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End of Life Procedures for Low Earth Orbit Air Force Missions: CloudSat and TacSat-3

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At altitudes of less than 2,000 km., fragmentation wreckage caused by accidental explosions aboard spacecraft accounts for 42% of catalogued space debris, spanning all sizes and widely distributed through the orbits of their host satellites. Using operational satellites CloudSat and TacSat-3 as examples, this paper discusses Air Force Space Command, NASA and Department of Defense requirements for mitigation of orbital debris during creation of an End of Life (EOL) plan, and lays out an outline for writing such plans with special applicability to military missions. EOL spacecraft passivation, re-entry survivability analysis, casualty expectation analysis, methods to assess debris generation at EOL due to intentional breakup activities, accidental explosions, and on-orbit collisions; as well as operational execution of EOL for both maneuverable and non-maneuverable space vehicles, with a specific focus on Low Earth Orbit satellites that are unable to relocate to a graveyard orbit, are covered.

Nomenclature

ΔV = Delta-v: measure of propellant expenditure

I. Introduction

THE rising significance of the orbital debris problem in Low Earth Orbit (LEO) has resulted in increased awareness and mitigation becoming part of both spacecraft design and spacecraft End of Life (EOL). EOL procedures are written largely with the aim of reducing long-lasting space debris that can linger for decades in the orbit of the erstwhile satellite.

Depending on the propellant aboard, a satellite may have the capability to relocate to a designated "disposal orbit" for EOL. Such satellites are mostly geosynchronous, as reaching these orbits require significantly less ΔV than de-orbiting. However for satellites in LEO, standard practices for orbital debris mitigation dictate[1] relocation to an orbit with a perigee above 2000 km and apogee below 19,700 km, a goal that is often unachievable. Satellites are therefore commonly decommissioned in orbits that will ensure de-orbit due to atmospheric drag. Therefore, debris mitigation after contact has been lost or during re-entry must be actively considered as part of an EOL plan. The various elements involved in this planning are discussed below.

A. CloudSat

CloudSat is a NASA satellite that is currently being operated out of the Research, Development, Test and Evaluation (RDT&E) Support Center (RSC) at Kirtland Air Force Base (AFB), New Mexico. Launched in April 2006 from Vandenberg AFB into a 705-km circular sun-synchronous orbit, this satellite carries a unique 94 GHz Cloud Profiling Radar (CPR) on board that yielded the first vertical probing of clouds from space; measuring cloud bases and heights, cloud layer thickness, cloud water and ice content[12]. CloudSat was designed to be part of the "Afternoon Constellation" or the A-Train, flying in formation with five other satellites – Aqua, Aura, Parasol, Calipso and OCO. This configuration is shown in Figure 1 below.

Currently CloudSat is in an extended operations phase, controlled from the RSC and managed by NASA JPL. For six months since April 2011, the CPR was unable to function due to persistent battery and under-voltage problems; had the ops team been unable to validate an operational methodology that allowed CloudSat to return to a nominal condition with positive data collection, the satellite might have faced an EOL condition.

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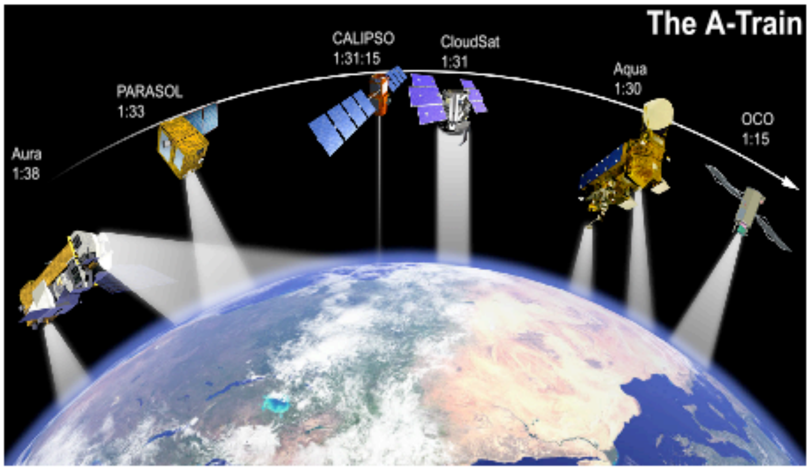

Figure 1. CloudSat's position in the A-Train

B. Tactical Satellite III (TacSat-3)

TacSat-3 was the third in a series of military technology demonstrator satellites, designed to test the capability of rapid development and deployment of space assets at a low cost. The 'standard' satellite bus for TacSat-3 was designed by Alliant Techsystems (ATK), and was assembled by the Space Vehicles Directorate, part of the Air Force Research Laboratory (AFRL) at Kirtland AFB. TacSat-3 was launched into a 460 km. LEO orbit on 19 May 2009 from the Mid-Atlantic Regional Spaceport (MARS), Wallops Flight Facility, Virginia.

The satellite has since graduated from its original R&D mission to an operational mission, providing regular images of use to various eligible government customers. Figure 2 shows an artist's conception of TacSat-3's hyperspectral utility. Unlike CloudSat, TacSat-3 has no propulsion system onboard, and will therefore serve as an example for EOL planning on non-maneuverable satellites.

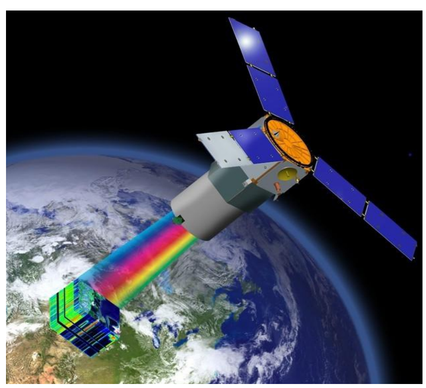

Figure 2. Artist's conception of TacSat-3 in orbit

II. Leading up to End of Life

A. Military EOL Approval Process

For satellites owned or operated by the Department of Defense (DoD), EOL plan approval is initiated at the Space Operations Squadron (SOPS) level, where day-to-day operational command of the vehicle happens. The Satellite Operations Crew Commander (SOCC) is the SOPS technical expert on the mission, and it is the responsibility of the organization with Spacecraft Control Authority (SCA) to provide him/her with the satellites' EOL plan. Approval must then be sought from Safety Directors at the wing, center, numbered Air Force and/or Major Command (MAJCOM) levels as necessary. Input from space vehicle manufacturers, payload primary investigators, Network Operations Squadrons and the Joint Functional Component Command (JFCC) for Space should be solicited as well.

As an example, for TacSat-3, the final EOL approval authority is the 14th Air Force Commander, a three-star general. Therefore, it is crucial that any proposed EOL plan is both thorough and well understood prior to dissemination. In this light it will be useful to briefly discuss the execution of an operational EOL plan as it applies to satellites operated by the military. Both CloudSat and TacSat-3 fall into this category, and must follow policies laid down by US Air Force Space Command (AFSPC), regardless of which organization holds SCA. As an example, though all planning and maneuver decisions for CloudSat are made by NASA JPL (CloudSat SCA), those decisions must be in compliance with regulations set out by the Space Operations Branch at Kirtland AFB (and, by extension, AFSPC), whose operators actually communicate with the satellite.

During pre-launch readiness activities and approximately two months before EOL execution, the SOPS Safety Expert and the SOCC will evaluate the EOL procedures provided by the SCA and provide guidance if necessary to ensure compliance with Air Force Instructions (AFIs) and Department of Defense Instructions (DoDIs). Once the EOL plan is approved, written notification regarding the date and time of EOL will be disseminated to all involved parties. SOPS operators will begin closing out all open mission paperwork and remove Mission Unique Software (MUS) from the ground system architecture. Every satellite that flies on the Air Force Satellite Control Network (AFSCN) is assigned an Inter Range Operations Number (IRON) that uniquely identifies the satellite to the network.

In addition to the AFSCN, NASA operates the Tracking and Data Relay Satellite System (TDRSS). CloudSat has a Space Network Web Server Interface (SWSI) that communicates with TDRSS. Both TDRSS SWSIs and IRON shared products must be closed out prior to EOL execution. Once EOL has been executed and verified, the Network Operations Squadron will terminate and re-assign the IRON, and the satellite's frequencies will be decommissioned.

B. Spacecraft EOL Triggers

There are a number of factors which can trigger a satellite's EOL. Some of the most prominent are discussed briefly here.

1. *End of Funding.* Most space programs, due to the large funding amounts required, are funded incrementally, in pieces across fiscal years. The needs of the Air Force, a change in political conditions or a sharp climb in needed funds due to technical support for troubleshooting persistent satellite anomalies can all contribute to a lack of funding for the upcoming year. If responsible for funding, the SCA may decide that future mission products are no longer worth a continued investment, as happens often with scientific missions that have been in orbit for several years past their baseline.

   Sometimes, the satellite can be placed in a safe mode configuration while the SOPS searches for a new funding "customer", but finance or contract constraints may require money tagged for EOL to be used up by the end of the fiscal year, in which case EOL procedures must be executed as outlined above.

2. *Degradation of Control Authority.* Failure of crucial sub-systems may be another trigger for EOL. This is especially relevant to R&D satellites, which are typically designed for a shorter lifespan and are single-string on most, if not all, of their subsystems. This lack of redundancy in the event of a malfunction may reduce the satellite's ability to perform its core mission. Certain malfunctions may result in loss or degradation of control authority over the satellite, which could make it a danger to other orbiting satellites, especially if it is designed to be a formation flyer like CloudSat.

3. *Low altitude.* Atmospheric drag lowers a satellite's altitude over the course of its life. Maneuverable satellites can maintain life with station-keeping maneuvers, however at a certain altitude determined by the satellite's design, it will begin to lose its ability to point at a target on the Earth accurately enough to provide usable images or signals. This will be followed rapidly by total saturation of the momentum wheels by atmospheric torques, which will rob the satellite of attitude control. At this point the satellite is practically useless, and the orbit will continue to decay exponentially, until total loss of control authority. Between the loss of pointing and saturation altitudes, while the satellite is still able to accept commands and provide verification of its status, EOL will have to be executed, and the satellite subsequently monitored for burn-in.

III. Components of an End of Life Plan and Execution

This section describes a number of diverse components that go into a full EOL plan. When the mission is shared with a military SOPS, policies of both the SCA organization and DoD will be the standards against which the EOL plan is assessed for compliance.

A. Spacecraft Description

The components onboard a spacecraft have a large role in determining the level of detail that must go into EOL planning. One of the primary drivers is bringing the spacecraft to a minimum energy configuration, to minimize the destructive capability of its components after contact with it is no longer possible. The large amount of debris floating in LEO makes impact with the satellite at some later point in its orbit almost inevitable. A collision that produces an explosion due to the satellite being in a high-energy state can create thousands of debris particles that will remain in the orbit of the original satellite and become a hazard to future missions.

Therefore every stored energy source must be deactivated or dissipated to the maximum extent. If any of the following components are present aboard the spacecraft, mitigation measures must be addressed as part of the EOL plan.

1. *Fluids.* Fluid and thermal management issues aboard the spacecraft must be addressed. Cryogenic liquids, in particular, have been widely used aboard scientific missions, and are stored in various hazardous states. Some examples include high-pressure Joule-Thomson expansion devices for cooling of infrared detectors and storage of super-critical low-pressure helium to provide oxygen and nitrogen for manned missions[2]. The design for cryo-coolers on a short-term mission may be different from those on, say, the International Space Station, and the means by which these devices will be safed or jettisoned must be addressed accordingly.

2. *Propellant.* Every maneuverable satellite should have a ΔV budget dedicated exclusively to EOL operations. Once a degenerating or disposal EOL orbit has been achieved, fuel onboard must be jettisoned to the maximum possible extent. CloudSat uses a diaphragm that will aid in expulsion of remaining hydrazine fuel; however approximately 0.5 kilograms will remain trapped between the fuel tank's inner wall and diaphragm. To mitigate this, the satellite was designed with latch valves that will close, in addition to the thruster valves, to prevent excess hydrazine from escaping. In the event that design does not permit such mitigation, further perigee lowering maneuvers are an excellent way to burn off excess fuel and fulfill the DoD burn-in requirement discussed later in this paper.

   Many two-axis stabilized spinning satellites utilize on-orbit center-of-gravity (COG) adjusting mechanisms to 'pre-set' the attitude control planes. After depleting on-board propellant, it may be feasible to utilize such apparatuses to free inaccessible propellant in the lines or tanks, thus ensuring maximum evacuation of on-board fuel. Additionally, in the case where such satellites utilize tension components such as springs, torque-rods, pulleys, magnets, etc., it may be worthwhile from an energy management perspective to analyze and induce a lowest-energy state configuration for these COG adjusting devices.

   With regard to fuel lines, depending on specific design considerations, it may be safest to leave all fuel line valves, including thruster valves, in the open position. Hydrazine freezes at 30 degrees Fahrenheit, which can cause fuel line ruptures and subsequent explosions or low-energy debris. When the satellite is not in eclipse, leaving fuel lines open shortly after fuel depletion should ensure sufficient heat for thorough sublimation of all remaining or 'trapped' fuel.

3. *Pyrotechnic devices.* Spacecraft utilize pyro or firing circuits for functions such as severable bolts to jettison parts, operation of certain actuator valves, extending appendages from their storage compartments, etc[2]. Procedures to disconnect or safe the charging bank of capacitors should be included in the EOL plan to prevent accidental discharge of these devices.

4. *Radioactive material.* Depending on the mission, a spacecraft could carry radioactive materials onboard for purposes such as instrument calibration, as a heat or power source, as structural members or as part of a space experimental payload[3]. A satellite with radioactive material would likely have to be designed with enough fuel to reach a disposal orbit, due to the possibility of that material surviving re-entry and being distributed into the atmosphere. Various US and international regulations, to include the International Atomic Energy Agency (IAEA) Safety Series #6, "Regulations for the safe transport of radioactive material", would govern this decision and compliance would have to be captured in the EOL plan.

    5. Power design. The power system onboard the spacecraft, with special reference to the batteries, are the most common source of stored energy left onboard. Some satellites may be designed with a mode to configure batteries to disconnect from the spacecraft bus. Completing this before final shut-off procedures will avoid uncontrolled charging/discharging which can lead to battery explosions. However, many spacecraft have fault protection logic built into their automatic tasking engines (ATEs) to prevent them from being accidentally commanded off or from being discharged beyond a certain critical level. If such logic exists it may not be possible to dissipate battery energy as easily. Indirect methods to bring the power to the lowest possible configuration should therefore be carefully addressed.

CloudSat, for example, is designed with fault protection logic that commands the solar array DC current to switch directly into the power buses onboard. The indirect method involves setting the Voltage-Temperature curve to its lowest setting, and then triggering the onboard Emergency Mode Controller (EMC). This will fix the solar arrays at a pre-determined orientation with respect to the spacecraft, and all onboard electronics, including the Spacecraft Computer (SCC) automatically turning off. Even in this configuration, the direct transfer of power from the arrays to the loads and battery is expected to produce between 195 – 285 watts of power, depending on the spacecraft's solar orientation.

Though low, CloudSat's power margin will remain positive all the way through end of life or solar array degradation. In such a situation, the risk of an accidental explosion due to a buildup of charge must be evaluated. This is discussed later in this paper.

B. Passivation of the satellite

The checklist for passivation of a satellite will be highly dependent on the spacecraft's mission and design. This section presents a general outline to follow when writing an EOL plan.

1. *Start of EOL procedures.* Firstly, as described above, stored energy sources must be identified and measures to minimize or dissipate should be well thought out. For example at EOL TacSat-3 will have two stored energy sources; the reaction wheels and the charge in the battery. By design, Mission Engineers (MEs) have the ability to override all fault protection and autonomy imposed by the ATE. Therefore the plan for passivation for TacSat-3 will involve disabling the Peak Power Trackers and ensuring they do not enter bypass mode. This will prevent the batteries from charging when the solar arrays are exposed to the sun, instead drawing power from them and allowing the momentum wheels to spin down.

2. *Turning off non-essential equipment.* All non-essential equipment such as GPS, Star Trackers, Inertial Reference Units (IRU), back-up power, wide-band transmitters, Attitude Determination Control Systems (ADCS), etc., should be permanently turned off. For classification sensitive payloads, appropriate measures to ensure that no one else can command the satellite once the DoD has ceased control must be documented.

    Payloads can be left on for a period to accelerate discharging of the battery, but should be turned off before an under-voltage trip occurs. However, sensitive payloads remaining active as the satellite's state of health degenerates may not be an attractive risk. In such cases, battery discharge may be accelerated by slewing the spacecraft to an anti-sun attitude. It should be noted, however, that when the Guidance, Navigation and Control

[2]From http://www.braeunig.us/space/systems.htm

(GN&C) system is placed on standby (non-operational), atmospheric torques may cause the satellite to tumble, possibly lengthening the time for discharge.

3. *Making the spacecraft inert.* Once all measures to dissipate stored energy aboard the satellite are complete and only those systems needed to complete EOL commanding are on-line, the spacecraft is considered decommissioned. It will be at the lowest possible energy state and un-commandable except for the time-tagged EOL command block uploaded to the SCC that will turn the satellite into a non-functional piece of space debris. This will complete the passivation sequence.

C. Assessment of spacecraft debris released during and after passivation

Though passivation is crucial to reducing orbital debris, the potential for debris that may be released as a result of passivation must also be captured as part of an EOL plan. Examples of such debris may include clamps, de-spin devices, wraparound cables, pyrotechnic jettison hardware, sensor covers, lens shields[4], etc. A simple tether system or other low-cost containment system can be designed into the spacecraft to prevent such release. If such systems exist, their use should be captured in the EOL plan.

D. Assessment of generation of debris by accidental explosions

Especially once the spacecraft is beyond commanding, the potential for accidental explosions due to thruster malfunctions, tank failures due to small debris impact, battery ruptures, structural degradation or accidentally induced high rotation rates[4] can be high. If the satellite is approaching burn-in, accidental spacecraft breakup could occur during the final orbit. If a spacecraft contains any of the systems listed below, the EOL plan must incorporate a formal Failure Mode and Effects Analysis (FMEA). This analysis should be conducted as part of pre-launch readiness approvals, and updated prior to EOL. The FMEA's Risk Priority Numbers (RPNs) highlight the areas of greatest concern for accidental explosions, and should be used to justify any recommended passivation decisions.

1. *Range Safety.* It is estimated[4] that nearly 20% of all spacecraft breakups may be attributed to the unintentional detonation of on-board self-destruct or range-safety systems. Though many consider the space shuttle's Solid Rocket Booster (SRB) range safety to be the only publicly necessary mechanism, to prevent civilian casualties in the event of a deviated launch trajectory, such a picture is overly simplistic. Military launches are a large percentage of space activity, and the cutting-edge sensitive technology they carry onboard can be highly desirable to foreign nations. When executed properly, a range safety system can be designed to minimize orbital debris.

2. *Hydraulic systems.* Hydraulic cylinders, drive systems or motors find use in propulsion systems, gimbal servoactuators, Thrust Vector Control (TVC) systems and in power systems similar to the Hydraulic Power Units (HPUs) on the erstwhile space shuttle's SRBs. Such systems typically have a variety of pressurized moving parts such as fuel supply modules, hydraulic reservoirs and fluid manifold assemblies, and can present a significant hazard that must be addressed as part of EOL planning.

3. *Acoustic generators.* Thermo-acoustic generators are used in space to convert heat to electricity using sound-based generators. In addition, piezoelectric acoustic generators are lightweight and free from RF noise, and find a variety of applications in satellite microprocessors and amplification or oscillation type circuits[3]. Another example application is onboard the Cassini spacecraft, to reduce the acoustic environment at the mountings for the three onboard radioisotope thermoelectric generators (RTGs) [5].

   RTGs, for example, pose a significant risk of radioactive contamination: previous failed Russian Cosmos missions have burned up in the atmosphere and released radioactive material. Mitigation measures to these and similar risks should be considered during EOL, especially if the satellite will reach EOL due to orbit degradation in the upper atmosphere.

E. Assessment of generation of debris by intentional breakup

Examples of intentional space vehicle breakup debris include jettisoning frangible bolts or using pyrotechnic devices to separate the spacecraft from its payload or other component parts. Intentional breakup has also been executed as part of structural testing, destroying classified equipment aboard military satellites to prevent recovery

[3] From "Kyocera Piezoelectric Acoustic Generators" - http://www.avx.com/docs/masterpubs/piezo.pdf

by non-allied nations, space-borne explosive testing and in Anti-Satellite (ASAT) and other space weaponization testing[6]. Lately, however, the growing concern over the space debris problem and its impact on current space operations has led to the DoD clamping down on intentional break-up activities.

An excellent example of space operations impact can be found in China's recent destruction of its Fengyun-1C weather satellite with an ASAT device. Now widely viewed as the most severe fragmentation in 50 years of space operations, NASA estimates that the breakup of Fengyun caused over 950 pieces of space debris with a size of greater than 10 centimeters; each with a velocity in excess of 12 km/sec, spanning 200 to 3,800 kilometers above the surface of the Earth. CloudSat alone has faced over twenty Collision Avoidance (COLA) threats from Fengyun, and has been forced to maneuver out of the way more than once.

Current US Space Policy dictates that any intentional breakup plans must be approved on a case-by-case basis by the Secretary of Defense[7].

F. Assessment of spacecraft potential for on-orbit collisions

Two categories of on-orbit collisions must be considered: vulnerability to space objects smaller than 10 cm in diameter and to objects larger than 10 cm at the orbit altitude of the satellite. The objective is to determine if the current altitude is the most optimal for executing EOL, taking the debris and potential for post-EOL collisions at that altitude into consideration. Figure 3 shows the curves for an analysis conducted for predicted conjunctions with objects smaller than 10 cm in diameter vs. altitude for TacSat-3[8].

There are several approved software packages that can calculate the number of small debris impacts: Object Re-entry Survival Analysis Tool (ORSAT), Spacecraft Atmospheric Re-Entry and Aero-thermal Breakup (SCARAB), Spacecraft Entry Survival Analysis Module (SESAM) and NASA's Debris Assessment Software (DAS) are some of these. Lips[9] performs an excellent comparison of the fidelity and results of these various tools. The analysis shown in Figure 3 was performed using DAS, and spans a timeframe between 2012 and 2013.

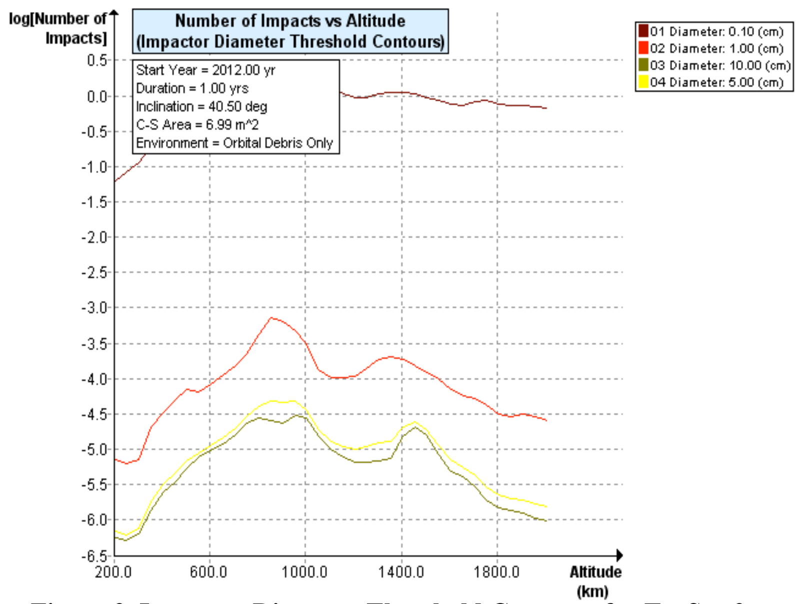

Figure 3. Impactor Diameter Threshold Contours for TacSat-3

Table 1 shows the number of impacts as compared to debris size for TacSat-3's injection altitude of 460 km using DAS v2.0.1. EOL plans should attempt to include an updated version of a similar table for the projected EOL altitude.

Table 1. Debris size vs. Impacts for TacSat-3 at 460 km. altitude

Debris Size	Number of Impacts
1 mm	0.316228
1 cm	0.000040
5 cm	0.000003
10 cm	0.000003

G. Assessment of re-entry within 25 years

DoD instructions for space operations attempt to limit the probability of collisions and explosions post-EOL. According to DoDI 3100.12[15] paragraph 6.4, EOL procedures must "leave the satellite in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission". NASA also has adopted similar policies, namely, NASA Procedural Requirement NPR 8715.6[13], "NASA Procedural Requirement for Limiting Orbital Debris Generation" and NASA Technical Standard NASA-STD 8719.14[14] "Process for Limiting Orbital Debris".

Since CloudSat has maneuvering capability, we shall use it as our example. The design delta-V budget for the satellite was 107 m/s with a reserve of 20 m/s and an allocation of 35 m/s for EOL perigee lowering. The fact that almost 33% of the nominal delta-V was earmarked for EOL should highlight the importance of EOL operations. However, CloudSat was loaded with 97 m/s of excess propellant, bringing the total delta-V to 204 m/s, which could conceivably leave as much as 65 m/s at the end of the mission for perigee lowering to meet the DoD and NASA guidelines.

The first step would be to lower out of the A-Train. CloudSat's draft EOL plan outlines a strategy to lower the apogee by a minimum of 15 km below the orbit of the constellation[11]. A total propulsive maneuver of 10 m/s would change the orbital semi-axis up to 18.9 km without violating the thermal soak-back constraint of CloudSat's thrusters. Half a revolution later, another maneuver would be performed to circularize the orbit beneath the A-Train. From this new altitude, CloudSat would begin to systematically reduce its semi-major axis with maneuvers at apogee, each on the order of 10 m/s but no greater than 13 m/s, to consistently reduce the perigee. Calculations show that re-entry within 25 years can be assured by lowering the perigee of CloudSat to below 550 km. With the projected fuel aboard, however, the perigee can be taken as low as 175 km. Though the EOL plan must allow Orbit Analysts (OAs) leeway to adjust burn times and orbital positions according to operational needs or AFSCN contact times, it must provide sufficient detail to prove the capability to re-enter within 25 years.

H. Survivability Analysis

Even after space vehicle breakup in the upper atmosphere, certain component parts made out of tungsten, titanium, stainless steel, beryllium or carbon-carbon may not reach their melting point by aeroheating. In many cases these components survive re-entry, which leads to the study of "casualty area". The recent entry of NASA's Upper Atmosphere Research Satellite (UARS) was a stark highlighter of this area. A measure of satellite survivability during uncontrolled entry and break-up, casualty area is defined as the area around a debris impact point within which a person present will become a casualty[4]. NSS 1740.14 Section 7 narrows the maximum casualty area permissible for a re-entering body to 8 m^2.

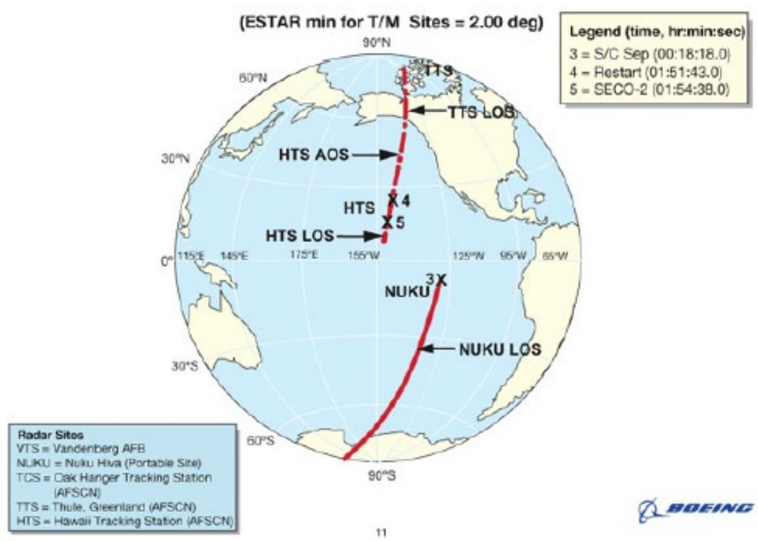

Figure 4. Tracking of Delta II Controlled Re-entry with AFSCN Remote Tracking Stations

DoDIs do not mention a limit for casualty area, focusing instead on "casualty expectation". This is defined as the average number of casualties that can occur as a result of a re-entry event if the event were to be repeated thousands of times. DoDI 3100.12 sets the maximum casualty expectation at no greater than 1 in 10,000. Neither DoDIs nor NSSs require a controlled re-entry guaranteed to avoid inhabited areas, unless the casualty expectation is above this

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[4] From http://www.space.gov.au/SpaceLicensingSafetyOffice/Documents/FSC_Pubn1_20050602105043.pdf

† AOS: Acquisition of Signal, LOS: Loss of Signal.

limit. At that point the satellite will be required to budget propellant for a final entry maneuver that will steepen the flight path angle and allow for Earth-impact at a selected longitude and latitude, most likely in the Pacific Ocean. *Therefore, a military or military-affiliated non-maneuverable satellite must, from design inception, meet these casualty expectation criteria*.

An example of this is the 2006 Delta IV[10] mission depicted in Figure 4 above†. DoDIs only enforce a maximum casualty expectation instead of casualty area, Delta II and Delta IV vehicles do not have to comply with NSS 1740.14 Section 7 (Delta II second stage casualty area is 10.8 m^2). After releasing its meteorological satellite payload to an 850 km. orbit, it re-ignited its own second stage motor and staged a controlled re-entry over the Pacific Ocean.

Every component piece of the re-entering spacecraft bus and payload must be modeled to determine its ablation temperature, demise altitude (measure of survivability) and casualty area. Table 2 below shows a selection of the burn-up break-down by component part for CloudSat, created with DAS.

When combined with a similar analysis for the CloudSat CPR payload, the casualty areas sum to be 5.02 m^2. Therefore as a NASA asset CloudSat complies with NSS 1740.14, and as an Air Force controlled satellite, with DoDI 3100.12.

I. Casualty Expectation Assessment

From the analysis presented in Table 2, a picture of surviving pieces can be drawn. Created with DAS, this is in fact a conservative analysis. Lips[9] points out that DAS assumes higher heat capacities and emissivities than SCARAB and ORSAT, possibly artificially increasing the survivability of re-entering parts.

Table 2. CloudSat Satellite Bus Survivability Analysis

Total Debris	Casualty Area	3.8321 m^2						
Object Surface Identification	Object Type	Object Diamete (m)	Object Length (m)	Object Height (m)	Object Mass (kg)	Material Type	Demise Altitude (km	Casualty Area (m^2)
Parent	Box	1.4	2.87	1.6	776	Al 6061-T6	77.999	0
CloudSat inst	Box	1.4	1.4	0.4	255	Al Sol Pan	49.72	0
"+X" wall panel	Box	1.549	0.762	0.027	9.93	Al Sol Pan	75.249	0
"+Y" wall panel	Box	1.524	1.016	0.027	13.03	Al Sol Pan	75.2488	0
"-X" wall	Box	1.549	0.762	0.027	9.19	Al Sol Pan	75.3859	0
"-Y" wall panel	Box	1.524	1.016	0.027	13.3	Al Sol Pan	75.2486	0
mid deck	Box	1.168	0.889	0.027	8.08	Al Sol Pan	76.0341	0
"-Z" deck	Box	1.27	1.27	0.028	33.9	Al Sol Pan	71.7415	0
"+Z" deck	Box	1.397	1.27	0.027	14.6	Al Sol Pan	75.5178	0
payload sup (1)	Box	0.08	0.16	0.08	1.03	Titanium	0	0.5086
payload sup(2)	Box	0.08	0.16	0.08	1.03	Titanium	0	0.5086
payload sup (3)	Box	0.08	0.16	0.08	1.03	Titanium	0	0.5086
payload sup (4)	Box	0.08	0.16	0.08	1.03	Titanium	0	0.5086
propulsion deck	Cylinder	0.914	0.04	0	7.36	Al Sol Pan	76.2612	0
corner posts(1)	Box	0.01	1.448	0.127	3.35	Al 6061-T6	77.2016	0
corner posts(2)	Box	0.01	1.448	0.127	3.35	Al 6061-T6	77.2016	0
corner posts(3)	Box	0.01	1.448	0.127	3.35	Al 6061-T6	77.2016	0
corner posts(4)	Box	0.01	1.448	0.127	3.35	Al 6061-T6	77.2016	0
balance mass	Box	0.08	0.45	0.3	3.8	Copper	74.5845	0
t shields (1)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (2)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (3)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (4)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (5)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (6)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (7)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (8)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
t shields (9)	Box	0.127	1.372	0.003	0.64	Al 6061-T6	77.2349	0
thermal fin +X1	Box	0.025	1.397	0.003	1.51	Al 6061-T6	74.4363	0
thermal fin +X2	Box	0.025	1.397	0.003	1.56	Al 6061-T6	74.298	0
thermal fin -X1	Box	0.025	1.397	0.003	1.56	Al 6061-T6	74.298	0
thermal fin -X2	Box	0.025	1.397	0.003	1.56	Al 6061-T6	74.298	0
thermal fin +Y1	Box	0.025	1.372	0.003	1.65	Al 6061-T6	74.0188	0
thermal fin +Y2	Box	0.025	1.372	0.003	1.59	Al 6061-T6	74.2992	0
thermal fin -Y1	Box	0.025	1.372	0.003	1.64	Al 6061-T6	74.16	0
thermal fin -Y2	Box	0.025	1.372	0.003	1.64	Al 6061-T6	74.16	0
S/C adapter	Cylinder	0.952	0.127	0	10.4	Al 6061-T6	73.228	0
sun sen mast 1	Cylinder	0.114	0.305	0	1.08	Al 6061-T6	73.8582	0
TT&C ant (1)	Flat Plate	0.349	0.21	0	0.96	Al 6061-T6	73.9628	0
TT&C bckt (1)	Box	0.11	0.406	0.23	1.08	Al 6061-T6	76.6265	0
sun sen mast 2	Cylinder	0.114	0.305	0	1.08	Al 6061-T6	73.8582	0
TT&C antennae2	Flat Plate	0.349	0.21	0	0.96	Al 6061-T6	73.9628	0
TT&C bracket 2	Box	0.11	0.406	0.23	1.08	Al 6061-T6	76.6265	0
torque rods (1)	Cylinder	0.025	0.635	0	1.7	Copper	71.358	0
torque rods (2)	Cylinder	0.025	0.635	0	1.7	Copper	71.358	0
torque rods (3)	Cylinder	0.025	0.635	0	1.7	Copper	71.358	0

Figure 5 below shows the distribution of population plotted against orbital inclination for 2009 and 2010. When this population density number is multiplied by the summed casualty area of all re-entering parts, the total casualty expectation for random re-entry during a particular year can be calculated.

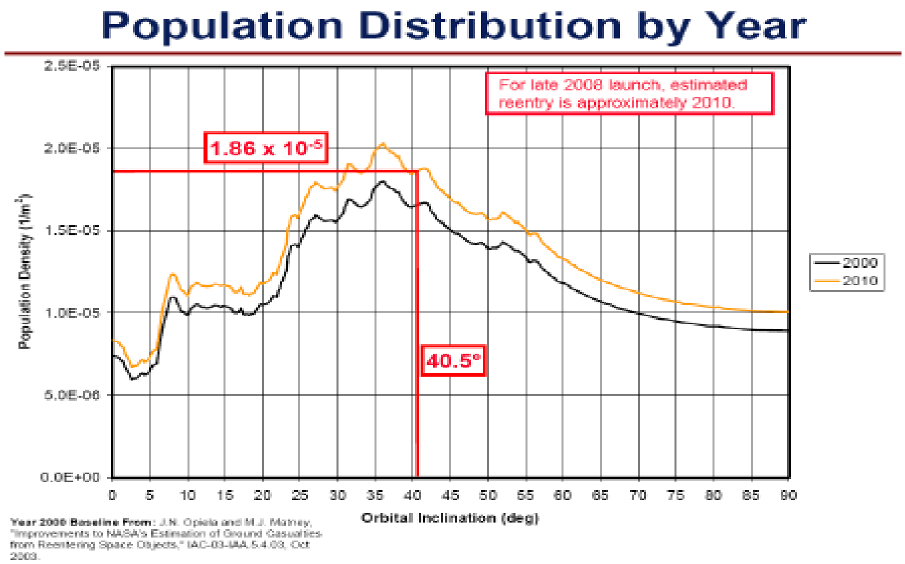

Figure 5. Average Population Density Estimate

The graph evens out after approximately 80 degrees into the retrograde inclinations. As can be seen, the highest population density occurs right around TacSat-3's inclination of 40.5 degrees. CloudSat's inclination is 98.2 degrees due to its Vandenberg AFB launch location. For a 2010 re-entry, the casualty expectation would have been calculated as:

$$\text{Expected Casualty} = \text{Casualty area } (m^2) * \text{Population density } (1/m^2) \quad (1)$$

For CloudSat, Equation (1) becomes:

$$\text{Expected Casualty} = 5.02\ (m^2) * 10^{-5}\ (1/m^2) \quad (2)$$

The expected casualty for CloudSat for 2010 is 0.0000502 or 1 in 19,920. This is well within the limit of 1 in 10,000 specified in DoDI 3100.12.

IV. Conclusion

Satellite EOL planning is an exhaustive process that incorporates many elements, many of which have links to the design process of the satellite. The problem of orbital debris during and after execution of EOL will require foresight and planning, as well as adherence to guidance and instructions put in place by NASA and/or the Department of Defense.

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