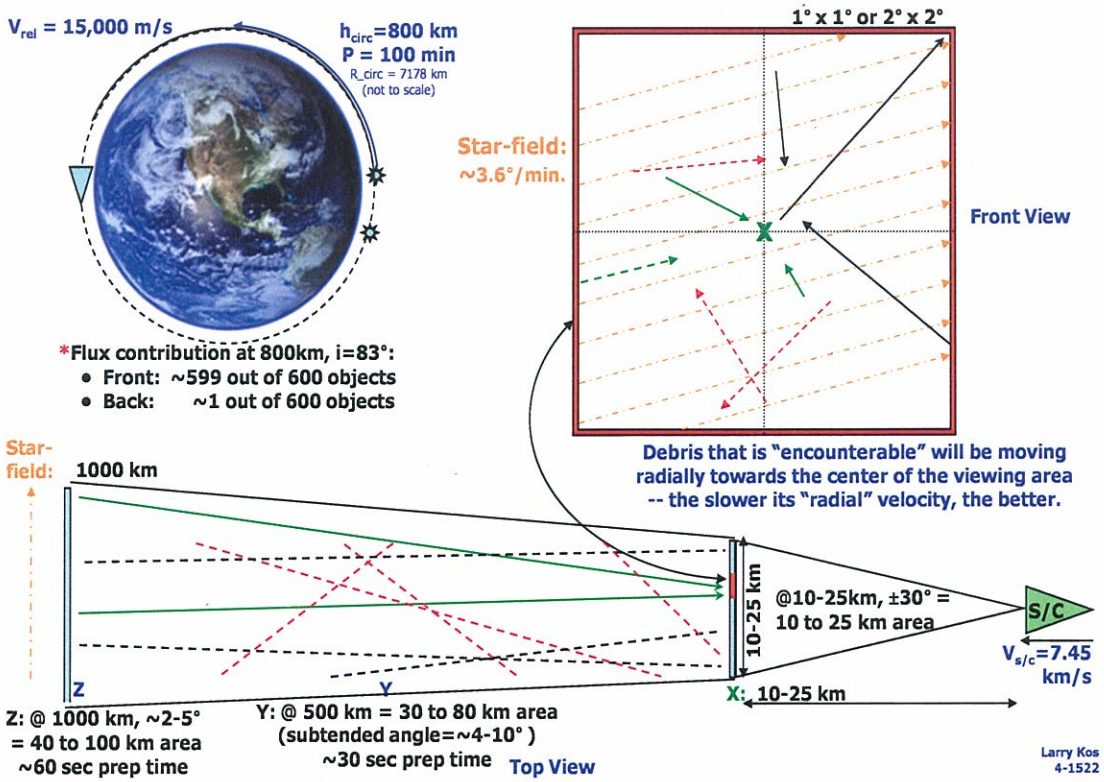

Fig. 3 Concept of operations for detecting debris.

SODDAT Spacecraft Hardware: Instrument Package

The primary instruments aboard SODDAT will be those used to sight and track orbital debris. MSFC has developed many real-time tracking and monitoring sensors through the years, including three generations of Video Guidance Sensors flown on the Space Shuttle, on the Demonstration of Autonomous Rendezvous Technology (DART), and on Orbital Express, where they were used to control the first automated docking in U.S. history. Various other flight video systems have been used for onboard Space Shuttle monitoring and the WB-57 (NASA aircraft) Ascent Video Experiment (WAVE) which tracked and monitored Space Shuttle ascents telescopically from the nose of a high-altitude plane after the Space Shuttle Columbia incident. These two technologies are combined on SODDAT to detect and track small orbital objects using fast optics and high-speed image tracking with a laser Time of Flight (TOF) LADAR added to define range and close range tracking. The basic scheme is use high-speed complementary metal oxide semiconductor (CMOS) imagers and photo-detectors with high-speed, wide-angle Cassegrain telescopes to produce fast 2x2 deg telescopic one (1) megapixel video cameras and sensors.

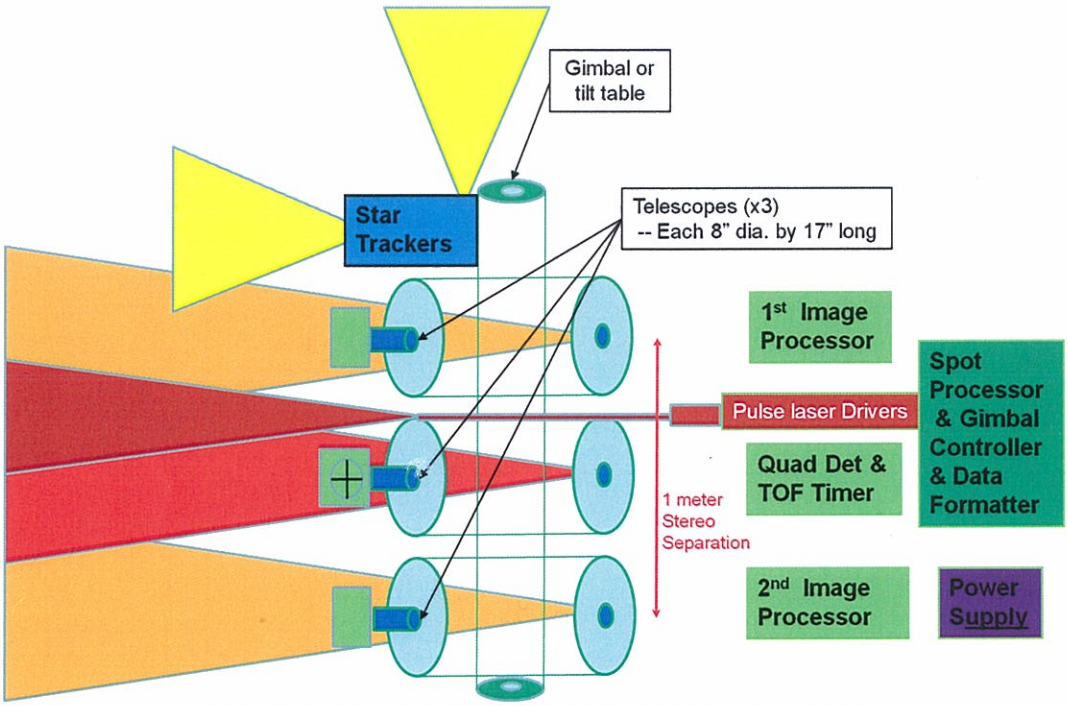

Fig. 4 Conceptual diagram of the SODDAT instrument platform.

This camera will look straight down the velocity vector on the orbit plane, looking for the solar glint off of objects coming straight at the spacecraft at 15 km/s. The video images captured at one to four times a second will be processed in real time. The orbital debris coming toward the telescopic camera will appear to move very slowly across the video images, while the stars and other celestial objects will move through the images at 3.6 ° degrees per minute due to orbital mechanics. Using the spot tracking and data formats developed for AR&D, the video images are compressed over two orders of magnitude while retaining qualitative and spatial data of the orbital debris spots along with the star field data for location and attitude recovery.

While tracking the objects coming straight toward the telescopic camera and therefore staying stationary in the images, SODDAT will use a second, parallel telescopic camera spaced a meter apart from the first to detect the range to the object as it gets within 30 km due to the relative stereoscopic shift between the pair of video images. A third telescope between the two main telescopes will be mounted with the two telescopic cameras; this center telescope has a different detector, a multi-segment, high-speed avalanche photo detector with a bank of pulse laser diodes forming a directional wide-angle laser rangefinder or LADAR. Having a laser illumination angle as wide as the telescopic cameras and detector, the laser will reflect off the approaching object and hit one or more of the photo-detector segments to measure direction and the LADAR chronometer will measure the TOF and the range to the object hundreds of times a second.

The speed of the LADAR tracking will allow the whole sensor system to be pointed from side to side to track the larger number of objects that will fly pass to either side for longer periods of tracking. There are several technical challenges to perform dynamic tracking including spacecraft layout and stabilization, on-board tracking gimbal design, control, and operations. Other considerations include intensified imager chips, larger imager chips with larger FOV and longer stereo range, and more intense lasers for longer range LADAR detection. Testing the integration of these technologies will be a primary objective of the SODDAT mission.

Fig. 5 Conceptual design of the SODDAT Spacecraft.

4. PASSIVE OPTICAL ORBITAL DEBRIS SENSOR DEVELOPMENT

From the two above mentioned studies it was determined that a sensor suite to detect and track small orbital debris would be needed in the near future especially if more LEO satellite collisions occur (like the recent Iridium & Cosmos collision in February 2009) and developmental work has started on such a sensor suite at MSFC.

To determine sufficient ranging data passively, stereo imagery is required and an example of the stereo optical devices are shown in Fig TBD below. The design goal of this instrumentation is to have the ability to detect a 2 cm object with an albedo of 20% at distances up to 100 km away. In addition, the relative velocity of the debris object to satellite mounted sensor will be usually from 12 km/sec to 15 km/sec as 99% of the debris that will be seen is coming toward the orbiting spacecraft in a shallow angle. Once completed these sensors will be tested and evaluated in the newly developed MSFC high fidelity Dynamic Star Field Simulator (DSFS).

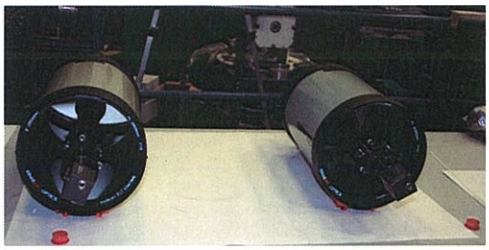

Fig. 6 Prototypes of the SSA/OD Sensor Suite (Under Development at MSFC)

5. MSFC HIGH FIDELITY DYNAMIC STAR FIELD SIMULATOR (DSFS)

To test the functional capabilities of passive sensors to detect small debris under development at MSFC, a high fidelity Dynamic Star Field Simulator (DSFS) is required. The MSFC DSFS is a system to simulate the star field (down to 12^{th} magnitude brightness stars) from any apparent position, time, and angle. A space debris object that is two centimeters in size at a distance of 100 km away, having an albedo of 20%, has a visual magnitude of 12. In order to detect such faint objects, all stars in the FOV greater than a 12^{th} visual magnitude will be observed as well. All of the stars observed in the FOV via the sensor will have a radial motion in the same direction of 3.6 degrees per

minute whereas the simulated debris will have differing radial motions that are proportional to the crossing angle of the debris objects' trajectories through the sensors relative FOV.

This simulator will be used to test and evaluate the passive sensory functions that are needed for a SODDAT type mission and to test the functionality of current and future enhanced star trackers as well. In addition, it is expected that this simulator will be used in the test and evaluation of sensors under development for future rendezvous and capture missions envisioned, such as orbital debris removal missions, satellite servicing missions, or asteroid rendezvous missions.

The DSFS is being developed under contract with the Texas A&M University's (TAMU) Space Engineering Research Center (SERC) and is scheduled to be delivered in October 2012 to the MSFC. The DSFS consists of a precision black and white display monitor, a color filter, a collimating lens, and the software required to create the simulated star fields.

Upon arrival at MSFC, the DSFS will be installed in the Flight Robotics Laboratory (a facility with all black floors, walls, and ceiling and a solar simulator). Initially the DSFS will be tested with a low light camera, frame grabber, and telescope combination to test the limits of the limits of the sensor suite being developed to a combination of a simulated small or large orbital debris objects: speed, crossing angle, and representative albedo.

6. FY13 MSFC ORBITAL DEBRIS ANALYSIS PLANNED

Two specific investigations are planned to be conducted in Fiscal Year 2013. The first investigation is focused upon examining the feasibility of using excess Peacekeeper hardware (30 plus excised 4th stage assets) as the backbone of a LEO space transportation system to perform active debris removal missions. This study will examine a variety of architectural options including but not limited to the use of a single stage option vs. the benefits of a dual stage option. The resident space objects (RSOs) investigated for removal in this study will be selected from USA owned assets (spent Delta or Centaur stages or dead satellites) only.

The second investigation will be focused on the pros and cons of various active debris removal methods and is entitled "The MSFC Sensitivity Analysis of Active Debris Removal Options (SAADRO) Architecture Study." While this architecture study will focus on the ultimate removal of those Resident Space Objects that are shown to cause the greatest risk to the worsening of the LEO OD environment via the various means identified in the trade tree (propulsive options, Electrodynamic tether options, or drag device options) that is shown in Fig. 7 below, a good portion of the front end analysis will focus on data-mining the existing unclassified USAF data relating to LEO Conjunction Assessments (CA). For example the daily CAs that have a high probability of occurring multiplied by the masses of the RSOs involved will determine a 'Probability-Severity' (P-S) value for each CA identified for that date. If these CA were exhibited in a Prado graphic the study, participants could easily determine what assets have the highest probability for creating a worsening environment on a daily view. Analysis of this type would be done rearward in time (six months to two years of a time interval) and then the frequency of CA events per individual tracked RSOs above a certain minimum P-S threshold can be determined. The focus of the architectural study will then be on the selected removal of these high risk identified assets (high 'P-S' values equate to higher risk) through the various aforementioned active debris removal methods. Whereas some methods tend to work better at lower altitudes such as drag devices, these methods may not perform adequately at altitudes above 750 km. This study will examine the best methods for removal (based upon cost, complexity, schedule, and risk) of these identified high risk assets.

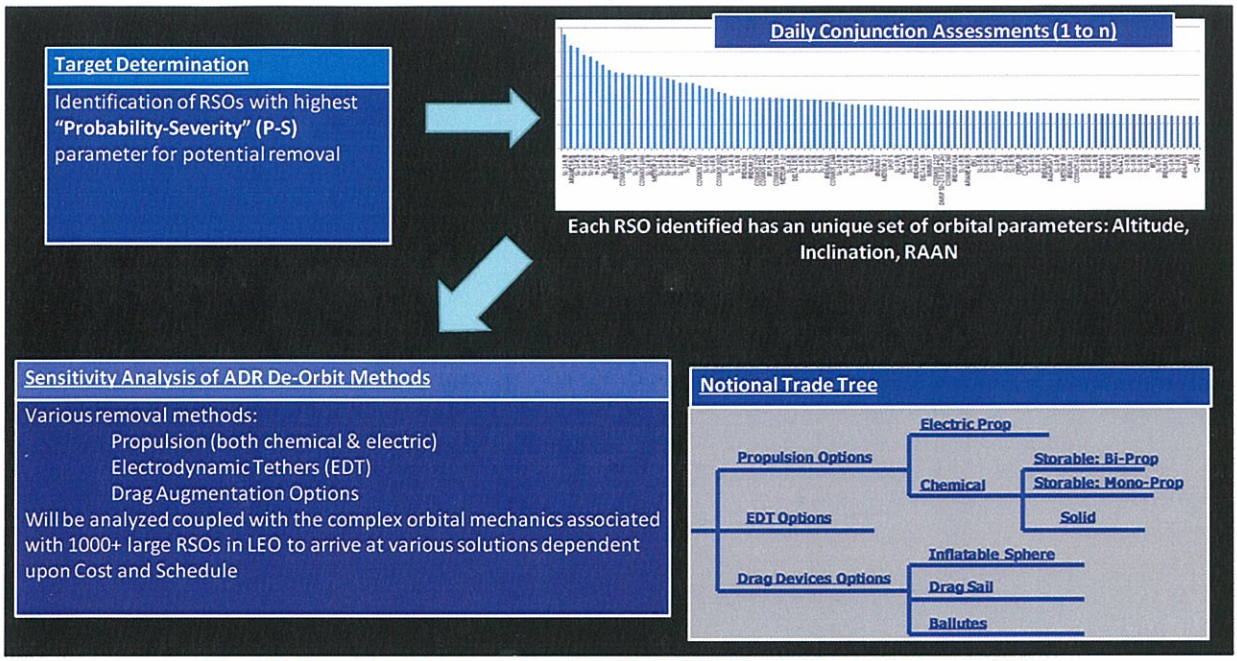

Fig. 7 Notional Data Flow and Trade Tree of FY13 SAADRO Architectural Trade

7. MSFC'S ROBOTIC LAB'S "FLAT FLOOR FACILITY"

The MSFC Robotics Lab's Flat Floor Facility provides a full scale, integrated simulation capability for the support of the design, development, integration, validation, and operation of orbital space vehicles. Included in the facility are two Spacecraft Simulators shown in Fig. 8 and a Dynamic Overhead Target Simulator (DOTS) shown in Fig. 9.

Two self-contained air-bearing Spacecraft Simulators are available and capable of carrying 400lb payloads. They provide 3 Degrees of Freedom maneuvering and are closed-loop computer controlled for sensor/docking testing. Wireless communication and video is available with real-time displays.

The Dynamic Overhead Target Simulator is an 8 Degrees of Freedom overhead gantry that provides a 500 pound payload capability for simulating relative motion with respect to a fixed target on the facility floor. A computer system provides inverse kinematics and allows the gantry to act as a target or as the 6 DOF rendezvous vehicle. The target reaction dynamics are simulated through force/torque feedback from sensors mounted at the payload interface. Manual scripts or closed loop control can be used to follow vehicle simulated flight trajectories.

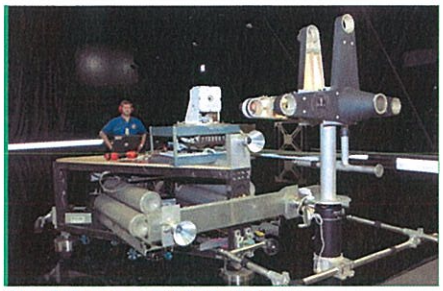

Fig. 8 Spacecraft Simulators

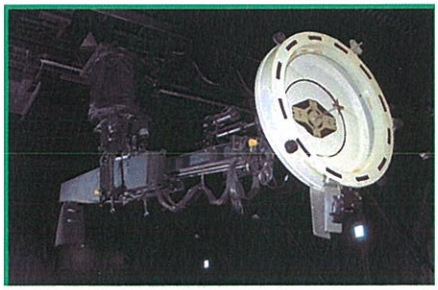

Fig. 9 DOTS

8. REFERENCES

Number citations consecutively in square brackets [1]. Refer simply to the reference number, as in [3]. Do not use "Ref. [3]" or "reference 3" except at the beginning of a sentence: "Reference [3] was the first…". The title of the book or of the journal shall be italicized.

8.1 Sample References

1. Johnson, N.L. and McKnight, D.S., *Artificial Space Debris*, Orbit Book Company, Malabar, Florida, 1991.
2 Grun E. et al, Collisional Balance of the Meteoritic Complex, ICARUS, Vol. 62, 244-272, 1985.