MINIMUM DV FOR TARGETED SPACECRAFT DISPOSAL

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ABSTRACT

The study analyzes the minimum capability required to dispose safely of a space object. The study considers 3-sigma (3-σ) environmental uncertainties, as well as spacecraft-specific constraints such as the available thrust, total impulse, the achievable increase or decrease in commandable frontal area under stable attitude (or stable tumble), and the final controllable altitude at which any such dV may be imparted. The study addresses the definition of the length and location of a "safe" disposal area, which is a statistical manifestation of uncertainty in this process. Some general legal concerns are raised that are unique to this prospect of low dV disposals. Future work is summarized. The goal of such research is to improve public safety by creating optimally safe disposal strategies (and potentially, applicable regulations) for low-dV and/or low-thrust spacecraft that under more traditional strategies would need to be abandoned to fully-random decay with its inherent higher risk of human casualty.

1 QUALITATIVE ASSESSMENT

In a targeted decay, the energy change to get from a stable low Earth orbit (LEO) to a guaranteed capture in the atmosphere is far less than 1% of the total orbital energy. For example, cargo ships to the International Space Station (ISS) deliver around 100 meters per second change in velocity (delta-V or dV) to execute their dive from station altitude of 400 km, which compares to initial orbital speed of 7700 m/sec, or 1.3% of the speed, and .017% of the kinetic energy. Drag has always done the lion's share of the work to completely de-energize the spacecraft. Still, the application of such propulsive delta-V has always been essential to overcome the uncertainties in the atmosphere. By analogy, the traditional approach to bringing our ships home through this uncertain high-drag portion of the atmosphere is similar to motoring one's way into port, against varying winds, currents, tides, and occasional obstacles that are part of the limitless energy in the ocean. This paper discusses the alternative, to sail most or even all of the way to the dock. To do that, we need to gather some new nautical skills, and understand the subtleties of the final disposal environment in ways we have not had to ponder in the past.

Not surprisingly, it will be seen that with drag performing all but the smallest portion of the needed deceleration, the manipulation of the projected area of the spacecraft becomes a disproportionately powerful tool, as (nearly) our only means to manipulate directly the local environment's effect. Such drag dwarfs most of the small propulsive techniques endemic to this problem. For the purpose of this study, we assume that there are exactly two available commanded spacecraft states or attitudes with an area ratio N, where in the most difficult case, N= 1.0. One of the two states is the expected final state that will be enforced by aerodynamics (either tumbling or by aerodynamic stabilization, such as with a parachute or aerobrake). The other area, whether higher or lower than the final value, is generally used constantly until the final mode is commanded. (This was the case of the Skylab de-orbit in 1979, when the lab was maintained in a high-drag torque equilibrium attitude until approximately 9 hours before entry, when it was commanded to a lower-drag tumbling mode. More on this event later.)

2 RATIONALE FOR THIS STUDY

Over 98% of the mass in orbit is in objects >10 kg. The population of such objects contains the totality of the man-made material that will ever impact the ground. There is a finite Expectation of Casualty (E_c) for most such impacting pieces. Most space objects—even the functional, maneuverable ones—do not possess the propellant budget to dispose of themselves afterwards in controlled entries to unpopulated areas. Some, like the 10,000 or more satellites of the proposed mega-constellations, totalling well over 1000 tons of orbiting hardware, will have only ion thrust that can deliver just a fraction of one meter per second per orbit even with unlimited available propellant (a high cumulative dV, low thrust scenario). Others with thrust that is more substantial are often limited by residual propellant load, throughput capability, or both (high thrust, low cumulative dV). The vast majority of the mass in orbit is associated with derelict objects, over which we have no control (Fig. 1). The larger of these are conceptually the targets for active debris removal (ADR).

However, under any currently proposed ADR techniques, such derelict objects cannot be economically targeted to unpopulated areas unless it is done with a proportionately miniscule tug, providing much lower dV and/or thrust than has been traditionally applied to targeted re-entries.

Therefore, the development of reliable low-dV, and of low-dV/dt targeted reentry techniques could theoretically be a significant enhancement to ground population safety, affecting Ec during the disposal of up to 90% of the mass in Earth orbit. A reliable low-dV disposal methodology could reduce residual risk at the end of life of every functional spacecraft in contingency or degraded scenarios, and could generate significantly improved profit margins that might make targeted-entry ADR commercially viable.

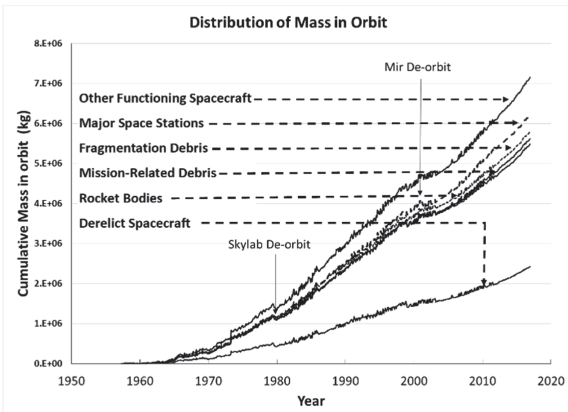

Figure 1. The mass of objects in Earth orbit exceeds 7000 tons, and the coming constellations of ion-thruster spacecraft alone will add another million kilograms. Only about 15% of the total mass is under attitude or propulsive control, and of that group, a small fraction has full de-orbit capability as traditionally practiced. This notably includes the ISS, at 1/3 of the functioning mass in orbit. ISS can execute perhaps a fifth of typical disposal dV in the nominal EOL plan. Contingency scenarios may dictate a lower-dV targeted entry. Thus, only a small fraction of the uppermost wedge of the chart above fits the profile for a targeted entry as is routinely practiced among the world's spacefaring nations.

3 APPROACH

The historical prediction accuracy is assessed for all fully natural decays for which a firm entry time and location was later established, with net error from the true entry time reported as a function of the prediction's time before actual entry. Key physical and environmental influences are explored to expose constraints on control points and capabilities to overcome the existing dispersions. As these are identified, they are highlighted in bold as "**Control Point:**". After some basic qualitative physical arguments, a broad parametric study explores two limiting scenarios for a targeted entry that accommodate these dispersions.

4 FULLY NATURAL DECAY

We start with the historical record of accuracy in predicting the time and place of decay of a non-cooperative naturally tumbling object. This uncertainty establishes the bounding uncertainty that a ballistic planner may have in setting up a drag-dominated decay. In exploring the decays parametrically, nonlinearities or clustering in the results can highlight potentially useful driving factors and sensitivities to be used for the design of low-dV navigation techniques. (*i.e.*., we gather the experience of being tossed about in the waves while we learn how to use these waves to surf.)

The art of decay prediction is the subject of annual exercises coordinated within the Inter-Agency Debris Coordination Committee (IADC). This paper will elaborate on only the published decay predictions of the Joint Space Operations Center (JSpoC), which is only one representative supplier of such predictions. This choice is because such JSpOC data is publicly available and covers many hundreds of events, whereas other efforts have been more limited. It is not to imply that the published decay predictions of JSpOC are extreme state-of-the-art, but they are clearly comprehensive and representative of it.

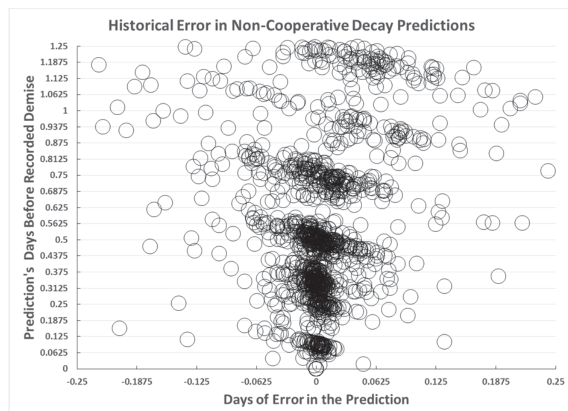

Figure 2. The history of JSpOC decay time predictions for completely passive, uncooperative objects of varying ballistic number and inclination, for which the true final decay time is known to within one minute. Most of the error can be attributed to imprecise knowledge of the final (tumbling) ballistic number and the timing of the transition of the spacecraft to this final mode. Both axes are plotted in fractions of one day with major markings corresponding to one orbit (1/16th of a day: 0.0625). The plot scale is greatly compressed in the vertical relative to the horizontal. Generally, the data converges to a good record of accurate prediction, but has some unsettling large errors. Even excluding the notable outliers, the 3-σ error in forecasting the decay is approximately +/- 2 orbits one day before actual entry. Generally, the later one can wait to get a prediction, the more accurate it will be, up to a point. (See Fig.3).

A note regarding Fig. 1: the slope of the dense data clusters in Fig. 2 is an artifact of the event-dependent release schedule of predictions at set times before the predicted decay. Thus, a decay that ultimately occurs an orbit later than predicted (*i.e.*, the error prediction itself is left of center in the horizontal scale), occurs 1/16th of a day higher on the vertical axis, because it was released on what was believed to be exactly one day's notice.

Control Point: It is fair to assume that commandable spacecraft with active radio-telemetry transmission can give vastly better orbit determination than is evidenced in the passive radar data, especially if it is equipped with GPS (or comparable) space navigation capability, as is becoming common. Low elevations with the consequent short window and thick atmosphere distortion lead to increased tracking uncertainty using solely ground radars during the final low pre-entry orbits, compounding the errors endemic to passive radar tracking in the general sense.

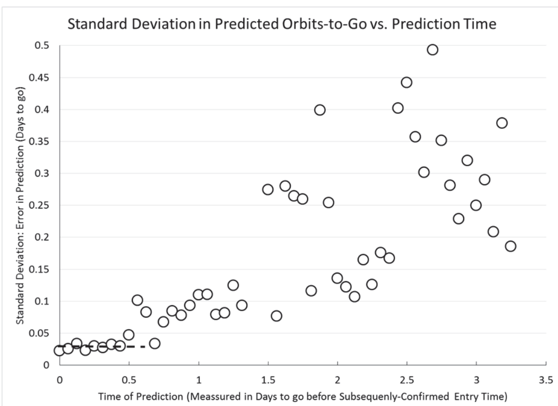

Figure 3. The standard deviation of the error in the forecast of entry time, vs. prediction time. The value of sigma is assessed over all recorded entries with precisely-known ArgLats in single-orbit (90 minute) prediction time bins in advance of actual entry times (between 11 and 70 data points per bin). This data represents most historical non-cooperative passively radar-detected objects in many inclinations and atmospheric conditions.

Notice in Fig. 3 that the one sigma error shrinks to a near-constant value of approximately .0294 days at approximately the T-0.5 day mark, or just under one-half orbit uncertainty. Three-sigma (3σ) dispersion is therefore 0.0882 days, equivalent to +/-508 degrees Argument of Latitude, (ArgLat) or a little less than +/-1.5 orbits. (ArgLat is defined as the degrees of arc to the spacecraft along the orbit path, measured from the ascending node). Because no unpopulated zones are anywhere close to this length, it is clear that under the current state-of-the-art, it will not be sufficient to simply coast to final entry even from a timeframe as short as one-half day. **Control Point:** As with higher-dV targeted entries, the final maneuvering will need to come very late in the planning.

It will get a little better, however. Better cooperative tracking (*especially* if the spacecraft has GPS), emerging commercial spacecraft-tracking businesses, the pending United States Air Force space fence, and assured control over the spacecraft frontal area should all, in theory, reduce this uncertainty. It remains to be seen how much the uncertainty can be affected, but until better estimates are available, 1.5 orbits in footprint location is reasonable and conservative to assume as the combined contribution of environment and initial ephemeris uncertainty to the final decay profile.

The historical data is conservative in that the tracked object's ephemeris is often generated with less-than-optimum radar elevation or range (especially at low altitude), and its drag properties must be derived. A spacecraft with GPS onboard, and/or assistance from augmenting radars owned by the spacecraft operator or by commercial entities, may greatly reduce this uncertainty. Flohrer, *et al.* [4] have shown that compared to GPS, errors in LEO propagation from radar-only sources can reach more than 100 meters in altitude within a day. Simulations to support the current discussion have indicated that such a pure *positional* altitude error heading into the final day of propagation can easily lead to ArgLat errors between 3 degrees (at 28.5 inclination) and 31 degrees (at 90 inclination). However, if the 100-meter, one-day altitude error derives from uncertainty in the true ballistic number of the spacecraft, calculated (in the case of Flohrer, *et al.*'s data) in a region where decay is only a fraction of a kilometer per day, the effect can be huge in the final stages where the spacecraft may lose over 50 km in the final day. In practice, the two-line element-based error includes a combination of both.

Further, absolute control over the attitude of a spacecraft will reduce uncertainties associated with random orientations. **Control Point:** Ballistic number derivation and orbit forecasting is very difficult for an object that is tumbling at a very slow rate (0-5 times orbit rate, approximately), because a single ballistic number value is generally propagated against an undulating atmosphere. The combination of large density variations around the orbit and the (random, unknown) varying phase of the projected area of the object with respect to that varying density can defeat the precision of even the best atmosphere model, when seeking to estimate the drag of the spacecraft.

4.1 Defining the Future Environment

As noted in the qualitative discussion at the beginning of this paper, it is important to have firm understanding of—and control over—the projected area of the spacecraft. The loss of attitude control (LOAC) point cannot be left to chance. An entry point can move by over 11,000 km if the altitude at which a natural transition to a 2X area LOAC configuration is off by even 10 km. It is impossible to find unoccupied target regions this long (Fig. 12). **Control Point:** Therefore, step 1 is to plan a ballistic profile where the final configuration is commanded at a set time while the spacecraft is still under positive control. If one leaves enough margin before the last commandable moment, and sets this planned control point sufficiently after the most relevant short-term atmosphere prediction, there is maximum room to adjust for any final corrections in the short-term model. By setting a planned transition point that can be moved in time, one gains maximum control over whatever is left in environmental uncertainty. **Control Point:** The transition point used in these studies is one quarter day (4 orbits) before the predicted entry (predicted accounting for the transition). The command is timed based upon the T-12 hour or T-9 hour atmosphere forecast. The question is, is that control point enough?

4.2 Bumps in the Atmosphere

The good news is that the answer is apparently "yes." The two major effects that will create dispersions in the plan to reach the desired footprint location are the late atmospheric density perturbations (global and local) and the local Earth shape under the orbit.

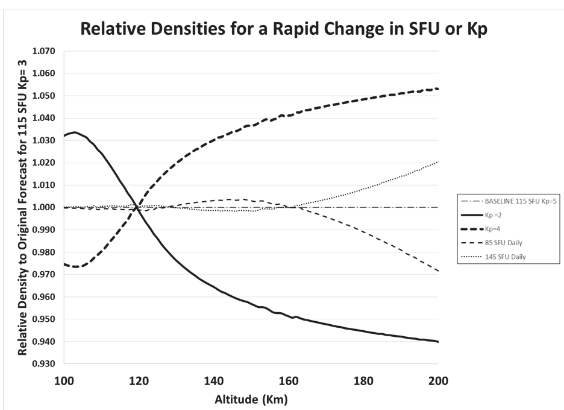

Figure 4. The relative short-term change in atmospheric density at mid latitudes compared to its base value under large short-term variations in F(10.7) and K_p as a function of altitude. Towards the equator and the poles, these extremes grow to 5% for a change of one unit of K_p over the prior atmosphere.

To first order, the growth in density is exponential as a spacecraft decays. However, the second order effects associated with space weather and season can easily swing the modeled density profile by several percent. As an exponential curve, compounded small, early density model errors can lead to dramatically larger errors shortly thereafter. Even being off by +/-1% in the forecast density model, with eight orbits to go, is equivalent to being +/- 3200 km uprange or downrange of the desired point. **Control Point:** A surprise to many, the atmosphere during the final day of decay is essentially unaffected by the F(10.7) solar flux, which challenges the ballistic plans of higher spacecraft.

As can be seen from Fig. 4, the planetary geomagnetic index (K_p) is the dominant uncontrolled environmental variable in the final stages of decay. Its future value can be predicted with fair accuracy (+/- 0.333) on the index. Even a large excursion in daily F(10.7) has negligible effect below 170km. (In the figure, the miniscule effects of F(10.7) are shown for a daily swing of +/- 30 janskys from the prior day.) The relative importance of K_p is seen at all 90-day-mean and daily values of F(10.7), and the relative atmospheric perturbation at every altitude scales nearly linearly with the change in K_p.

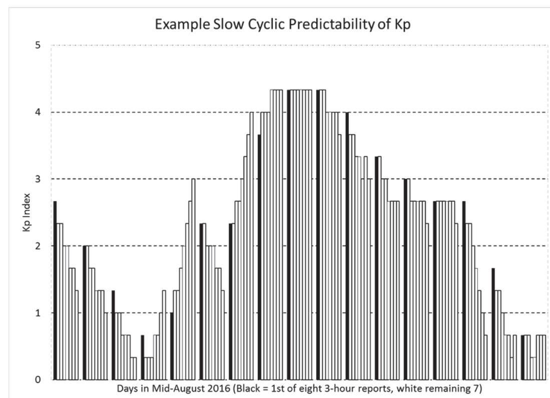

Figure 5. Planetary index Kp during one of the most dynamic geomagnetic periods of 2016.

The next question is how much short-term variation one can expect in K_p. While K_p can vary by up to a full unit in one-half day, such variations are rare. For example in 55% of the 3-hour reporting "bins" in 2016 (and 63 times just in the shown 17 days of highly volatile change), zero change in K_p was reported. Over all bins, there was a median shift of +/- 0.17 units from the prior bin, and standard deviation of 0.227. Thus the typical 3-σ K_p shift in the 3 hours following a prediction is more like Δ K_p =0.6666, and peak geomagnetic impacts in the lower atmosphere's density (from Fig. 4) are something on the order of 3%. **Control Point:** K_p exhibits strong cyclic behavior, and can be predicted with accuracy well within the 3-σ absolute change rate, allowing excellent planning. However, it is crucial to follow and react to these changes. See Fig. 14 for an illustration of an uncorrected trajectory in the face of a late major change in K_p.

4.3 Non-Spherical Earth

Bacon and Matney [2] have characterized an effect in fully natural decay that biases all entries towards the equator. The bias increases with the square of the inclination, and has a weak ballistic number dependence. The effect is particularly evident in the latitudes of real polar orbit decays, but can be seen in the simulation data of even moderate orbits. Figs. 6-10 illustrate this effect. It is attributed to a large amplification in the local rate of decay as the spacecraft crosses the equatorial bulge, where the height of the bulge (or reduction in effective altitude) is several times the density scale height at altitudes over which the last few orbits of final decay occur. Thus, there is an enormous relative increase in deceleration near the equator. This pulsing of sharp deceleration in the "wall of air" starts to turn the decay from a spiral into something more resembling a series of Hohmann transfers at the nodal crossings.

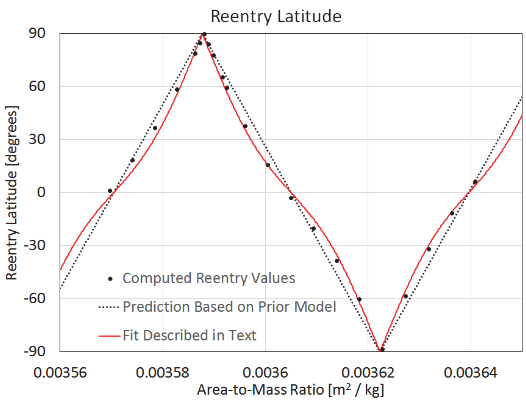

Figure 6. A distortion in the distribution of natural decays is evident in the calculated argument of latitude of final decay (curved line) and the predicted uniform distribution of ArgLat for infinitesimal linear tweaks in initial mass over a 50-orbit decay in identical conditions. The effect also is seen clearly in historical decay data. [2]

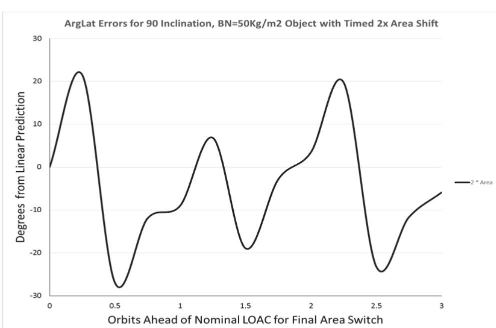

Figure 7. Cyclic perturbations up to 35 degrees ArgLat in downrange entry locations occur due to the equatorial bulge perturbing an otherwise linear scaling of drag forces. Here the argument of latitude is varied over one and one half orbits, Note the repeating waveform.

Further, while the latitude bias shrinks with inclination, the effect on <u>Argument</u> of Latitude (crucial for entry targeting) is less affected by inclination. The effect at low inclinations can still be +/- 2000 km or more in downrange location. **<u>Control Point:</u>** This location "error" creates extra dispersions when targeting entry at extreme latitudes because of the natural tendency to cluster away from those regions. (Figs. 9, 10).

The ArgLat error between the actual entry location and the simple linear advance of the decay location is plotted in Fig. 7. In extreme cases, true ArgLat of decay can be altered by +/- 27 degrees (+/-3000 km) from a predicted entry that follows a purely linear control law. The most rapid swings occur where the final entry zone is near the equator. It generally is harder to target a shallow entry into the zone more than 20 degrees of ArgLat beyond each nodal crossing and before the next pass through a latitude extreme because the atmosphere can "fall away" from under the orbit path. Such geographic fall-away of the atmosphere can partially or even fully negate the rate of altitude decay (and hence density increase) until the earth surface again starts to climb.

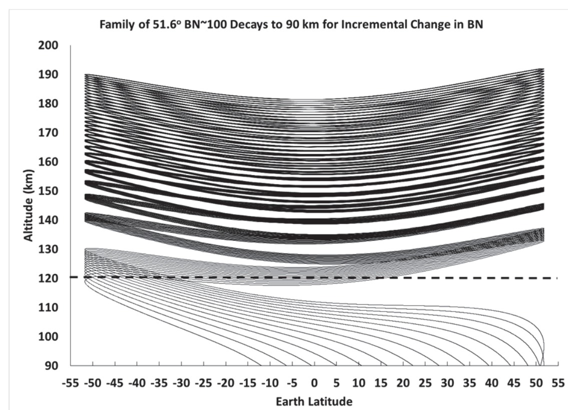

Figure 8. A family of linearly-dithered curves of 0.1% mass increments in a BN=100 kg/m² spacecraft, with increasing latitude of decay from identical starting conditions 29 orbits earlier as mass increases in this selected range. Note the flattening of the top decay curves to near horizontal as the path passes approximately halfway between the equator and peak latitude. This is caused by the localized matching of the slope of the spacecraft's decay to the fall of the Earth's oblate surface under the orbit. This effect is maximized half-way between the equator and peak latitude, where Earth's radius changes most rapidly under any given orbit. This effect leads to wider dispersions as one attempts low-dV de-orbits in extreme latitudes vs. equatorial regions. The Earth's oblateness is clearly visible in the early orbit trace, where the altitude at both extreme latitudes is higher than at either nodal crossing.

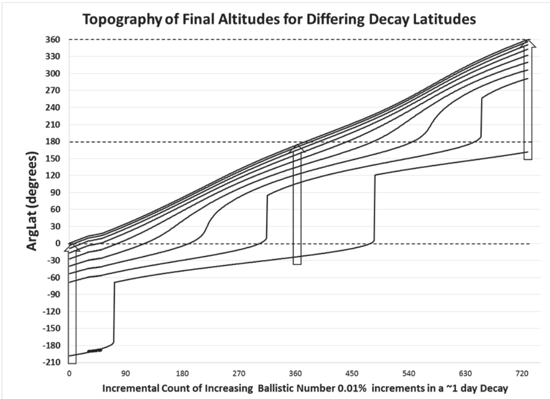

Figure 9. The location dependence of the altitudes transitioned by a spacecraft in spiral final decay over the oblate Earth (51.6^o inclination, BN=100).

Fig. 9 holds a wealth of important information related to final targeting. The curves represent altitude lines every 5 km from 80 km to 120 km, and are plotted against the argument of latitude at which they are encountered. The final decay location is the uppermost curve (80 km). It is useful to think of this as a topographical map, where any selected entry path is a walk due North.

The arrows represent the path of a spacecraft to decay at the nodal crossings. A "flat" area on the map (and thus, a potential source of dispersions for any decay critically dependent upon modelling the density exactly in that altitude range) occurs wherever there is maximum spacing between any two elevation lines. (The very nonlinear jumps in higher altitudes result from "orbit jumping" to later in the orbit. This can be seen in Fig. 8 at the dashed 120-km line, where some paths reach it on the ascending node, while some slightly higher paths must reach it on the descending node, causing a 120-degree ArgLat shift in the spacecraft's encounter with that density, The most rapid shifts are evident at the higher altitudes.)

Below 115 km for the 100 kg/m^2 object in the chart, the "jumps" are smoothed because the spacecraft is descending faster than the most rapid change in local surface height. As the final entry target point progresses in ArgLat, the most flattened region will occur in a different altitude band. The rate at which one transitions this terrain map is proportional to the spacecraft's area: To zeroth order, a doubling of the final area halves the total range of ArgLat over the decay, and causes the sharp jumps to move to even higher altitude bands. **Control Point:** High drag is thus very beneficial in reducing dispersions in the final phases. However, the most important thing is that the drag is known. Therefore, if the commanded final state is lower drag than the prior state, one must plan on using the lower area, and live with the dispersions.

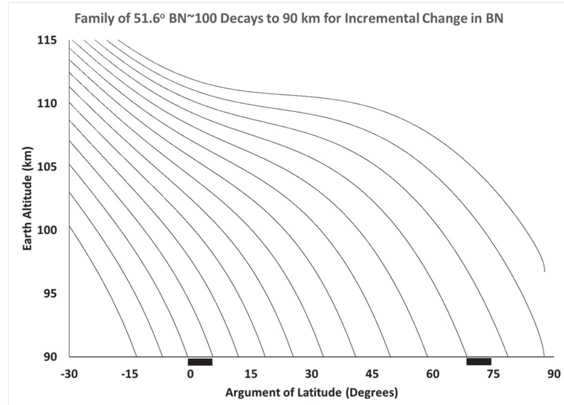

*Figure 10. The same decay data as Fig. 8 plotted vs. ArgLat for the final quarter-orbit. **Control Point:** Note the compression of the gap between increments near the equator vs. the gap between increments at extreme latitudes (common-sized pair of black markers at lower axis). This indicates wider targeting dispersions at extreme latitudes.*

5 LOW-DV SCENARIO DESCRIPTION

In the preface, it was mentioned that two scenarios would be explored. In both scenarios we assume full command capability for dV and attitude control until the 130-km altitude mark, where aerothermal heating matches solar flux. Beyond this point, avionics are assumed unreliable. We do not invoke attitude commanding in Scenario 1, to elicit the maximum demand for propellant as a bounding case. It is probable, of course, that each unique spacecraft will have a slightly different critical LOAC altitude, but 130 km is a reasonable simulation assumption. **Control Point:** It is possible to slightly tune this natural LOAC altitude if there is control over the long-term decay profile to put the final controllable perigee passes in darkness (*e.g.*, a target in the southernmost part of the orbit benefits from having the event occur near the negative extreme of the beta cycle). This condition removes both the concurrent sun heating and lowers the density (and aerodynamic torques) at any given altitude.

We assume every-orbit situational awareness and active/cooperative ephemeris determination, and "any-time" stored command execution capability. As mentioned before, we assume two drag configurations, with a single commanded transition between them to achieve the configuration that is naturally stable throughout the final phases of entry. (This may be a tumble or a parachute-like arrangement, and may be higher or lower area than the prior configuration.) **Control Point:** Generally, we assume ONE such transition, and assume that the remaining necessary dV is handled propulsively.

Note that lower inclinations become problematic because available ocean regions that are both continuous and unoccupied get much smaller below 28 degrees. In each scenario we divide the operations into two phases: those that occur before the final day (strategic), and those that occur during the final day (tactical).

For **Scenario 1** we assume a functional maneuverable vehicle that possesses very limited remaining propellant at its end-of-life (EOL). (The maneuver capability may be inherent to the spacecraft, or the spacecraft may be assisted by a space tug performing ADR).

For **Scenario 2**, we assume a functional spacecraft with only high-specific impulse (I_{sp}), low-thrust delta-V capability, with a characteristic dV accumulation rate limited to about .4m/sec per orbit and unlimited propellant below a circular starting orbit below 400 km. (See later discussion for rationale of these initial conditions).

Definitions: The goal of a targeted entry is to place all surviving debris within a region on Earth called the footprint that is devoid of population and does not contain politically determined economic or other territorial boundaries. The broader region in which a footprint may lie is known as the "target zone." Typically the target zone is much broader in longitude than the width of a footprint (defining an allowable range of the disposal orbit's longitude of ascending node), and generally contains ground tracks much longer than the expected length of the footprint (this defines the available margin in the disposal plan). The most famous and commonly-used target zone is called the South Pacific Ocean Unpopulated Area (SPOUA). Its specific bounds vary among the different agencies and private corporations that target there, based upon subtle legal and technical constraints.

Process: Targeting is done in four steps.

Step 1: A target zone (or more likely, a portion of one) is selected. Typically, there are numerous possibilities of entry even into one common zone, but the preferred location will generally meet a variety of constraints, including command coverage. **Control Point:** Generally in a very low-dV operation, assuming that capability exists to target regions less than 6000 km long, the final selection from the available target zones can be made late in the planning, potentially only a day in advance of entry, depending upon the cumulative effects of random space weather variations on the trajectory. This late selection of target zone is analogous to selecting the closest port to enter, based upon where conditions have caused your boat to drift.

Step 2: The second step of targeting is to phase the orbit such that the orbit path places the ground track exactly along the desired footprint on or near a chosen entry day. **Control Point:** If the entry requires the longest possible target zone, careful and very early attention (measured in months) must be exercised in Step 2 to assure that the spacecraft will overfly that narrow zone (See Fig. 12). One delays or accelerates the decay to drift westwards or eastwards. A rough rule of thumb is that a spacecraft will be able to phase once around an orbit relative to its original trajectory (and thus, can achieve the full range of longitudes of ascending node) in 24 weeks by applying one meter per second of dV. **Control Point:** Assume either active drag management OR 0.5 m/sec as the required dV to phase for Step 2, since it can be applied either posigrade or retrograde to meet any phasing requirement if given 24 weeks or more to prepare for a targeted low-dV entry. Budget dV phasing maneuvers as the inverse ratio of 24 weeks to the time before an intended targeted entry into a tightly-constrained single zone: If 6 weeks, plan 24/6 = 4x the reference maneuver, or 2 m/sec.

Note that essentially, it is impossible to move the longitude of ascending node of an orbit on short notice. In late stages, the ground tracks are pre-ordained to lie in very narrow tracks about 22.5 degrees apart in longitude. Generally, small amounts of dV allow the choice to enter on any of these 16 pre-ordained potential orbits on a given entry day, even late in the game. With 2 days remaining, one needs only to adjust plus or minus eight orbits of the remaining life (32 orbits, adjusted to either 24 or 40) to select any of the 16 daily orbits as the expected decay orbit. Once phasing is established, over the final day or days the ground track of possible footprint locations is essentially locked.

Step 3: The third step is to adjust incrementally the altitude of the decaying orbit to put the predicted natural decay in the right time relative to the ability to control it. In a high-thrust, low-dV case this will likely be just a few orbits after the groundtrack passes through the desired footprint. This step minimizes the control authority (dV) needed for step 4, while avoiding early decay under extreme late atmospheric changes. This step can be done concurrently with iterated adjustments in step 2. **Control Point:** Any such burns should be done to position the perigee of the orbit where it will migrate via the natural precession of the line of apsides to align just uprange of the footprint area on the day of entry.

Step 4: The fourth step is to induce the spacecraft to achieve a ballistic (parabolic, Earth-intercepting) trajectory that locates the earliest debris in the desired footprint (known as the "heel") at the proper time in the proper orbit. This location is defined by an angle (the ArgLat) along the final orbit with ArgLat= zero defined at the ascending node. In this step, the tools available are propulsion (posigrade and retrograde) and the manipulation of drag (increased or decreased). In the low-dV scenario, this step is where the largest dispersions accumulate, resulting in movement of the footprint uprange or downrange of the intended location along the groundtrack.

6 ZERO PROPULSIVE DV CASE

6.1 Zero dV Case (Drag Manipulation)

As noted, even in a high-dV propulsive deorbit, well over 98% of the total deceleration is from drag. Even in decelerating from T-1 day to the 130-km mark, the accumulated dV due to drag is approximately 36 m/sec for a Ballistic Number (BN)=100 kg/m^2 object. Most of this dV is accumulated on the final orbit.

If we consider the hypothetical case of a spacecraft with no propulsive dV capability, but a reliable, commandable attitude or configuration that can vary the projected area of the spacecraft in the velocity vector, we can sense some limits and scales applicable in all other approaches.

Drag manipulation is demonstrably effective at adjusting final ballistics. For instance, to create the different ArgLats to build Fig. 7, an initial orbit case with an expected ArgLat of 60 degrees was adjusted by tumbling a spacecraft in a near-circular orbit at successively earlier times. This achieves a 2X area increase before a modeled T-1 orbit natural instability time where the same final 2X area is assumed (to be explained in more detail shortly.) This control step causes the decay to occur earlier, such that if executed two full orbits ahead of the assumed natural tumble (or three orbits before previously expected entry), one should achieve one full orbit acceleration of decay.

Drag is proportional to area. Therefore the most effective way to gain control of the final target area is to have the ability to switch between (at least) two commandable, stable configurations. (Most likely, the latter of these either is a naturally aerodynamically-stable, minimum drag configuration with the center of gravity in front of the center of drag, (such as an arrow, or an object with a parachute), or a rapid tumble, such as was executed during the Skylab deorbit in 1979.

6.2 Latest Command Capability

Generally, as aerodynamic forces build, there will be a specific set of conditions where the spacecraft naturally orients to one of the available positions when the ability of the spacecraft to determine its own attitude (*e.g.*, thrusters, or momentum wheel) is overwhelmed by such forces. Notably, somewhere near 130-km altitude aerothermal collisional heating matches full sunlight in watts/m^2 energy deposition, soon overwhelming any passively cooled avionics optimized without such heating considered. In planning the command sequence to achieve a planned, timed transition between the two modes, all operations must precede this avionics failure threshold.

Generally then, we must build variations of any ballistic plan starting backwards from the trajectory that occurs after the latest possible assured transition to the ballistic coefficient for the final phase. For this study, we universally assume this last-possible transition point occurs at 130 km. We exercise variable control over the process by forcing the transition to occur at any earlier time than the latest attitude transition time (= latest command capability).

6.3 Earliest Practical Commanding

The constraint on latest possible commanding competes with growing uncertainty in the remaining atmospheric drag, which is growing exponentially as the spacecraft decays. For those familiar with compensating for ballistic errors under unpredictable solar flux environments, the F(10.7) variations have surprisingly negligible effects in the terminal phase of a spacecraft decay, compared to other issues. This is because the ultraviolet heating of the upper atmosphere deposits most of the energy into gas above the 150 km mark. Instead, the K_p is the dominant factor in driving short-term local atmospheric density variations, which respond to charged particle penetration to and energy deposition in the lower altitudes.

The practice adopted in simulated runs has been to build the final ballistic plan, assuming a reference trajectory with the drag mode that is ***not*** the final stable mode, maintained until the (assumed final) command to the expected stable/tumbling drag mode made halfway between the two times:

a) the earliest time that the final aerodynamic drag mode is potentially unavoidable (*i.e.*, the highest altitude where expected natural tumble or other natural stable orientation of the spacecraft will occur), and
b) the earliest scheduled K_p update after T-12 hour time.

Note that this strategy intentionally forces transition to the final configuration substantially earlier than it would naturally occur, to build in some variable capability to delay or accelerate that command. This allows us to accelerate or delay the decay, proportionally.

This strategy typically gives a +/- 5 hour window around the nominal commanded final drag mode to delay or advance the area change. As we have seen in earlier sections, the change is driven by late-breaking changes in K_p for its short-term forecast. The short-term forecast of K_p is updated every 3 hours.

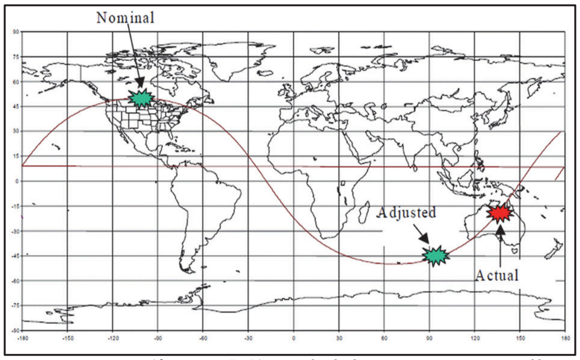

Figure 11 (from [3]). Skylab entry controllers commanded a tumble 9 hours before decay to increase the ballistic number of the station in the final orbits, with the intent to change its intended entry point downrange to open ocean. Two factors were likely at play in the overshoot. The more widely discussed effect is that Skylab fragmented lower in the atmosphere than expected, resulting in continued high ballistic number propagation downrange of the expected rupture point. Another contributing factor may be the recently-documented tendency of natural decays to be more clustered towards the approach to the equator, and sparser at extreme latitudes. The targeted latitude has larger dispersions than an equatorial entry, and indeed, the entry point migrated towards the equator. The groundpath is along the lowest-populated groundtrack available in the orbit band, at < 1/12 the world average.

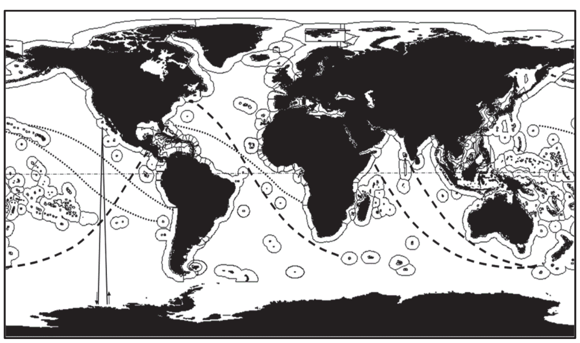

Figure 12. The difficulty in finding landing areas. The world's exclusive economic zones (EEZ) are plotted. Many agency and national policies protect the full extent of these zones. Some of these are around uninhabited land masses (or even solitary rocks), and the entire Antarctic region +50 km is officially recognized under other UN treaties as a protected zone for purely scientific activities. The longest available (~ 1/4-orbit, 10000 km) ground tracks are shown for 28.5- (dotted), 51.6- (medium dash), and 90-degree orbits (solid lines) that meet all criteria. One northbound and one southbound quarter-orbit 90-degree track are shown. The two 28.5-degree target zones in the Pacific are not on successive orbits. The two 51.6-degree paths in the Indian Ocean are.

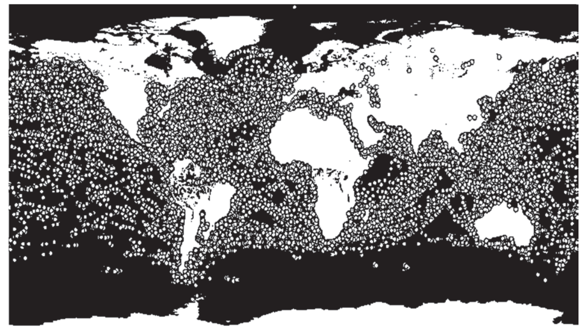

Figure 13. Global ship detection during 14 hours of Norwegian Automatic Identification System (NorAIS) payload operations aboard the ISS in June 2010 (image credit: FFI.)

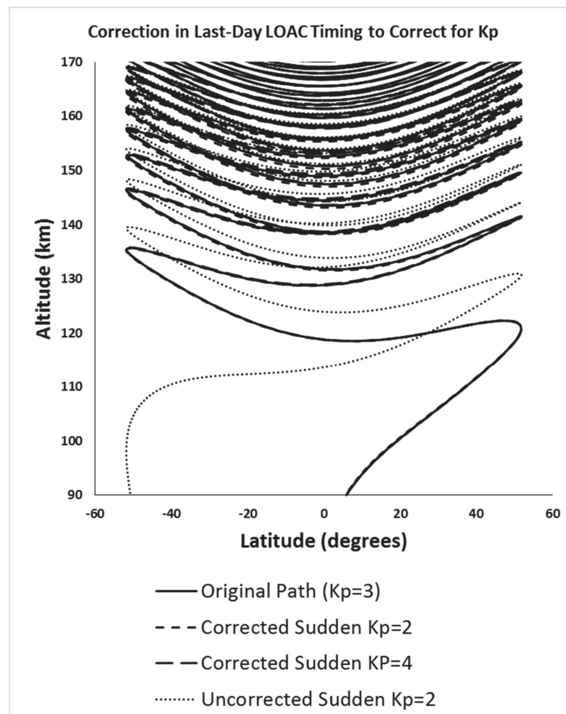

Figure 14. Three perfectly superimposed final trajectories in quiescent and maximally-perturbed atmospheres using only the timing of a +20% incremental drag transition within the last half day of orbital life. The timing of the drag transition is solely responsible for aligning the $>5\sigma$ perturbed cases. Without the correction, the entry point varies by over 90 degrees of ArgLat. The sensitivity of the curve to such subtle timing and drag variation is both a curse and a blessing. Such controls require high confidence in the drag values and the atmosphere prediction. Without such knowledge, they become large dispersions.

To demonstrate controllability using drag manipulation alone, a series of simulations were conducted wherein an object was allowed to decay in a quiescent, stable atmosphere from the T-0.5 day mark to the T-0.25 day mark, and then commanded to the LOAC attitude with a 1.2 factor in area. The decay history was recorded. Then the atmosphere was simulated to jump dramatically by stepping Kp beyond its 3σ extreme change of 0.66 units to 1 full unit at the T-0.5 day mark, simulating a maximum 5σ stress on the controllability of the decay plan. A new command time to force the spacecraft to LOAC configuration was calculated and executed, resulting in achieving the exact same location and time as the prior quiescent case. Notably, the simulation only required changing the timing by 10,000 seconds: well within the +/-0.25 day margin available to slide the command time. The superimposed cases are shown in Fig. 14 along with one case left uncorrected for comparison.

7 SCENARIO 1: CONVENTIONAL THRUSTER

The first case considers a spacecraft with conventional storable-propellant capable of delivering a Hohmann transfer. Our goal is to calculate the minimum total dV necessary to hit a given target region in the presence of atmospheric dispersions. For this study, we make no assumptions about improved tracking, nor about any ability to manipulate the frontal area, in a search for the bounding case of necessary dV in the absence of any other enhancements. With such enhancements, the minimum required dV will certainly be lower.

As seen in Fig. 3 and its following discussion, the typical 3σ dispersion in predicting a natural decay from passive radar data one-half day out is approximately 1.5 orbits either side of the central predicted entry target location.

The method that we have evaluated for purely propulsive dV assumes that two entry zones exist approximately eight orbits apart from each other. Such opportunities are visible by inspection in Fig. 12 for all three inclination orbits.

Because typical conditions force an uncertainty of about 1.5 orbits per day for each day in advance of an entry, we wish to execute step 3 of the previously outlined general deorbit plan with just one day to go, by boosting or deboosting a small amount to change our time-to-go by up to four orbits relative to our current trajectory. To set up our decay orbit prior to this time, we run the risk of spending more propellant to get back in to the desired phase, because even 1σ daily drifts one day in advance of de-orbit rival our 3σ final targeting precision.

This adjustment is to cause our revised decay time to occur as we are passing over one of the two generally "safe" regions we've identified. (This means that one of the two roughly opposed zones is typically about four orbits of any position we can pick.) Note that the required dV approximates the total natural decay over four orbits, which is on the order of 3 meters per second for most typical-BN objects.

We execute the phasing solely by dropping perigee near the target footprint's ArgLat. This strategy will help when it is time to do the final push to capture.

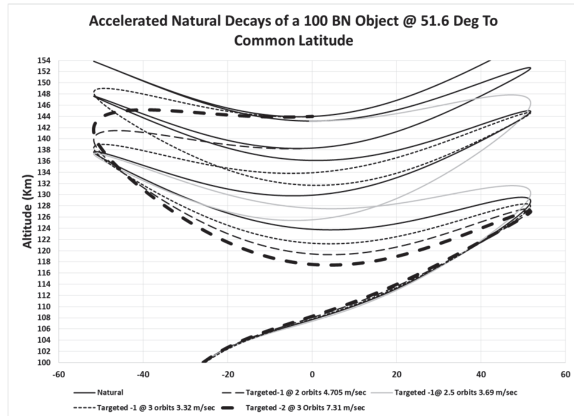

Figure 15. Propulsively-accelerated decay of a 100 kg/m² BN object without drag manipulation (heavy dashed line). In order to overcome a potential 3-σ(1.5 orbit) uncertainty in the final entry location, the orbit is set up slightly biased to come in one-half orbit late, and is then forced propulsively to come in two full orbits early, starting at the 3-orbits-to-go altitude (in this case, ~144 km). To come in within one orbit, 7.3 meters per second are required vs the three left to go at time of burn. Drag manipulation can significantly reduce the needed thrust.

As of this Step 3 set-up burn, we have roughly 12 to 20 orbits to go before entry, with inherent uncertainty of between 1.2 and 2 orbits. We have already accounted for 1 meter per second in Step 2 phasing, for a total of four m/sec. Fig. 15 shows the maximum burn required to overcome a 3σ late entry path. For a 100 kg/m² object this impulse is 7.3 meters/sec to enter two orbits earlier than a passive entry will bring. This strategy of accelerating the latest decay keeps the spacecraft in a controllable region for the final burn, no matter what happens in the atmosphere, but requires that one protect to come in up to two orbits ahead of natural decay. (Other atmosphere scenarios will require a lower dV value) Thus, assuming that phasing was optimally bad in steps 2, 3, and 4, we calculate a maximum dV demand of 11.3 meters/sec.

8 SCENARIO 2: ION THRUSTER

The second scenario involves spacecraft with ion thrusters. The propulsive case illustrates that the necessary dV to force a correction over a Hohmann transfer is well outside the range of dV/dt that is available in the high-I_{sp} regime. We can estimate a representative dV/dt capability for any spacecraft in the following calculation.

Electric high-I_{sp} systems use electricity that must be gathered from sunlight. If we take the ballistic number of a spacecraft to be say, 100 kg/m^2, that implies (for Coefficient of Drag of 2) that for every m^2 of frontal area there are 200 kg of mass to move. Assuming that the frontal area is typical of any particular projection, this implies that the solar collecting capability per kilogram is (1361 * e /200) where e is ~0.2, representing the efficiency of the solar cells. This calculates to about 1.361 Watts/kg. Assuming that this represents the kinetic energy in the ion plume of say, 2000 I_{sp} (thus, exhaust velocity = 2000*g = 19,620 m/sec) the specific thrust (acceleration) in this example is:

Force/Mass = (2*(power/mass) / exhaust velocity)

= (2* 1.365/ 19620)

= 1.39E-4 newtons/kg (=m/sec^2)

While this number is only a characteristic value, whose real value will depend upon several efficiencies and the geometry of the spacecraft, its approximate scale is indicative of the ability of an ion drive spacecraft to directly control its fate in its de-orbit throes. This sort of acceleration results in only a fraction of one meter per second per orbit. Such characteristic thrust-based acceleration can be matched with the deceleration of drag to identify where the drag forces per orbit dominate those of any ion jet. This balance happens well before the final few days of decay (in this example, near 185 km altitude). Note that for any class of high-I_{sp} thruster and spacecraft geometry, the altitude at which the drag and thrust are matched is independent of ballistic number, since mass is the same and thrust and drag are both linear constants times the area.

Note however that systems with large power consumption (such as an ion drive) likely will have asymmetric geometry designed to maximize solar collection. Therefore, it is probable that spacecraft with electric propulsion will have a significant range of commandable drag that correlates with the angle of the solar cells (or the spacecraft as a whole) to the V-bar. Thus, the very last control points of an ion drive spacecraft demise look a lot those one would employ for the zero-propulsive case analysed before.

Ion jets may not be able to perform the final de-orbit control, but they can do significant things in step 3 that can help reduce footprint dispersions. This is done by establishing highest possible eccentricity to put the penultimate perigee just before the intended footprint area.

Once a decaying spacecraft is brought below the operational altitude of the key spacecraft (*e.g.*, Hubble, ISS) one can start firing the ion jet at every apogee to drop perigee into a dramatically higher-eccentricity orbit. As always, it is important to position this perigee such that the precession of the line of apsides puts it just uprange of the footprint area on the day of de-orbit.

Note that because of an active-collision-avoidance problem it is important to encourage large fleets of ion-drive satellites <u>not</u> to cross the operational altitude of high-value assets in eccentric orbits. This nearly guarantees that it will be a long-term collision risk with those high-value assets. It is preferred that decaying objects cross the circular lower orbits in a low-eccentricity spiral orbit that has only short-term interactions with the asset. In principle, it is very easy to set up the phasing of the descending spacecraft to cross the orbit pane and altitude of a high-value object completely out of phase with that spacecraft, but this is only simple if the two spacecraft are not in the same altitude band very long.

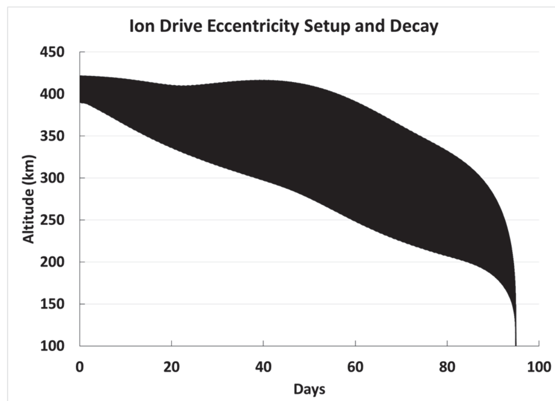

Figure 16. Decay of an ion-thrust spacecraft with one-eigth-orbit apogee retrograde firings every orbit after passing 400 km mean circular altitude. The black region bounds the orbit altitude vs time. The undulation of apogee and perigee is the expected result of the precession of the line of apsides over and away from the equatorial bulge. (Such precession rate varies with orbit inclination).

The apogee and perigee of a typical hall thruster firing for 45 degrees of arc around apogee is shown in Figs. 16 and 17. **<u>Control Point:</u>** While most of the eccentricity is removed in the very last orbits, random-entry objects are observed (Fig. 19) to cluster in entry location near the ArgLat of the perigee of eccentric orbits on the final day. Note the interesting near-constant 100 km difference for most of the decay. One can use additional tricks to exaggerate the eccentricity further. These would include either:

A) **<u>Control Point:</u>** A drag-intensive option of a one-half-orbital rate pitch maneuver to alternately present to the V-bar a broad profile at apogee and a narrow area at perigee, or

B) **Control Point:** A solar-inertial option with thrust applied both posigrade at perigee and retrograde at apogee. (Fig. 18).

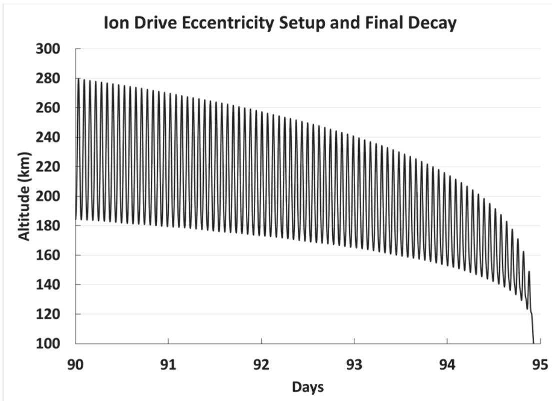

Figure 17. The final orbits of the trajectory shown in the prior figure. The last orbit still has nearly 20 km of altitude separation between apogee and perigee, which strongly influences the dispersions of final entry to cluster entries near the ArgLat of the orbital perigee.

The use of the drag vs. propulsive extra techniques (and the corresponding attitude mode) depends strongly upon the spacecraft configuration, and the strategy will change depending upon the relative contributions of drag and of thrust for the specific spacecraft design.

Control Point: Note that the drag technique might be useful in the conventional thrust or zero-thrust scenarios as well. The propellant demand for eccentricity is not expected to be worth the trade against propulsive demands in final targeting. One should be wary that in the final days of decay, likely it is better not to have a cyclic area change occurring, if the ballistic propagation software is not prepared to handle such minute-by-minute variations.

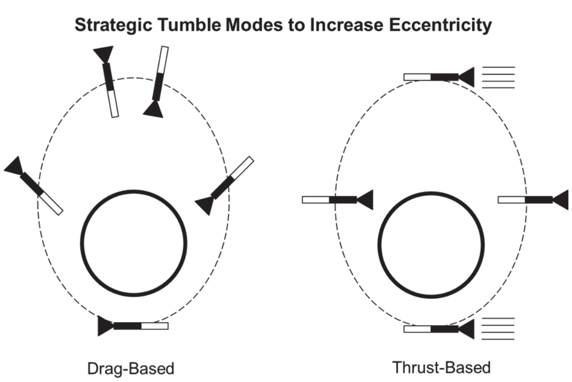

Figure 18. Alternate smooth tumble profiles to increase eccentricity.

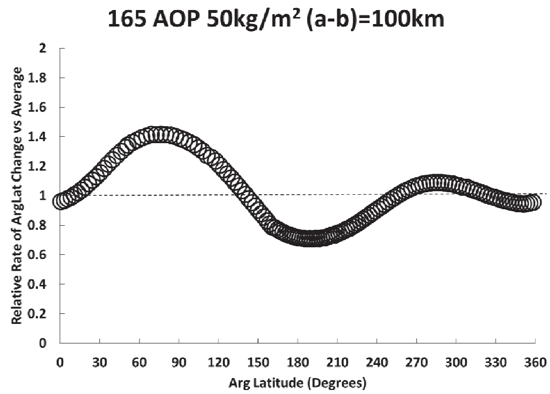

Figure 19. Dispersions decrease when targeting an entry just downrange of the perigee of a slightly eccentric orbit, as is recommended for ion-propulsion spacecraft with sufficient propellant margin at end-of-life. For this plot the BN of 50 kg/m^2 is linearly dithered just enough to force 360 degrees of ArgLat, which occurs in nonlinear steps. The location of the lowest-dispersion entry point moves downrange of the late-stage argument of perigee by 20-125 degrees for BN from 50 to 200 kg/m^2 respectively. The variation is dependent upon inclination and upon the initial argument of perigee as well, and becomes more dramatic with increasing eccentricity. In this example the entry is forced to be near the descending node from an initial argument of perigee at 165 degrees three days prior. Extreme latitudes of entry lead to higher dispersions, in general. The relative change in entry ArgLat for incremental small steps in Ballistic Number heading into the final few days of decay is plotted as the ratio of the incremental change in ArgLat compared to the average step size (i.e., normalized to 1). It is simultaneously visible as a clustering of the data points near the lower ratios, representing many runs with very little dispersion between the steps.

9 LEGAL ISSUES

In the marginal dV cases examined, it is clear that success in avoiding protected areas depends upon having a long enough target region to handle dispersions larger than commonly needed in high-dV scenarios. From Fig. 12 it is evident that when searching for a "safe" target region (Phase 1 of the entry process) the established practice to protect Exclusive Economic Zones (EEZs) can be problematic. EEZs are defined by 200-nautical-mile (3.333 degrees, or 370 km) radius arcs from the low tide mark of any land mass. Their use in bounding spacecraft disposal zones stems from a very broad and conservative extrapolation of the United Nations Law of the Sea, in the absence of specific space object disposal agreements. A case can be made that the contiguous zone should be the preferred boundary, as it is the limit of the prohibition to "pollute." No such constraint applies to the EEZs.

EEZs generally are protected under most current national or agency policies and interpretations of international laws, with a few specific exceptions unique to each agency. In many cases, an additional buffer around the zone is added by the spacecraft operator to the restriction, to account for the 3-σ width of the footprint, such that less than 0.3% of any surviving debris can impact within the EEZ. The protection of EEZs around uninhabited areas is a political rather than a safety issue. Note that a minimum 125,000 km^2-each EEZ is at least the size of the country of Nicaragua. It is useful to note a snapshot of the ships at sea on one particular moment (Fig. 13) to understand the true safety vs. political issue. The ocean outside of EEZs can hardly be thought of as being "open," and more humans reside on any one of the ship locations shown than on many of the tiny landmasses protected by an EEZ.

Further, laws vary with regard to liability after a failed attempt at a deorbit. It is even worse if the *nominal* plan includes possibility of overflying a populated area in the nominal case. This conceivably could be the only way to achieve a thousand-fold reduction in risk, but would expose a specific population to the residual. Japanese law requires that if all steps are executed as planned in a targeted entry, the chance of injury to the ground population must be <1 E^{-6}. This requirement is unlikely to be achievable for the low-dV scenarios explored here, which can generally meet 3-σ, but not 5-σ conditions.

To avoid this legal issue, the Japanese operator could be forced to allow a spacecraft to decay naturally at a higher risk to the public, than to fail in this part of the law. U.S. practice is to assume that the average world population density lies downrange of any de-orbit attempt, and requires that the product of the natural decay's E_c over this average population times the probability of failure in performing the targeted entry must be E-5 or smaller. Note that in this calculation no consideration is officially weighed regarding the <u>specific</u> populations downrange of an operation. In a contingency case, it has always been standard practice to minimize the exposed population as was done with Skylab, but "targeting the smallest group" is hardly the basis of a nominal operations plan for disposing of a constellation of individual spacecraft. Somewhere at the borders of low-dV de-orbit strategies the specific at-risk population may need to be considered. There is great legal danger, of course, if such populations are considered. Once the lowest-risk footprint for a particular orbit inclination is optimized, it puts a very specific population forever directly downrange of this "safest" entry zone.

Thus liability becomes a special concern for the low-dV case. If the dispersions of a low-dV attempt can include populated areas downrange, some laws would prohibit a pro-active attempt to dispose of even a crippled spacecraft there. This begets the dilemma that to do nothing is riskier for the population, but if spacecraft operators take proactive steps to minimize the risk, they may become <u>more</u> liable. This is a manifestation of the Good Samaritan laws often passed to protect those who make a best effort to protect people, with some chance of failure. There is no such law for spacecraft disposal.

Possible Legal <u>**Control Points:**</u> The options in the legal realm that would most benefit low-dV disposal of space objects would include:

1) Eliminating spacecraft disposal restrictions around un-inhabited or sporadically-inhabited islands
2) Shrinking the protection zone to be some safe margin around other definitions of sovereign territories
    a. (*e.g.*, Territorial waters (12 nautical mile radius) or even
    b. Contiguous waters (24 nautical mile radius). Such restrictions are often flexible depending upon the inhabited zone is owned by the country of origin for the re-entering spacecraft.
3) In polar orbits the protection of the Antarctic for any intentional disposal is a particularly severe restriction that, if lifted, could open up a wide range of opportunities for low-dV spacecraft disposal.

10 SUMMARY OF CONTROL POINTS

Throughout the text, 18 Control Points have been highlighted as features that will be important in low-dV targeted entries. These are repeated in summary form below.

1) Global Positioning System (GPS) (or comparable) space navigation capability is an enabling feature for very low-dV targeted entries.
2) As with higher-dV targeted entries, the final maneuvering must come very late in the plan execution.
3) Ballistic number derivation and orbit forecasting requires active control of the spacecraft's projected area.
4) The final configuration must be commanded at a time while the spacecraft is assured to be under positive control.

5) The transition point used in these studies worked well to overcome late K_p dispersions. The baseline timing is one quarter day (4 orbits) before the predicted entry accounting for the transition. The command is timed based upon the T-12 hour or T-9 hour atmosphere forecast.

6) The atmosphere during the final day of decay is essentially unaffected by the F(10.7) solar flux

7) K_p exhibits strong cyclic behavior, and can be predicted with accuracy well within the 3σ absolute change rate

8) Along-track dispersions are greater in the extreme latitudes than near the equator.

9) Highest possible drag is beneficial in reducing dispersions in the final phases.

    a. However, the most important thing is that the drag is known. Therefore, if the commanded final state is lower drag than the prior state, one must plan on using the lower area, and live with the dispersions.

10) If possible manage the long-term decay profile to put the final controllable perigee passes in darkness. This allows the spacecraft to remain under control slightly lower in the atmosphere.

11) Propellant demand numbers in this paper assume only one attitude transition, such that the remaining necessary dV is handled propulsively. However, ongoing projected area control is an opportunity to reduce propellant use in earlier phases.

12) If multiple allowable target zones exist, the final selection from among them can be made very late in the planning, potentially only a day in advance of entry. This can minimize propellant demand.

13) If the entry requires the longest possible target zone, careful and very early attention (measured in months) must be exercised in step 2 to assure that the spacecraft will overfly that narrow zone.

14) All phasing burns should be done to position the perigee of the orbit where it will migrate via the natural precession of the line of apsides to align over the footprint area on the day of entry.

15) Objects are observed to cluster in entry location near the ArgLat of the perigee on the final day, so eccentricity should be maximized while meeting all other constraints.

16) One can use one-half orb-rate tumble to add to the eccentricity, in the right conditions.

17) One can use solar-inertial attitude and every-half-orbit firing to exaggerate eccentricity.

18) In ion propulsion, there is a trade to be made on which of propulsive- or drag-intensive eccentricity enhancement modes is preferable based upon specific spacecraft characteristics. However in conventional-thrust or zero-thrust cases, only the drag mode would apply.

10.1 Legal/Regulatory Discussion Points

19) Eliminating spacecraft disposal restrictions around un-inhabited or sporadically inhabited islands will open many potential zones to improve public safety in the inhabited zones.

20) Many additional safe target zones could become available if the protection zone around populated regions were redefined to be some safe margin around “Contiguous Waters” (24 nautical-mile radius).

21) For polar orbits the protection of the Antarctic against any intentional spacecraft disposal is a particularly limiting restriction for all orbits inclined more than 60 degrees that, if lifted, could improve public safety by opening up a wide range of opportunities for low-dV spacecraft disposal. This is of particular importance to the business of ADR that is expected to be primarily targeted in high-inclination orbits.

11 FUTURE WORK

The work to date has examined the factors that lead to natural decay dispersions, and has assessed the minimum capabilities of propulsive and drag-based techniques to compensate for them, with encouraging results. While general ability to compensate for 5-σ environmental disturbances has been shown, it remains to be shown what total dispersions remain in footprints while targeting specific ArgLats under various tolerances in knowledge of ephemeris, spacecraft drag, and environment. This will be done using the 18 control points in Monte-Carlo simulations that include disruptions in the environmental variables after the last available forecast, and uncertainties in spacecraft ephemeris and drag.

12 CONCLUSIONS

Eighteen control points have been identified as being relevant to low-dV entry targeting, and three Legal/Regulatory discussion points have been elevated. Simulations across a wide range of conditions indicate that if a spacecraft has a total delta-V capability of 11 m/sec in high thrust scenarios, targeted entry to a safe zone in unpopulated ocean waters is possible over nearly all atmospheric conditions and in inclinations from 28.5 to 90 degrees (and presumably their negatively-inclined variants.) Less propulsive dV is necessary if drag techniques can also be incorporated.

Attitude control between different stable projected area modes has been shown to be able to compensate for 5-σ atmosphere dispersions, although such capability requires precise knowledge of spacecraft area projection and real-time updates to the plan.

In ion thrust scenarios, the thrust is applicable to setting up phase 2 and 3 of the four entry planning steps, and in suppressing entry dispersions in the target region, but is not particularly useful in direct targeting. For this, the non-propulsive drag techniques are needed.

The success of low-dV entry plans strongly depends upon every-orbit communication with the spacecraft, and "anytime" time-tagged command capability. The largest tactical control feature of low-thrust high-dV spacecraft is the ability to change to and hold an alternate drag configuration (including, generally, a tumbling configuration that does not aerodynamically self-stabilize). To preserve confidence in the ballistic plan and margin to make late adjustments, this commanded change in drag must occur with several orbits of margin before it would naturally occur.

In all scenarios, it is useful to create the most elliptic orbit possible after reaching circular orbit below all major operational space assets, and to plan carefully for the precession of the line of apsides to put the perigee just uprange of the desired region on de-orbit day.

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