Iridium Deorbit Strategy, Execution, and Results

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ABSTRACT

Debris remediation starts with a responsible operational posture and completes with end-of-life disposal. Iridium has just completed the largest technology refresh in space by replacing their entire fleet of LEO satellites. As part of that effort, Iridium developed and then implemented a deorbit program to ensure space was safe for future generations by meticulously ensuring each satellite being replaced was deorbited in an efficient, cooperative, and responsible manner. This paper addresses the efforts and status of the Iridium deorbit program and provides lessons learned that should be applied as best practices for future space assets.

In 2010, Iridium embarked upon an ambitious effort to replace their existing satellite system, commonly referred to as Block 1 (B1), with a more capable system called NEXT. This involved a one-for-one replacement of satellites in each of the 66 mission slots. Iridium immediately recognized the need to safely replace each B1 satellite without impacting services to their customer base using a “slot swap” technique while, just as importantly, the Iridium team and management also committed to carry out an effort to retire each operational B1 satellite responsibly.

A deorbit program involves many facets of satellite operations as well as a tight cooperative nature with external entities supporting the LEO environment including CSpOC, NASA and the manned spaceflight program. It must also include internal cooperation between mission planning, operations, guidance navigation and control, system engineering, and designed following a rigorous code of responsible disposal - namely the “7 D’s” of end of life process: Deboost, Drag, Direct, De-spin, Depressurize, Discharge and Demise.

- Deboost - accomplish a 25-year or better deorbit profile
- Drag - maximize atmospheric drag imparted on the satellite
- Direct - maintain command and control of the satellite
- De-spin - remove all energy from wheels and other kinetic energy devices
- Depressurize - safely passivate any fuel or pressurants
- Discharge - deplete batteries and open electrical connections, prohibiting accidental recharge
- Demise - design satellite to disintegrate upon re-entry, limiting any potential hazards

Since early 2017, Iridium has not only launched a new fleet of satellites with Iridium NEXT but also used these fundamental principles to deorbit their B1 satellites. The process has been optimized while building upon these anchor concepts. A review of the internal/external processes employed and challenges that Iridium faced resulted in the deboost of 64 B1 satellites, 59 of which have re-entered Earth’s atmosphere, with a median time from satellite passivation to reentry of just 19 days.

1 RESPONSIBLE CONSTELLATION MANAGEMENT

The original Iridium Satellite constellation, or B1, consisted of 66 low earth orbit satellites with on-orbit spares. Most satellites were launched from 1997 through 1998, with additional spares launched in 2002. During the Iridium NEXT launch campaign which started in January 2017, 75 new satellites were placed in orbit and Iridium began the largest space cleanup in history.

When Iridium was designed, space cleanup initiatives were just becoming a topic of interest. NASA and IADC guidelines for a 25-year burn-in was not a commercial standard. As one of the first mega-constellations, Iridium foresaw the need to remove unused satellites from Low Earth Orbit (LEO) and minimize the potential for debris generation. They included design and operational requirements for end-of-life disposal with a significant propellent allocation. Twenty years of on orbit experience provided additional insights into software and operations upgrades that could ensure the best possible de-orbit success.

Iridium management support for reliable deboost was a key driver ensuring success. During B1 operations, Iridium became acutely aware of the risks that derelict spacecraft pose; notably the destructive collision of Cosmos 2251 and Iridium 33 [1]. This event strengthened Iridium's resolve to do everything possible to be a good space steward. In 2013 Iridium embarked on a project to evaluate de-orbit risk and determine how to safely deboost all its B1 satellites as part of Iridium's overall responsible constellation management activities. This responsible space cleanup was far more than just sending a "deboost" command.

1.1 Iridium Deboost Project

Iridium initiated an internal project to address six of the "D" goals to (1) Deboost the satellites as low as possible, (2) Set up a high Drag profile for the satellite at the end of deboost, (3) Direct and maintain active control of the satellite (4) De-spin the momentum wheel, (5) De-pressurize the propellent tank, and (6) Discharge the battery.

The Iridium B1 satellites were designed to disintegrate upon atmospheric re-entry, meeting the 1 in 10,000 casualty risk guidelines. Iridium Communications Inc. acquired the on-orbit assets of the constellation in 2001. So, for the "Demise" portion of the "7 D's", there was nothing more to be done. The Iridium satellites were originally designed to support a 1-year re-entry timeframe. However, they did not possess the control authority for a controlled/targeted reentry. The "Directing" aspect of the "7 D's" was limited to maintaining custody/control of the satellite while it was actively maneuvered.

The end of life deboost maneuver was one of the most taxing that Iridium satellites had to execute. Thus, it was critical to establish a nominal baseline as well as contingency procedures to compensate for potential failures. Twenty years of operational experience indicated that improvements could be made to enhance deboost reliability, performance, and ultimate success. During the deboost project, several engineering challenges were addressed: satellite hardware constraints (ADCS/Propulsion/Computer/Power/Communication), propellant constraints, non-nominal orbital environment, increased external forces at lower altitudes, external coordination, and passivation; which goes against all the built in safety features designed to protect the satellite.

2 IRIDIUM BLOCK 1 SATELLITE BACKGROUND

The Iridium satellites, or Space Vehicles (SV), were designed and built in the 1990s. The construction of the SVs was unique at the time, designed for a high rate production (1 per week) and for efficient packing such that seven SVs could be launched on a single rocket. A triangular bus structure of carbon fiber, 406 cm "tall" with 78 cm sides, provided a foundation for mounting equipment. Twin articulated Solar Arrays (SA), 346 cm x 117 cm, attach at the top of the body. Three phased array Main Mission Antenna (MMA), 188 cm x 87 cm, panels were deployed at 40 degrees. Four square crosslink antennas allowed communication between SVs at mission altitude. Four SV to ground Ka-Band antennas on 2-axis gimbals were used for high bandwidth communications. A single omni antenna was used for contact when attitude or timing was off. Figure 1 shows the general components of an Iridium B1 SV.

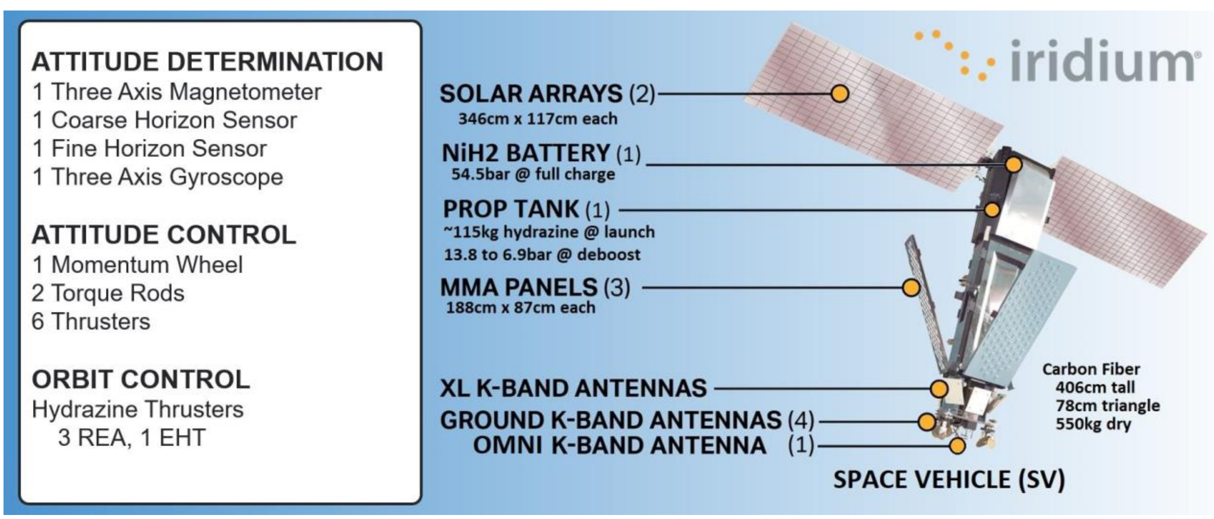

Fig. 1. Iridium Block 1 Satellite

2.1 Space Vehicle Hardware

Propulsion System

The propulsion subsystem supplied the thrust for all orbit transfers, on orbit station-keeping adjustments, as well as attitude control in some modes. The propulsion subsystem consists of seven Aerojet MR-103G Reaction Engine Assemblies (REAs) each providing 1N (0.2-lbf) of thrust. One or three REAs were used for orbit velocity changes, two of which could additionally control pitch, while four were used for roll/yaw control. One Aerojet MR-501B Electrothermal Hydrazine Thruster (EHT) was available for high efficiency thrusting, albeit at a lower thrust of 0.369N (0.08-lbf), and at a high-power draw. REA and EHT performances are shown in Fig. 2.

Parameter	**REA (MR-103G)**	**EHT (MR-501B)**
Photo		
Total impulse	79,512 N-sec	326,928 N-sec
Steady specific impulse	224 to 202sec @24.1bar feed pressure (P_f)	292sec average over P_f =24.1bar to 6.9bar
Thrust	0.939N@P_f =24.1bar to 0.272N@P_f =6.9bar	0.37N@P_f =24.1bar to 0.041N@P_f = 6.9bar

Fig. 2. Thrusters Capability

The thrusters were fed hydrazine through propellent lines coming from a helium pressurized titanium propellant tank (64cm x 74cm, 10kg). The tank was a blowdown design with no membrane separating pressurants from propellant, though there was a surface tension device and a screen at the tank outlet to prevent gas from entering the propellant lines until the tank was nearly empty. Initial propellent load varied across the constellation, dependent on launch vehicle, drift requirements, and contingency maneuvers.

Electrical Power System

Iridium SVs had two Solar Arrays (SAs) comprised of solar cell assemblies that were adhesively bonded to a composite substrate. A goal prior to passivation was to re-orient the SAs to a high drag configuration to satisfy the “drag goal.” If left to chance, SA positions at passivation may be left in a non-optimal, low-drag position. Therefore, Iridium chose to place the arrays into a custom high drag position during passivation.

Iridium SVs used a single nickel-hydrogen pressure vessel battery (25cm x 63cm, 30-37 kg). Under operating conditions, the battery was pressurized to 54.5 bar at full charge. Discharge of the battery was part of passivation.

Attitude Determination and Control System

The Iridium SV Attitude Determination and Control System (ADCS) included equipment that was used for different modes of operation and various phases of the satellite life. Attitude determination equipment included a Fine Horizon Sensor Assembly (FHSA) with two optical scopes and a narrow field of view (FOV) for use near mission altitude, and a Coarse Horizon Sensor Assembly (CHSA) with 2 scopes and a wide FOV for storage orbits. A Three-Axis Gyroscope (TGA) was available for maneuvers and wheel-off operations, however this was a life-limited ring-laser gyro. Also included was a three-axis fluxgate magnetometer (MAG).

Attitude control equipment included a single Momentum Wheel Assembly (MWA) that typically operated at about 6100 rpm. The MWA was used for deboost when the TGA was not available. When not using the MWA, six of the REA Thrusters (THR) were used for Pitch and Roll/Yaw control. Two Magnetic Torque Rods (MTR) were used to manage MWA momentum, or to help keep attitude within thruster deadbands.

Iridium SVs did not have onboard GPS, but instead relied on ground tracking for orbit state updates.

2.2 Software Modes

Three Attitude Determination (ATDT) modes used on Iridium were applicable to Deboost. The primary mode was MGAD, a MAG+TGA determination system. This mode was reliable and preferred over a CHSA+TGA mode which was susceptible to upsets when the CHSA was impinged by the Sun. The backup mode was CRYO, a CHSA+MWA+MTR mode. Where the MWA and TGA were not available, a Wheel-less-Gyro-less Attitude Determination (WGAD) was used which relied on MAG+Filter [+FHSA].

Three attitude control (ATCT) modes were used during deboost. The standard thruster (THR) mode was the most common and used exclusively with MGAD. It used REA23 for pitch control, and REA4567 for roll/yaw control. MTR was added into this mode to reduce fuel usage. A Coarse Magnetic Momentum Bias (CMMB) mode used the MWA and CHSA, which was used primarily with CRYO. Lastly, Fine Daedalus (FDAED) was a soft THR+MTR mode specifically tuned for use with WGAD.

Figure 3 summarizes various mode combinations used and the number of SVs (#) that used those modes. Note the fractional use of some combos, indicating that the attitude configuration changed part way through deboost.

ATDT-ATCT-ThrSelect	#
CRYO-CMMB-EHT	3.5
CRYO-CMMB-REA8	3.5
MGAD-CMMB-REA238	0.5
MGAD-THR-EHT	4.5
MGAD-THR-REA238	51
WGAD-FDAED-REA8	2
Total	**65**

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ATDT	#
MGAD	56
CRYO	7
WGAD	2

ATCT	#
THR	55.5
CMMB	7.5
FDAED	2

ThrSelect	#
REA238	51.5
REA8	5.5
EHT	8

Fig. 3. ADCS and deboost thruster modes

2.3 Configurations: Start State and Deboost

State of the Constellation

Iridium B1 SVs were originally designed as identical copies, but as time progressed and hardware degraded, each SV became a unique entity with their own capabilities and constraints. This affected the deboost plan, since key hardware that needed to be used might not be available. Over 58% of the B1 constellation was unconstrained while 42% had specific constraints affecting deboost. Figure 4 captures the constraints levied upon the B1 SVs. Fortunately, over the years Iridium became adept at handling these differences, and some limitations were addressed by software modifications and/or operational changes.

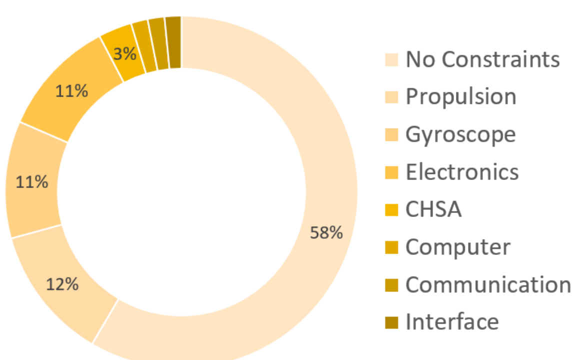

Fig. 4. SV constraints affecting deboost

Deboost Configurations

The nominal deboost configuration initially planned to use the CHSA+TGA, but the CHSA could become impinged during some Sun Beta seasons, causing attitude transients. Instead, the deboost configuration was changed to MGAD, substituting the MAG for the CHSAs. Thrusters were used for attitude control (REA4567 for roll/yaw, REA23 for pitch) and REA238 all contributed to the delta-V changes. The EHT could be used in place of REA238, but the attitude control thruster fuel usage was higher due the lower thrust and hence longer maneuver duration.

Fifty-one SVs used the nominal deboost configuration. Remaining SVs required different strategies and software development.

3 DEBOOST STRATEGIES

Maneuver Optimization and Planning

Deboosting a B1 satellite was a non-trivial process with many operational parameters such as: SV configuration, maneuver performance, tracking reliability, tracking site availability, attitude performance, state of health monitoring, command and control, contingency operations, space situational awareness and external coordination.

From a high-level perspective, Iridium's deboost maneuver sequence consisted of four phases:

1. Prior to initiating a deboost sequence, the satellite was updated with the final flight software. The software configured the SV for deboost operations with updated fault escalation and passivation sequences. The SV was then commanded to slew 180 degrees in yaw to a backward configuration for retrograde thrusting. The solar arrays were re-oriented to maintain power. All attitude determination and control hardware operations were verified.
2. The second phase applied to satellites located at Iridium's mission altitude. Phase 2 deboost consisted of both perigee and apogee lowering maneuvers to circularize the orbit and safely remove the satellites from the mission altitude orbital shell. Nominally, apogee lowering maneuvers were minimized and the propellant conserved for perigee reduction.
3. The third phase consisted of perigee lowering maneuvers, ideally targeting a 260 km perigee or lower where atmospheric drag was enough to induce a sub 1-year uncontrolled reentry. However, a lower perigee target altitude range of 165 to 160 km was chosen based on extensive attitude control simulations and ground tracking reliability, while at the same time minimizing on-orbit dwell time. Based on NASA Debris Assessment Software (DAS) version 2.1.1, a 165-kilometer perigee altitude equated to an orbital dwell of approximately three weeks.
4. For SVs with excess fuel, an additional deboost maneuver sequence was required to expel the excess propellant. Some SVs performed apogee lowering maneuvers, while others additionally executed fuel dumping crosstrack maneuvers that did not reduce orbital dwell times. These maneuvers were performed after the minimum target orbit was achieved while satellite controllability was maintained.

Figure 5 depicts the deboost maneuver plan for Iridium 62.

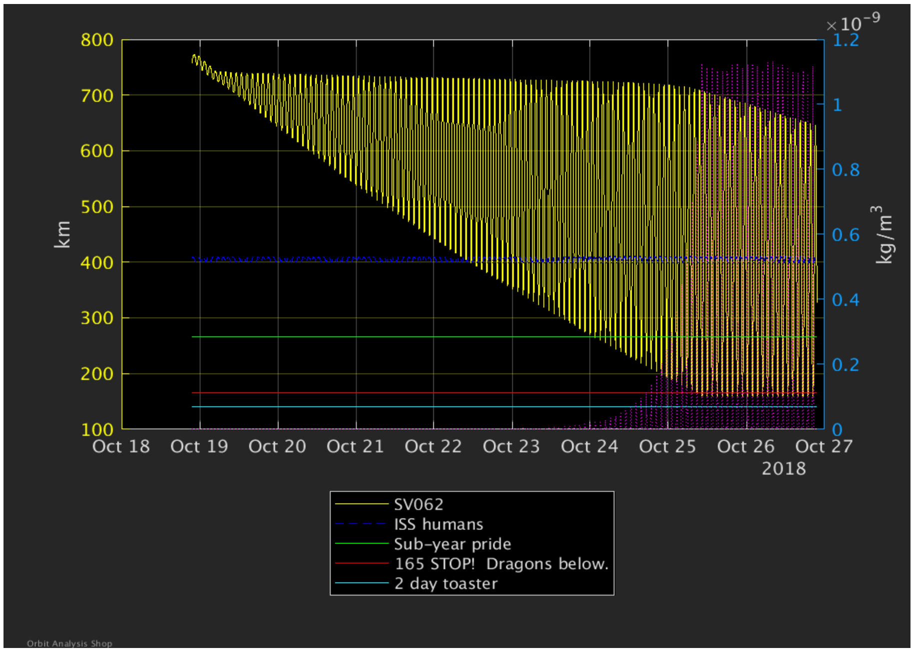

Fig. 5. Iridium 62 deboost maneuver trajectory

Conjunction mitigation criteria

Iridium's deboost conjunction-mitigation criteria was designed to reduce the risk of collision. The criteria were based on probability of collision and Mahalanobis distance. For conjunctions that were within 72 hours, mitigation criteria were defined as: a probability of collision greater than 2.0e-4 and a Mahalanobis distance less than 3.

Coordination between operational missions sometimes required modification to the predefined criteria and were handled on a case by case basis. Iridium's intent was to not interfere with existing operational missions. For example, International Space Station (ISS) conjunctions had an additional constraint to avoid penetration of a safety zone around the station of ±2 km radial, ±48 km in-track, and ±48 km cross-track.

ADCS Software Improvements

The most significant obstacle to achieving a 1-year deorbit/re-entry for some SVs was propellant availability. Iridium invested in design and development of a new attitude determination mode for deboost with the MWA spinning. This mode eliminated costly roll/yaw thrusting and improved EHT maneuver efficiency. Additionally, the MTRs were included in the control loop to dump excess MWA momentum.

MGAD compatible attitude control modes originally did not include the MTR controller or allow use with a spinning MWA. Software was enhanced to integrate the MTR control into the thruster control logic and separately to allow the addition of the stabilizing effects of the MWA. This allowed MGAD to operate within thruster control deadbands and reduce the need for thruster firing and wasting fuel.

WGAD was developed primarily for mission orbits. It required FHSA and XL measurements in addition to the MAG for 1 degree pointing requirements. But, if all else failed, Engineers found that WGAD could be "detuned" from precision pointing requirements and be a safe contingency attitude mode. Since FHSA was only usable to 30 km below mission, engineers developed a roll offset attitude profile to keep the horizon sensor scopes from saturating on the horizon. This mode was integrated into contingency plans and onboard Failure Detection, Isolation, and Response (FDIR) and was utilized on a couple SVs for deboost.

Maneuver Safety

Safely transitioning to a deboost mode was a concern for Iridium. In order to execute deboost maneuvers, the SV must be yawed 180 degrees to a backward configuration, to allow use of REA238 or EHT for retrograde maneuvers. This maneuver originally required spinning down the MWA to zero speed. Unfortunately, in some past cases, this resulted in MWA failure. Therefore, a software modification was developed to allow yaw slews while the MWA was still spinning. In this mode, the MWA was reduced to 7 percent of its nominal speed (450rpm out of 6100rpm) during the yaw slew. The MWA could then be spun back to nominal speeds after the yaw was complete. Additionally, the spin down/up was performed with torque bars dumping momentum instead of thrusters, saving propellant and avoiding orbit raising due to thrusting. This enhanced capability was extended to other operations besides deboost.

Perigee-lowering burn location was chosen to be at orbit nodes for several reasons: attitude control benefitted from the best observability of the magnetic field vector (required for WGAD), solar array positioning for the sun at the node allowed better aerodynamic balancing of the SV, and more accurate attitude control at nodes was available during burns. The best orbit estimates were obtained during tracking passes separated from burn execution, meaning northern hemisphere burns were not desirable since Iridium tracking antennas resided in the northern hemisphere.

Passivation

Designing passivation plans was interesting, since all previous software modifications helped to keep SVs alive. Initial simulations at passivation often resulted in the SV executing deeply embedded life-saving techniques. Similar passivation challenges are described in [2]. Though the ability of the SV to autonomously deboost existed in software, no passivation capability originally existed. The Iridium flight software team developed a passivation sequence to (1) turn off attitude control, (2) open opposing roll/yaw REA4567 thruster valves to dump propellant and avoid inducing attitude rates, (3) reposition solar arrays for high drag, (4) disable fault management, (5) switch to special telemetry reporting to allow the ground to monitor passivation progress. The solar array switches were commanded open in a controlled manner to discharge the battery slowly. During this time, the power engineers monitored battery state-of-charge to predict capacity and end-of-life [3]. With no attitude control, communication was limited to using the partial omni antenna, so communication could be intermittent. An SV was declared dead after three orbits with no radio contact with the ground after the battery was projected to be exhausted.

Timing of activities in the sequence was critical. With loss of power, thruster valves closed, so fuel needed to be dumped and the tank depressurized before that time. Similarly, the solar arrays needed to be fully repositioned to the high drag configuration, which was not necessarily sun pointing.

The passivation sequence was not loaded onboard until the final deboost software package was loaded for safety reasons. Ground system design made it difficult to accidentally trigger this sequence. Ironically, the passivation sequence trigger was based on low power monitoring that previously was used for extreme lifesaving measures. Limits for triggering were typically set to 50% battery state-of-charge and voltages that were projected to allow the passivation sequence time to fully complete before power was exhausted. Some satellite control components stopped working below a bus voltage of 18V, but computers have been observed operating at lower voltages. Once SV voltage went below a threshold, solar array connections opened, and it became impossible for an SV to spring back to life. Iridium had no unexpected passivation triggering.

Automation

Many critical deboost activities included operator in the loop commanding. This included SV mode changes and reconfigurations, burn planning, and passivation. However, in the case that the ground was unable to contact the SV, it could automatically generate deboost burn sequences and trigger the passivation sequence without ground input.

Iridium SVs were equipped with automated burn planning software, though the software did not include the ability to screen its own maneuver plan against a database of objects in space. Therefore, Iridium simulated a projected burn plan generation, verified the plan, and submitted the proposed plan to CSpOC. Once cleared, the SV would generate the actual plan and it would be verified against the original plan. Iridium always chose to manage burn plans with a person-in-the-loop and chose to use known and pre-coordinated plans to ensure active ownership of the maneuvers.

4 TESTING AND SIMULATION

A large part of the success of the deboost program was a result of the suite of satellite simulation and test assets used by Iridium. These assets allowed engineers to test existing capabilities, observe what-if behavior, play with different configurations, develop new software, test proposed deboost plans prior to actual activities, and refine ops plans in real-time.

A key test asset was the BusSim simulator developed for Iridium. This software-only simulator compiled together the actual satellite bus software with sensor and actuator models plus a space environment to allow true to code simulations of flight software behavior. BusSim runs at 6x-10x real-time and multiple instances could be run simultaneously. This capability was instrumental in testing configuration changes, mode selections, various maneuver options, FDIR and contingency operations, and used to evaluate SV performance. It was also important for flight software upgrade testing. Operationally, BusSim was used for actual maneuver planning and post maneuver rectification.

Iridium also used a full fidelity hardware in-the-loop qualification satellite (QM3) to perform final software verification and validation. With real flight computers and real hardware, Iridium was able to verify that software unit-tested in development labs was, in fact, going to run correctly on real SVs.

The initial deboost maneuver plan was incorporated in the flight dynamics software to generate a trajectory and perform an internal conjunction screening. The trajectory simulated thruster uncertainties to ensure a safe flight path. If a conjunction met criteria, then the maneuver would be modified. A final verification was performed by CSpOC before Iridium initiated the maneuver. Upon successful verification, the trajectory was incorporated into the Iridium mission scheduling system to allocate the required tracking and control antennas. Typically, a maneuvering satellite was tracked every orbit for state of health verification and orbit determination.

5 ORBIT OPERATIONS

5.1 Initial Orbits

Iridium mission orbits, the starting point for most deboost activities, are shown in Fig. 6. Some SVs were in storage orbits co-located within mission, and some were in storage orbit approximately 30 km below mission.

Mean Orbit Inclination	86.4 deg
Nodal Period	6028 sec (mean orbit radius of ~7158 km)
In-plane spacing	32.7 deg
Plane to Plane RAAN spacing	32 deg between adjacent planes

Fig. 6. Iridium Mission Orbits

5.2 Deboost goals and constraints

While NASA and the Inter-Agency Space Debris Coordination (IADC) committee recommend a 25-year reentry orbit for LEO satellite disposal [4], Iridium was designed with a more aggressive goal. Iridium's satellites were nominally loaded with 115 kg of propellent, of which only 11 kg of the propellant were consumed for twenty plus years of mission station-keeping. The remaining propellant was allocated for ascent to mission, contingency operations, and deboost.

The various combinations of attitude modes and deboost maneuvering thrusters provided a per-burn delta-V ranging from 0.25 to 3 meters/second. A complete deboost maneuver sequence consisted of 80 to 300 individual burns spanning 6 to 30 days, depending on the SV configuration. While Iridium B1 SVs had the capability to autonomously execute deboost maneuvers and passivation sequences, a fire and forget end of life disposal process could prove exceptionally risky for the overall space community.

Iridium developed a deboost process to maximize the probability of achieving the desired dwell orbit and minimize the risk of unwanted debris generation. The process, shown in Fig. 7, was supported by existing operational staff with a significant amount of automation.

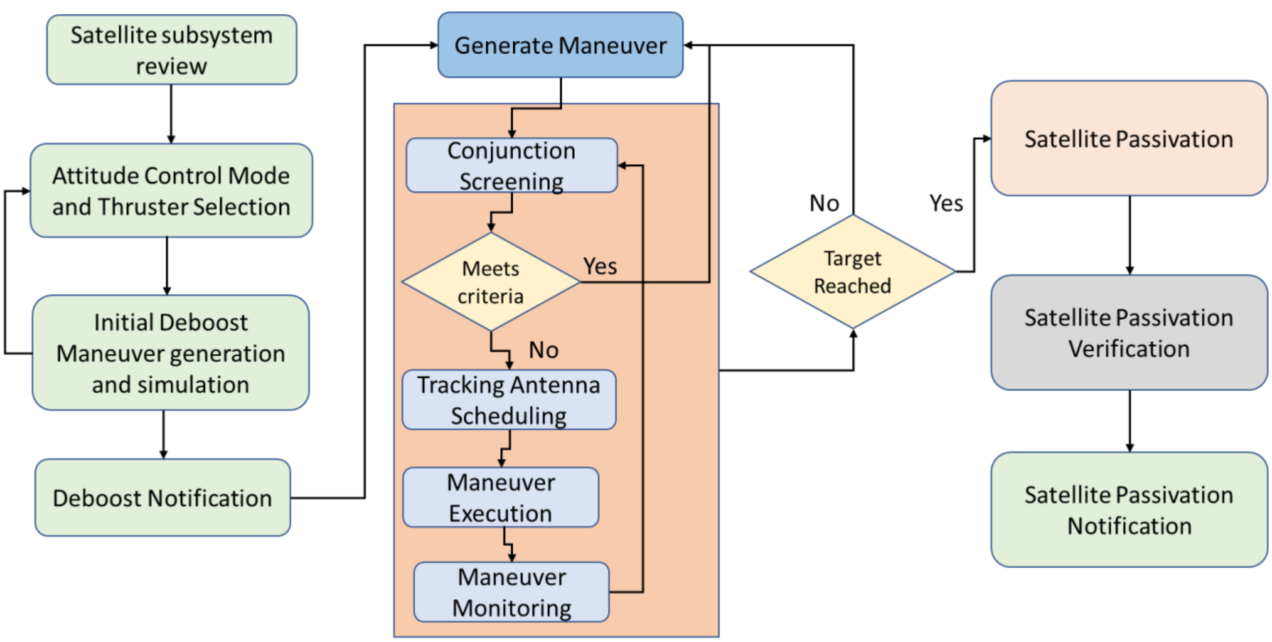

Fig. 7. Iridium Deboost Process

The first step in the deboost process was to determine the best configuration for the maneuver given the availability of propellant, power, hardware and attitude determination sensors. An initial hardware-specific maneuver plan was created and simulated using BusSim. The SV configuration and simulation steps could be an iterative process depending on satellite resource availability. Once the satellite configuration and maneuver plan converged to a feasible solution, a deboost notification was sent to various external agencies such as CSpOC and NASA, three to seven days prior to the start of the maneuver. The notification email consisted of a high-level timeline, CSpOC compliant maneuver ephemerides, maneuver OPM, and initial estimates of when the orbit was expected to approach the current ISS altitude.

As the deboost maneuver progressed, Iridium performed an internal screening using the CSpOC SP ephemeris data, and NASA ISS TOPO short term plan trajectory every orbit. The frequent verification accounted for thruster performance uncertainty and verified that the current trajectory was still within the CSpOC screening volume. An updated maneuver ephemeris file was uploaded to space-track.org and screened by CSpOC a minimum of every 24 hours or if the propagation error approached the screening volume.

Deboost maneuver sequences were adjusted whenever a predicted conjunction met mitigation criteria to ensure safety of flight and minimize any potential interference with other operational missions. The process iterated until the target orbit was reached or the SV was close to depleting its onboard propellant.

Upon completion of the deboost sequence, a final CSpOC conjunction screening was requested. The verification ensured that no additional maneuvers were required to avoid known upcoming conjunctions, and that satellite passivation could proceed.

The passivation sequence required multiple orbits to complete, during which time the satellite would start to slowly tumble. Iridium's ground network continued to track the satellite and verify that all propellant had been depleted and the tank depressurized, the solar arrays had been reconfigured for drag, and that the battery was discharging. Iridium continued to attempt to contact the SV for a minimum of 3 orbits after last contact to ensure that the satellite was inert, and no signal power was detected. The SV was then declared dead and a passivation notification was sent to CSpOC and NASA. The disposal notification consisted of passivation sequence start time, sequence stop time, apogee and perigee of achieved orbit, predicted dwell time, and an ephemerides file.

6 DEBOOST PERFORMANCE

Since the start of the Iridium NEXT launch campaign, Iridium has actively de-boosted 64 B1 satellites. Fifty-nine of the de-boosted satellites have already reentered the Earth's atmosphere with a median dwell time of 19 days. The last active B1 storage satellite will begin deboost in December 2019 with the expectation that it will achieve a 19-day reentry. The remaining 5 satellites currently with perigees ranging from 272 to 533 kilometers are predicted to reenter during the next Solar peak. The deboost status is shown in Fig. 8. The solar array repositioning during the passivation sequence was specifically designed to maximize the frontal drag area and thus reduce the reentry dwell time for satellites that did not reach a sub 260 km perigee.

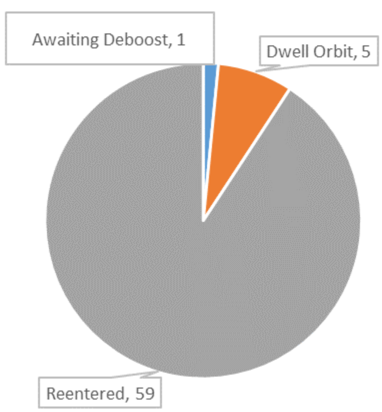

Fig. 8. Block 1 Deboost Status

Fig. 9. SV062 Re-entry on 2018-11-07

Based on the CSpOC reentry predictions posted on space-track.org, most of the satellites reentered over Earth's oceans or polar regions. For example, Iridium 62 re-entered the Earth's Atmosphere on 2018-11-07 06:16 UTC as it was ascending over the south Pacific as seen in Fig. 9.

7 LESSONS LEARNED

Designing for an end-of-life disposal starts in the vehicle design phase, but it is only a beginning framework. Engineers and operators must take all the experience they have gained operating the satellites and apply those skills and techniques to refine that framework into a successful deboost program. Engineering challenges will be encountered as satellites age and resources will need to be applied to overcome those obstacles. The processes and procedures used to extend the life of the mission must be applied to improve disposal reliability.

Management support was critical for a successful deboost program. Without this support, engineers would not have the time or resources to thoroughly execute the program.

Close coordination with CSpOC was imperative. CSpOC facilitated communications between Iridium, human space flight, and the operator community not in the catalogue. Iridium's ephemerides and maneuver OPMs uploaded to space-track.org were marked as "public" such that the satellite owner/operator community would have access, allowing for greater situational awareness. Iridium highly recommends that all members of the space community follow suit. Additionally, Iridium provided multiple points of contact on space-track.org to streamline communication and coordination between satellite operators.

8 SUMMARY

Iridium is acutely aware of the on-orbit risks posed by derelict satellites and has been a vocal advocate of responsible space operations. While the 25-year LEO reentry guideline is the current baseline, an internal analysis via ORDEM 3.0 determined that a more aggressive timeline may be needed to reduce the potential of on orbit debris generation, and a guideline of 1x operational life but less than 5-years may be a better choice [5]. Iridium embarked on an aggressive disposal program for its B1 satellites. Controlled re-entries were not possible due to the satellite design, so the focus was on minimizing the amount of dwell time to quickly remove the satellite from orbit. Iridium set an aspirational goal of a four-week dwell orbit and achieved a median 19-day dwell orbit. Iridium committed the necessary resources to develop new satellite software, operational procedures and simulation capabilities to comply with the NASA and IADC guidelines succinctly summarized as the "7 D's": Deboost, Drag, Direct, De-spin, Depressurize, Discharge and Demise. Iridium was able to safely deboost 64 satellites. Fifty-nine satellites have already reentered the Earth's atmosphere, removing more than 32,000 kilograms of mass from orbit. Of the remaining five satellites that have yet to reenter, Iridium 96 is predicted to reenter within the next 12 months. The other four satellites are expected to reenter during the upcoming solar peak. The last active B1 satellite is scheduled to begin its deboost maneuver in December 2019, coinciding with this conference.

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10 ACKNOWLEDGMENTS

The authors would like to recognize key members of the Iridium Deboost Team that designed, developed, and executed the Iridium deboost. They have provided countless hours of support during this project and used their expertise to ensure quality results and a successful deboost. The flight engineering team for software, ADCS, and propulsion is Jacob Leaskey, Audrey Puderbaugh, and James Sedler. The operations team for Mission Planning and Orbit Analysis is Ryan Shepperd, Ellen Slotterback, Mike Kirsch, Kristy DiOrio, Christian Irvin, Melissa Smith, Yoav Schoss, Jude Nimesh, Lewis Shroyer, and Sara Saleeb. Iridium would also like to thank NASA and CSpOC for their support in achieving a safe and successful deboost campaign.