Practical and Legal Consequences of Spacecraft End of Life Disposal

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Abstract

This paper examines the operational and legal consequences of satellite disposal from Earth orbit and will expose the vulnerabilities of safe disposal, demonstrating how it might be compromised despite exquisite diligence and best intentions. The paper will also study the legal consequences of such events, exploring application of the Liability Convention, issues surrounding joint and several liability, and possible alternatives for mitigating sanctions if disposal is not conducted in the expected or planned manner.

Introduction

IADC guidelines and resulting normative implementations include that satellites in the low Earth orbit (LEO) protected region be removed within 25 years of mission end, and those in the Geostationary Earth orbit (GEO) protected region be removed at end of mission to an orbit from which the protected region would not be breached for 100 years.[1] The necessity or the procedure of disposing obsolete satellites from other orbits has not yet been addressed, particularly on the regulatory level.

Safe disposal includes depleting spacecraft energy in all forms such as remaining propellants, batteries, flywheels, and momentum wheels. Dissipating energy changes the orbit. Maneuvers must be coordinated with passivation and avoiding encounters with resident spacecraft and debris. This is a complex choreography that has a reasonable probability of failure even if each contributing element enjoys high probability of success. For example, unanticipated collision avoidance may deplete propellants to the extent that further maneuvers

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[1] IADC Space Debris Mitigation Guidelines, IADC– 02-01, 15 October 2002.

are infeasible. Energy stores must be reserved to control the descent. If further maneuver is infeasible, potential subsequent encounters could have explosive consequences. Unanticipated strong solar activity might facilitate disposal through increased drag or unexpected long periods of low solar activity might render propellant stores inadequate for normative disposal. Operators might exploit the latter to plan disposal during high solar activity, which requires less energy, while anticipating low solar activity and knowingly making safe disposal less likely.

Uncertainty

The consequences of any action depend on when that action occurs. There is great uncertainty estimating these consequences. The uncertainty depends on the duration of the prediction horizon compared to the time span during which data was acquired.

Anything about the space enterprise that is projected more than about 50 years in the future is extremely inexact. The World hardly has 50 years experience or data on which to base estimates. Phenomena that occur on relatively short time scales are most predicable. The Moon attracts both water and land masses, particularly the Earth's nonuniform molten core. The Gravity And Climate Extraction Experiment (GRACE)[2] mission documented these variations very well. Phenomena that occur over years or decades are much less certain. For example, there is a resonance for satellites in geostationary orbit due to nonuniformities in the Earth's gravity. The inclination of uncontrolled objects in GEO varies plus or minus 15 degrees on approximately a 54 year cycle.[3]

Because the Equator is slightly elliptical there are two stable (at 75.3°E, and at 104.7°W) and two unstable (at 65.3°E, and at 14.7°W) equilibrium points. Any geostationary object placed between the equilibrium points would be slowly accelerated towards the stable equilibrium position, causing a periodic longitude variation. Uncontrolled Geostationary satellites can oscillate between the unstable locations or be locked close to the stable points over time.

The 25 year post-mission lifetime guideline is vexing because satellite demise due to drag depends strongly on the sunspot cycle. The charged particle flows associated with sunspot activity cause ionization and electromagnetic interactions that increase the extent of the sensible atmosphere. There is more drag at higher altitudes during solar maximum than during solar minimum.

Despite almost a millennium of sunspot observations, the solar cycle is still extremely unpredictable. Common wisdom accepts a cycle of approximately 11 years. The variation is extremely large.

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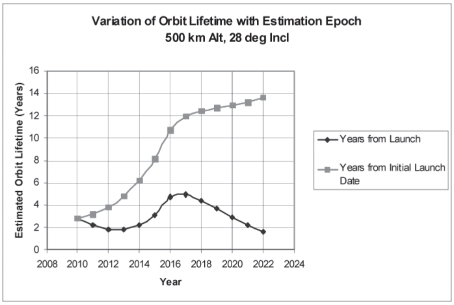
[2] <www.csr.utexas.edu/grace/>.

[3] Richard I. Abbot and Timothy P. Wallace, Decision Support in Space Situational Awareness, VOLUME 16, NUMBER 2, 2007 LINCOLN LABORATORY JOURNAL pg 297.

Figure 1 Variation of typical circular orbit lifetime estimate with end of mission date[4]



It is very difficult to measure atmospheric density directly. Density must be inferred from pressure and temperature or extinction of electromagnetic radiation over significant distances. Instead, density is inferred by correlation with the variation of the intensity of prominent electromagnetic wave emissions associated with sun spot activity.

Figure 1 demonstrates the variation of estimated lifetime of a typical LEO satellite with time on the scale of solar cycles.

The figure depicts estimated lifetime as a function of launch date assuming an initial intended launch date in 2010. If the launch were delayed two years, drag would be higher since solar max might have occurred, and lifetime would be a year less than if launched in 2010. If the launch were delayed until 2016, orbit lifetime would be four times longer than if the launch had occurred on time in 2010.

Operators can enjoy more mission payload if nominal launch dates are scheduled during solar max and then delay launch until solar minimum. They would have met initial requirements for orbit lifetime but not be able to meet those expectations when the launch finally took place. Orbit lifetime depends on the mass and configuration of the satellite. Satellites tumble and maneuver. They consume propellants and cryogens. The mass and orientation of every satellite changes with time.

There is only one normative document that can be used to enforce orbit lifetime claims,[5] and this only if the mission authorities choose to incorporate it contractually. Figure 2 is the operative element of that standard, averaging over different orbit regimes, possible satellite orientations, solar cycles, and other variables. It is an accepted standard for choosing operating altitudes, but still uncertain putatively by five to ten years out of 25.

Figure 3 estimates the propellant reserves required per unit mass for direct, non-maneuvering deorbit from several orbit regimes and the additional mission

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[4] D. Finkleman, Twenty-five Years, more or less?, AIAA Paper 2010-1252, Aug 2010.

[5] ISO 27852:2011, Space systems - Estimation of orbit lifetime.

Figure 2 Orbital lifetime regimes as a function of satellite drag characteristic and orbit altitude.[6]

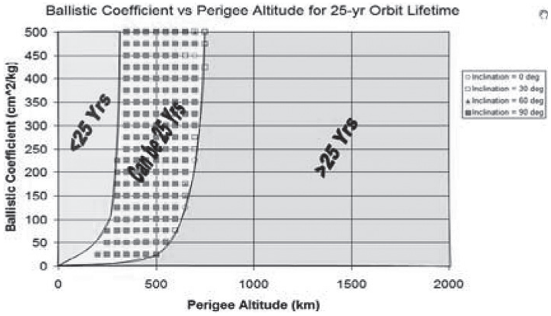
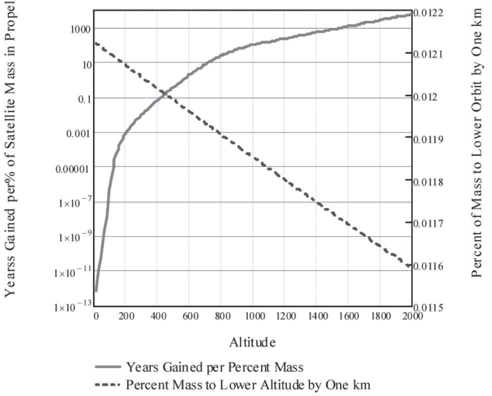


Figure 3 Years of Mission Lifetime Gained per Unit Propellant Mass Otherwise Dedicated to Safe Disposal[7]



duration on orbit that could be gained if this stored energy were used extend life. Particularly in Geostationary orbit, where stationkeeping maneuvers require very little energy, safe disposal can cost decades of productivity – at least within the lifetime of subsystem failure.

The figure shows that at an altitude of 600 km, approximately 9% of the mass of the satellite would be required for disposal through reentry while that amount of propellant could extend mission life by about five years. Which would you choose?

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[6] D. Finkleman, AAS Paper 11-177, Progress in Standards for Space Operations and Astrodynamics,, Feb 2011.

[7] D. Finkleman, Twenty-five Years, more or less?, AIAA Paper 2010-1252, Aug 2010.

These and other phenomena may make some broad guidelines and consensus standards meaningless and unexecutable.

Legal Consequences

In 2008, the UN General Assembly adopted the 2007 UN COPUOS Space Debris Mitigation Guidelines.[8] The Guidelines themselves are legally non-binding; the onus is on States to implement them through domestic policies, laws, and regulations. To that end, several jurisdictions have codified the Guidelines in varying manners and degrees of specificity.

For instance, *inter alia*, the new Austrian Authorization of Space Activities and the Establishment of a National Space Registry (Austrian Outer Space Act) has devoted a section to the subject, although it is in relatively general terms.[9] JAXA voluntarily registered ISO 24113 for Space Debris Mitigation and attempts compliance with this normative international standard.[10] And while Canada does not yet have a comprehensive space law per se, its Remote Sensing Space Systems Regulations includes a system disposal plan[11], and Industry Canada imposes debris-minimizing requirements on radiofrequency license procedures.[12]

To obtain a license, the French Law on Space Operations requires the satellite operator to demonstrate its ability to control the space object through all defined aspects of the control phase, including the last de-orbiting operations and passivation activities, loss of control, return to Earth, or full disintegration.[13] The US also implements debris mitigation measures via licensing mechanisms administered by the DOT/FAA and the FCC.[14] NASA and DoD follow

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[8] Resolution 62/217. While no express international obligation to mitigate debris-related risks currently exists, the principle of due regard may impose this obligation. Article IX of the Outer Space Treaty also levies its obligations that States must avoid harmful contamination of the outer space environment and consult together when such harm appears imminent. *Towards Long-term Sustainability of Space Activities: Overcoming the Challenges of Space Debris* (A Report of the International Interdisciplinary Congress on Space Debris) presented to UN COPUOS STSC February 2011 A/AC.105/C.1/2011/CRP.14, page 23.

[9] Austrian Outer Space Act §5

[10] Basic Plan for Space Policy: Wisdom of Japan Moves Space (2 June 2009) Strategic Headquarters for Space Policy, page 53, available at: <www.kantei.go.jp/jp/singi/utyuu/basi c_plan.pdf> (date accessed: 4 September 2012); ISO 24113:2011 – Space systems – space debris mitigation requirements.

[11] Remotes Sensing Space Systems Regulations SOR/2007-66 §12(d), available at: <http://laws-lois.justice.gc.ca/eng/regulations/SOR-2007-66/page-3.html#docCont> (date accessed: 4 September 2012).

[12] Space Debris report, *supra* note 8 at 30.

[13] LOI no 2008-518 du 3 juin 2008 relative aux operations spatiales, Article 1(5).

[14] Space Debris report, *supra* note 8 at 33.

internal Orbital Debris Mitigation Standards, which closely follow the UN COPUOS Guidelines.[15]

The preceding section described some of the factors that could contribute to imprecision and unreliability when calculating satellite end of life under the best of circumstances. When and how is liability assessed and attributed for the failure to meet debris mitigation guidelines in these various forms? As stated, the UN COPUOS Guidelines are not binding. Any teeth to enforcement will come in at the national level.

France's law actually contains criminal and administrative penalties.[16] Authorizations may be withdrawn or suspended and criminal fines may attach for breach, by the holder, of its obligations under the law. These obligations include demonstrated control through all phases. Perhaps in recognition of the far-reaching impacts of unexpected on-board events upon EOL operations, CNES appointed a Working Group to examine these anomalies.[17] The WG recommendations include regular updating of operational documentation that incorporate on- board irregularities once they have occurred, and a reactive decision process. In other words, the responsibilities for EOL are ongoing and organic and do not stop with the representations made in the license application. The operators are best served to govern themselves accordingly.

In the US, the license to launch includes the requirement that the operator ensure against unplanned physical contact between the vehicle and/or its components and the payload after separation, debris generation resulting from the conversion of energy sources, and for passivation.[18] The US laws do not include sanctions. While it is clearly not feasible to promise that these things cannot occur, nor would it be rational to ask an operator to pledge likewise, the text of the regulation directs us to the risk-allocation scheme in place. The operator is to ensure against these occurrences. In the unfortunate event that unplanned contact or debris generation are to happen, the financial responsibility framework in place will carry the burden, be it through insurance, or demonstrated ability to self-insure, or through government indemnification.

Many US commercial contracts now incorporate normative orbit lifetime constraints in enforceable contracts. If these representations are not met, regular tenets of contract law would be in force, determined by the law of the contract or the law of the jurisdiction where a claim is brought. If calculations were not made in good faith, i.e. fraudulently, then in US federal court, heightened pleading requirements would come into play.[19]

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[15] *See* U.S. Government Orbital Debris Mitigation Standard Practices, available at: <www.iadc- online.org/References/Docu/USG_OD_Standa rd_Practices.pdf> (date accessed: 31 August 2012).

[16] LOI no 2008-518 Chapter IV.

[17] Regis Bertrand, et al. "Emergency end of life operations for CNES remote sensing satellites – Management and operational process" Acta Astronautica 79 (2012) 79-87.

[18] CFR 417.129.

[19] Fed. R. Civ. Proc. 9(b).

However, apportioning liability form is calculations under a negligence theory will involve causation and foreseeability. We are discussing anomalies that are not predictable. The only thing that is predictable is that unpredictable things may happen. It is possible that space weather and solar cycles could be considered *force majeures*, for which contractual remedies can be fashioned.[20]

Risks and Uncertainties of Safe Disposal

End of life disposal cannot be planned confidently years in advance. The pitfalls of a disposal plan emerge as the satellite maneuvers. The following examples demonstrate the phenomena.

Consider a satellite in a retrograde orbit representative of polar orbits used for Earth observation or weather data. (SL-8 Rocket Body, Catalog Number 11379) The inclination is 98 degrees (which means that it orbits opposite to Earth rotation), apogee is 1000 km altitude, and perigee is 800 km altitude. Other parameters such as argument of perigee (the longitude of the point closest to the Earth), right ascension of the ascending node (the longitude of the point at which the satellite orbit crosses the equatorial plane, ascending), and true anomaly (where the satellite is in its orbit at the initial analysis time) are important but not relevant to this example.

Practice that is emerging for satellites above the International Space Station is to lower the orbit to a safe distance above the ISS and at an appropriately safe time to lower the orbit safely below the ISS from which natural decay will complete disposal.[21] In Figure 4, this satellite is called “GatorInitialDisposal.” The maneuver is a classical Hohmann, minimum energy transit through an elliptical orbit tangent to both the initial and final orbits at the times at which thrust is applied. In Figure 4, the initial elliptical orbit is green, the final orbit above the ISS is white, and the ISS orbit is red.

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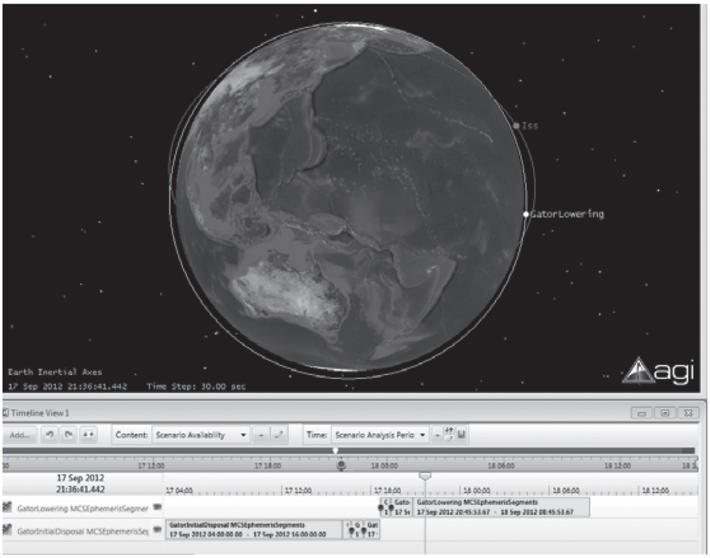
[20] For instance, a contracting party can include a clause that relieves it of its obligations in the face of an event beyond the control of the parties such as acts of God, usually defined as fires, explosions, earthquakes, drought, tidal waves, and floods. See “Sample Force Majeure Clauses” available at: <http://ppp.worldbank.org/public- private-partnership/ppp-overview/practical-tools/checklists-and-risk-matrices/force- majeure-checklist/sample-clauses> (date accessed: 4 September 2012).

[21] Craychee, T., Sturtevant, S., Bird, D., A Look into the Coordination Between a Commercial Satellite Operator and the U.S. Government Craychee, T., Sturtevant, S., Bird, D., A Look into the Coordination Between a Commercial Satellite Operator and the U.S. Government for the Deorbit of a Commercial Satellite, AIAA Space Operations and Technical Support Committee Workshop, Jet Propulsion Laboratory, Pasadena, CA, April 2012 ent for the Deorbit of a Commercial Satellite, AIAA Space Operations and Technical Support Committee Workshop, Jet Propulsion Laboratory, Pasadena, CA, April 2012.

Figure 4 Initial Maneuver of a Hypothetical Weather Satellite. Initial Orbit in Green, Final Orbit in White, ISS in Red



Content: Scenario Availability

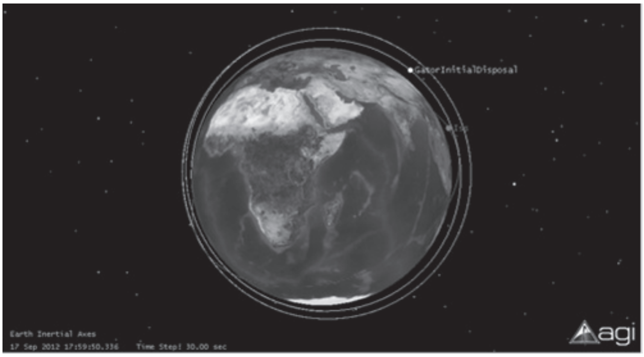
Time: Scenario Analysis Perio

17 Sep 2012
21:36:41.442

GatorLowering MCSEphemerisSegmer
GatorLowering MCSEphemerisSegments
17 Sep 2012 20:45:53.67 - 18 Sep 2012 08:45:53.67

GatorInitialDisposal MCSEphemerisSeg
GatorInitialDisposal MCSEphemerisSegments
17 Sep 2012 04:00:00.00 - 17 Sep 2012 16:00:00.00

Figure 5 Final Disposal Orbit and Sequence of Events for the Entire Maneuver Sequence



The final maneuver is a minimum energy transfer between two orbits only 200 kilometers apart, which is difficult to discern at the scale of figures in a paper. Minimum energy is not minimum time. Conserving energy increases the satellite's exposure to potential collisions Final orbit and sequence of events are in Figure 5.

Each sequence has initial thrust to establish the transfer orbit and final thrust at transfer orbit perigee to circularize at the final altitude. The total velocity increment (Delta V) is approximately 250 meters/sec for the initial maneuver and

50 meters per second for the second maneuver. This would consume about 6% of the mass of the satellite before the maneuver. From Figure 3, this otherwise could be used to extend lifetime in the original orbit by more than 15 years if functionality could be maintained that long.

In isolation, this would be a very safe maneuver. But it does not exist in isolation. Figure 6 shows that our satellite experiences close approaches with three other objects in orbit: Cosmos 1011-10917, Fengyun 1C Debris Element 29769, and a spent Thor-Abelstar D Booster, Catalog Number 00560.

Such a close approach is of some concern, although close approach does not imply high collision probability. That depends on how uncertain the orbits of

Figure 6 Close Approach with a Thor-Abelstar Spent Booster during Descent Maneuver. 17 Sep 2012 14:19:38, Minimum Separation is 3.8 km

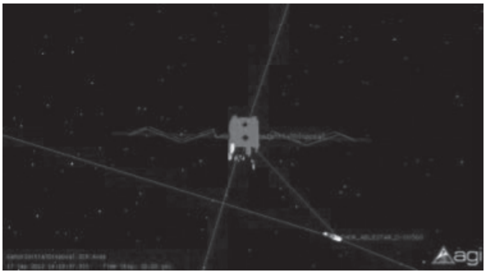
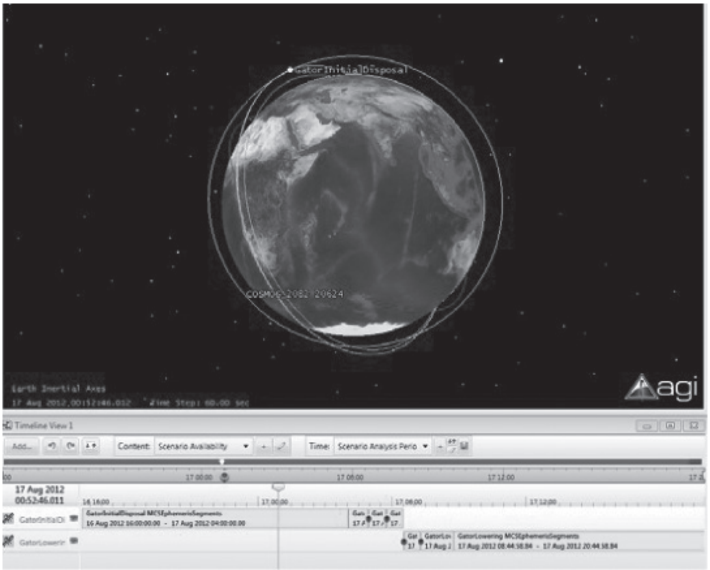


Figure 7 Disposal Maneuvers Executed a Month Early Showing Conjunction with Cosmos 2082-20624 at the Bottom of the Figure



Earth Inertial Axes
17 Aug 2012 00:52:46.012 Time Step: 60.00 sec

Content: Scenario Availability
Time: Scenario Analysis Perio

17 Aug 2012 00:52:46.011

GatorInitialDi: GatorInitialDisposal MCSEphemerisSegments 16 Aug 2012 16:00:00.00 - 17 Aug 2012 04:00:00.00

GatorLowerin: GatorLowering MCSEphemerisSegments 17 Aug 2012 08:44:58.84 - 17 Aug 2012 20:44:58.84

the objects might be. In normal operations, uncertainties could be greater than 5 km. This probably means that the descent should be replanned, since evasive maneuvers would require even more expendable mass.

But there is no guarantee that executing the maneuver at another time would be any less risky. For example, Figure 7 assumes that we execute the maneuver about a month earlier. There are even more close approaches within 10 km, and a 5 km approach with Cosmos-2082-20624 a 6000 kg electronic intelligence satellite launched in 1990.

Legal Consequences

This example demonstrates the uncertainties of disposing of satellites intentionally. It illuminates disposal issues for satellites in the higher altitude orbits of the designated Low Earth Orbit (LEO) region. Standard procedures at least do not exist yet. Satellite operators are extremely competent even executing such complex maneuvers. The UARS reentry[22] is a real world example. The investigators state that "All results of predicted maneuvers are completely uncertain."

What happens when things go wrong? First, in this context, ratifying States of the Outer Space Treaty are under a duty to consult with regard to potentially harmful interference with other States Parties' peaceful use or exploration of outer space.[23] This duty is triggered when the State Party has reason to believe either its own activities, or those of another State Party, will potentially cause harm. The starting place is avoidance of harm.

In the unfortunate circumstance that disposal maneuvers result in catastrophe, liability is assigned to the launching States.[24] States are liable for the space activities of their nationals.[25] Liability is apportioned in two tiers, depending upon the locus of where the damage is caused. If the space object causes damage on the surface of the Earth or to aircraft in flight, the launching State/s are absolutely liable.[26] If the damage is caused elsewhere, liability attaches through

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[22] Hughes, J., Marius, J., Montoro M., Patel, M., and Bludworth, D., Development and Execution of End of Mission Operations, Case Study of the UARS and ERBS End-of-Mission Plans, NASA Goddard Space Flight Center, Greenbelt, MD., 2009.

[23] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the moon and Other Celestial Bodies, Article IX (entered into force 10 October 1967) (hereinafter "Outer Space Treaty").

[24] Convention on International Liability for Damage Caused by Space Objects (entered into force September 1972) (hereinafter "Liability Convention") Articles II – III. A State becomes a launching State by satisfying one of the following four criteria: 1) a State which launches or 2) procures the launching of a space object; or 3) a State from whose territory 4) or facility a space object is launched. Article I(c). A space activity can, and often does, have multiple associated launching States.

[25] Outer Space Treaty, Article VI.

[26] Liability Convention, Article II.

fault,[27] can be joint and several,[28] and can be apportioned in accordance with the extent of the fault.[29]

The skeletal facts provided in the preceding example do not give us enough to assign liability. First, the maneuver occurring in outer space could result in damage either to aircraft underway or to the surface of the Earth, or simply in outer space. Hence, we cannot assume which standard will apply. Second, fault is a fact-driven analysis. And, is the enterprise executing the maneuver accountable for the consequences of matters beyond their control?[30] No matter when the maneuver is executed or how it is planned, we have demonstrated that there are always enforceable regimes that are operational ly consistent.

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[27] *Ibid.*, Article III.

[28] Liability Convention, Article IV.

[29] *Ibid.*

[30] It is possible that space weather could be construed as a *force majeure* or act of God.