



OBSTACLES TO ODMSP COMPLIANCE

A Case Study Approach

Marissa Herron, 2021

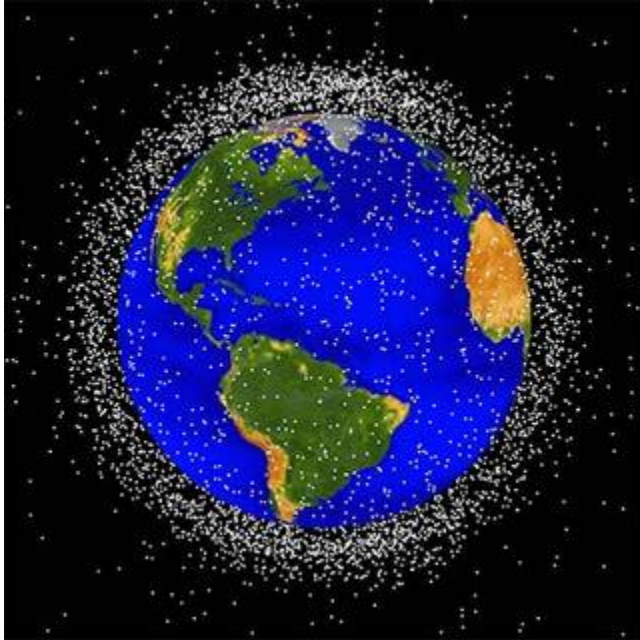


Image Source: NASA¹

What is ODMSP?

The Orbital Debris Mitigation Standard Practices (ODMSP) were first established in 2001 and most recently updated in 2019². These standard practices are intended to apply “...guidelines for USG activities...” and serve as a “reference.... for other domestic and international operators³.”

What is the “25-year rule”?

The “25-year rule” refers simply to the removal of an object from orbit within 25 years of mission completion. The 25-year

rule was introduced in the 1990’s in an effort to limit the growth of debris in Low Earth Orbit (LEO)⁴. The 2010 United Nations Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (UN COPUOS), in a similar spirit, calls for the limitation of a long-term presence of defunct spacecraft and rocket bodies in LEO, but does not explicitly identify the number of years.⁵ The June 2021 Inter-Agency Space Debris Coordination Committee (IADC) also specifies disposal within 25 years⁶.

A slightly more detailed look at the ODMSP for postmission disposal, or the disposal of a spacecraft following the completion of the mission, is shown in the graphic below. The original 2001 version and the recently updated 2019 version is shown graphically for comparison. Note that the figure is only referring to the postmission disposal aspects of the ODMSP and not the passivation, large constellation, or other objectives within the ODMSP.

¹ <https://www.nasa.gov/audience/forstudents/5-8/features/nasa-knows/what-is-orbital-debris-58.html>

² Discussion with NASA OSMA and ODPO, September 2021.

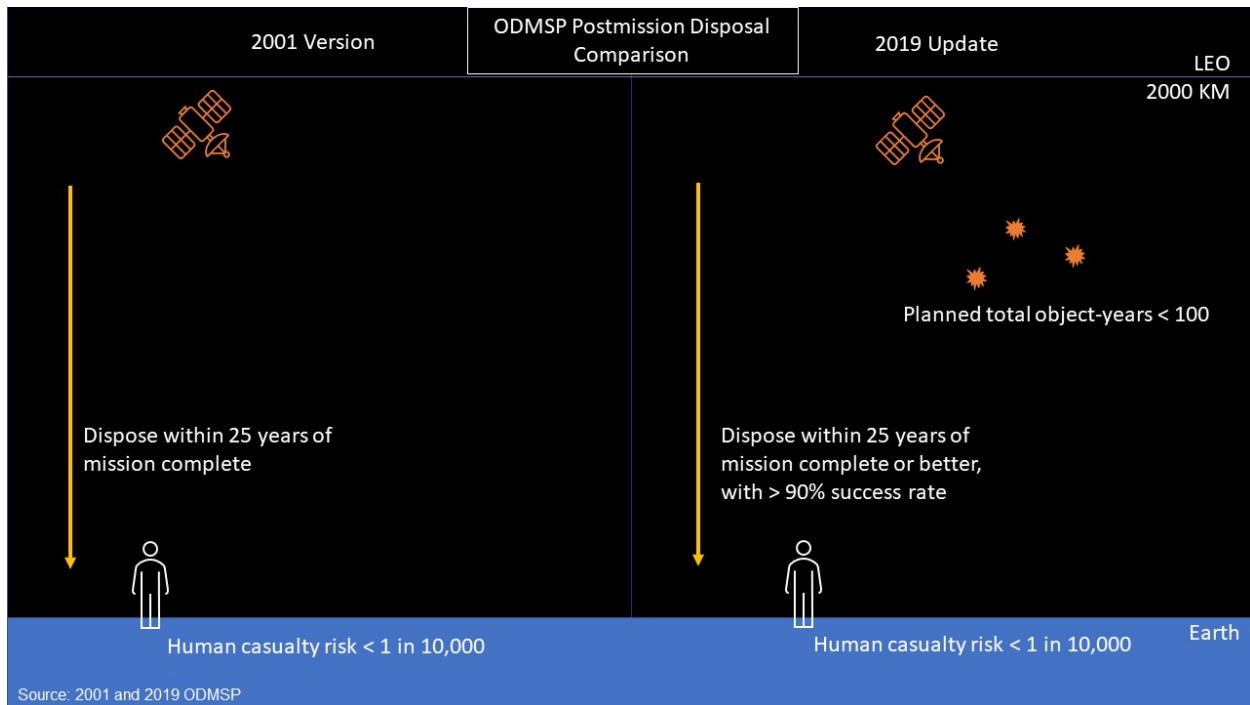
https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf, <https://spacenews.com/u-s-government-updates-orbital-debris-mitigation-guidelines/>

³ https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

⁴ Orbital Debris Quarterly News Volume 24, Issue 1, February 2020. <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNv24i1.pdf>

⁵ Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, A/RES/62/217, 2007, available at http://www.unoosa.org/pdf/publications/st_space_49E.pdf.

⁶ https://www.iadc-home.org/documents_public/view/id/173#u



When considering postmission disposal, there are three major aspects to consider:

1. Dispose of the spacecraft within 25 years of mission completion,
2. If atmospheric reentry is the disposal method, then ensure the human casualty risk (or risk to the public) is less than 1 in 10,000, and
3. Implement a disposal method with a probability of success greater than 90%.

Item one inherently refers to passivating the spacecraft such that batteries and energy sources are drained to minimize explosion potential. Ideally, a spacecraft will maintain the ability to do collision avoidance maneuvers and get as low as possible before passivation. The lower a spacecraft is in LEO, the more drag the spacecraft will experience which helps speed up an atmospheric decay disposal. Once the spacecraft runs out of fuel, and thus, the ability to perform collision avoidance maneuvers, the spacecraft is passivated and no longer operational. At this point, the spacecraft should be in an orbit such that the atmospheric disposal option takes no more than 25 years⁷.

Item number two involves a survivability analysis of the spacecraft components and design prior to launch. This can be accomplished using the ODPO's Debris Assessment Software⁸ or other means to demonstrate the spacecraft components will adequately break-up and disintegrate during reentry. The thermal ablative properties of materials used to build the spacecraft are a

⁷ This discussion refers to LEO spacecraft, not GEO. The latter maneuver to a disposal orbit above GEO.

⁸ <https://orbitaldebris.jsc.nasa.gov/mitigation/debris-assessment-software.html>

primary driver for survivability. Those items that do survive reentry are considered in the calculation of the human casualty risk.

Item three refers to the use of a proven and reliable method of disposal to ensure the disposal process does not experience problems in the process of disposing of the spacecraft. In other words, an operator does not want to accidentally abandon a spacecraft in a populated orbit due to the failure of the disposal system.

Who was involved in the creation of these standards and guidelines?

The UN COPUOS consists of membership⁹ from a number of spacefaring and non-spacefaring nations. The IADC¹⁰ membership includes international governmental space agencies¹¹. The 2019 update of the ODMSP was accomplished in response to Space Policy Directive-3¹². The update was led by NASA and supported by relevant government agencies, including regulatory agencies.

The higher level UN COPUOS guidelines were informed by the more technical IADC guidelines with the intent of achieving global consensus¹³. The IADC guidelines were informed by the ODMSP and a number of other resources¹⁴.

What is the effectiveness of the 25-year rule? Why 25-years?

The effectiveness of the 25-year rule is assessed (see figure¹⁵ below) for objects in LEO greater than 10 cm, a 90% postmission disposal (PMD) success rate, and simulated future explosions. The results presented below are based on a Monte Carlo analysis using the NASA LEGEND tool. Each curve presented below represents the average of 100 Monte Carlo runs.

LEGEND¹⁶ models debris as small as 1 mm and is capable of both historical analysis and future projections. The historical simulations are used to validate the model and produce accurate future projections. Averages are used due to uncertainties in parameters such as future launch traffic, solar activity, explosions, collisions, etc. Launch traffic can change dramatically due to large

⁹ <https://www.unoosa.org/oosa/en/ourwork/copuos/members/evolution.html>,

<https://www.unoosa.org/oosa/en/ourwork/copuos/stsc/2020/index.html>

¹⁰ https://www.iadc-home.org/what_iadc

¹¹ https://www.iadc-home.org/what_iadc and UN A/AC.105/C.1/L.260

¹² <https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/>

¹³ Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space, UN 2010

¹⁴ UN A/AC.105/C.1/L.260. Inter-Agency Space Debris Coordination Committee space debris mitigation guidelines

¹⁵ Orbital Debris Quarterly News Volume 24, Issue 1, February 2020. <https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNv24i1.pdf>

¹⁶ <https://orbitaldebris.jsc.nasa.gov/modeling/legend.html>

constellations (graphic on launches per year). Solar activity can influence the drag¹⁷ experienced by an object in LEO. Explosions can occur to improperly passivated spacecraft and manufacturing defects. Defunct satellites and/or debris further create collision opportunities.

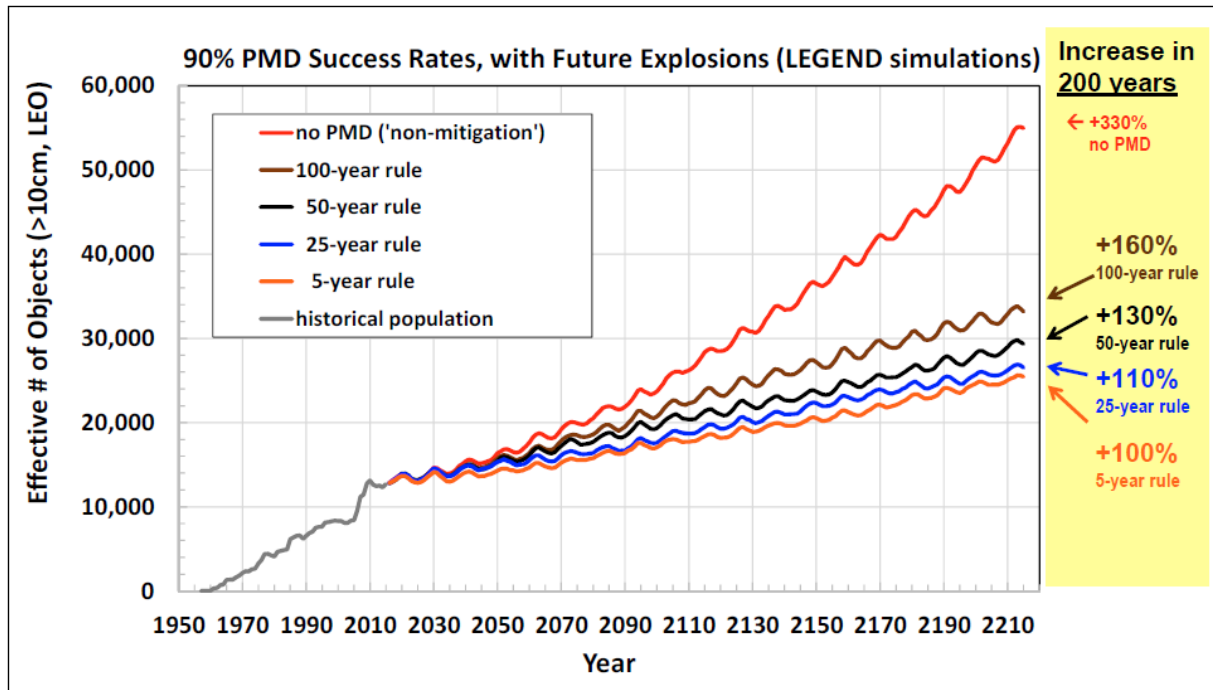


Figure 3. Effectiveness of the 25-year rule versus the non-mitigation scenario and other rules. The non-mitigation scenario assumes an 8-year traffic cycle in the future. Projection results are based on averages of 100 Monte Carlo simulations each by the NASA LEO to GEO Environment Debris (LEGEND) long-term debris environment model (<https://orbitaldebris.jsc.nasa.gov/modeling/legend.html>).

The above figure provides varying levels of mitigation. As expected, no mitigation produces a significant projected increase to the number of objects in LEO over time. With increasing levels of mitigation (or shorter rules), the projected increase in the number of objects in LEO decreases. The relationship between the different simulated rules does not appear to be linear with the number of objects projected.

A 2014 IADC¹⁸ study, using the DAMAGE model, concurred with the ODMSP 25-year rule. The IADC study cited that “very short times would involve a substantial increase in the de-orbit propellant requirement.” Both the IADC and ODMSP agreed that 25 years is a maximum timeframe and encouraged proactive steps by the satellite operator to pursue a PMD timeframe that is better than the 25-year rule. They both believed that 25 years was an adequate compromise between high mission cost for a short lifetime disposal (and, thus, effective PMD policy) and a low mission cost for a long lifetime (which increases collision risks).

¹⁷ <https://www.swpc.noaa.gov/impacts/satellite-drag>

¹⁸ https://www.iadc-home.org/documents_public/file_down/id/4135

Alternative opinions on the 25-year rule

The recent ODMSP update was not without controversy or disappointment¹⁹. There were some opinions that the 25-year rule should be reduced to a 5-year rule. Keep in mind that the ODMSP are intended for government entities but have been globally recognized (albeit in a high level, qualitative form) and have also informed the development of regulations for commercial spacecraft licenses. The latter is a key piece to consider and reflects the intent of SPD-3's direction to update the ODMSP to "promote efficient and effective space safety practices with U.S. industry and internationally."²⁰

As an alternative and proactive effort, a group of non-governmental entities, called the Space Safety Coalition, voluntarily stated their intent to strive for a 5-year disposal timeframe for those spacecraft with chemical or electric propulsion²¹. The group also raised the probability of successful disposal from 90% to 95%.

Whether the disposal time frame is best set at 5-years or 25-years remains a topic of debate - and perspectives. Intuitively, 5-years seems like the logical choice if your only concern is the sustainability of the space environment. However, if you are considering mission requirements and the cost to build to stricter requirements then operators may reconsider whether or not to build a satellite. If your concern is the growing popularity of large constellations (as opposed to one or two satellites), then separate requirements can be applied to the large constellations. This is the approach the updated ODMSP pursued in response to SPD-3's direct requirement to address large constellations²².

Can we do better than 25 years?

A shorter disposal timeframe will likely encourage future technologies. Under present day technology satellites will have shorter operational lifetimes if they use their fuel for a faster disposal. This will result in more maneuvering (vs. a gradual decay) out of orbit. The reduced operational time in orbit could lead to more replenishment of satellites and, thus, increased launch activity. The increased traffic going into and out of orbit may involve more spacecraft maneuvering which can challenge current collision avoidance capabilities and operators. This suggests the need for more sensors (in orbit and ground) with the goal towards achieving

¹⁹ Verspieren, Quentin. Graduate School of Public Policy, The University of Tokyo, The US Air Force compliance with the Orbital Debris Mitigation Standard Practices, 2020 Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS).

²⁰<https://trumpwhitehouse.archives.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/>

²¹ <https://spacesafety.org/best-practices/>

²² Although NASA led the ODMSP update, NASA does not have experience building or operating large constellations. The large constellation focus was included in the ODMSP update, because the ODMSP is historically used by the FCC to regulate non-governmental satellites. Thus, although the ODMSP only applies to governmental satellites, the update was created with the understanding that the regulatory agencies would likely implement the updated ODMSP as license requirements for non-governmental satellites.

continuous custody. This also suggests the need for automation and efficiency to reduce the manual effort involved with mitigating close approaches. Additionally, the operator community will need to work together to develop effective and efficient means of communication and coordination for the increased congestion in orbit. This series of steps are just some of the advances and maturation that could occur with a push towards shorter disposal timeframes.

The ideal approach is for a spacecraft to be removed immediately upon mission end so as to minimize the risk of collisions and explosions. However, the trade-offs to these advances are likely in the form of increased cost which may disincentivize the development of some satellites. What remains unclear, and a potential future area of study, are the mission requirement and cost implications to pursuing the ideal approach. How might a higher standard impact future satellite operators and launch vehicle development? Could new technologies and approaches be developed in response?

For both the launch vehicle and the spacecraft there will be cost implications. A 2021 paper recently cited a list of top 50 most concerning objects in LEO. This list of concerning²³ objects is primarily made of (39) rocket bodies which are derelict objects in an uncontrolled state with high mass. The primary factors used to create the list were “mass, encounter rates, orbital lifetime, and proximity to operational satellites.”²⁴

Legacy launch vehicles release debris in orbit and are estimated to cost 300-500 million dollars to upgrade.²⁵ Drag devices may allow spacecraft to maximize use of their fuel while maintaining reasonable decay time frames in LEO. These devices will need to be high reliability otherwise they risk a mission ending failure due to accidental deployment. A better understanding of the impacts and consequences may educate opinions on the appropriate balance for disposal timeframes.

²³ Worth noting is that concerning objects can also include small, untrackable debris. Differing perspectives exist on whether high mass, trackable objects that could produce a lot of debris are more concerning than mission ending, untrackable debris. The ability to track an object creates an opportunity to avoid the object and, thus, reduce collision consequences to impacted satellites and the environment. However, high mass objects could result in the creation of more debris (whether trackable or not). This would have a significant impact on the environment. Both perspectives have merit and pursue the same goal of a sustainable environment. Ultimately, measurement of both parameters (trackability and mass) will present a more accurate assessment of the environment.

²⁴ Darren McKnight a,*, Rachel Witner a, Francesca Letizia b, Stijn Lemmens b, Luciano Anselmo c, Carmen Pardini c, Alessandro Rossi d, Chris Kunstadter e, Satomi Kawamoto f, Vladimir Aslanov g, Juan-Carlos Dolado Perez h, Vincent Ruch h, Hugh Lewis i, Mike Nicolls j, Liu Jing k, Shen Dan k, Wang Dongfang k, Andrey Baranov l, Dmitriy Grishko m. Identifying the 50 statistically-most-concerning derelict objects in LEO, <https://doi.org/10.1016/j.actaastro.2021.01.021>, Received 3 November 2020, Revised 7 January 2021, Accepted 14 January 2021, Available online 22 January 2021.

²⁵ Verspieren, Quentin. Graduate School of Public Policy, The University of Tokyo, The US Air Force compliance with the Orbital Debris Mitigation Standard Practices, 2020 Advanced Maui Optical and Space Surveillance Technologies Conference (AMOS).

Below is a review of multiple NASA spacecraft that were decommissioned while in Earth orbit. NASA spacecraft were chosen for the large amount of publicly available information avoiding the need for concern over proprietary or otherwise sensitive information that might occur with commercial or defense spacecraft. Furthermore, NASA's reputation for technical rigor presents an opportunity to study the individual cases without concern for neglect of details or a lack of competence in the assessments leading to decision making. The scope of this effort is spacecraft in Low Earth Orbit (LEO). The sample of case studies will allow the observation of any patterns between spacecraft, but also permit the clarification of individual findings regarding any unique aspects. The research question under consideration is "What are the obstacles to ODMSP compliance?" This explanatory study will assess the decision making process, the decisions made, and the effect of those decisions.

Case Study: EO-1

NASA's Earth Observing-1 (or EO-1) satellite was launched November 2000 from Vandenberg Air Force Base on a Delta II rocket²⁶.

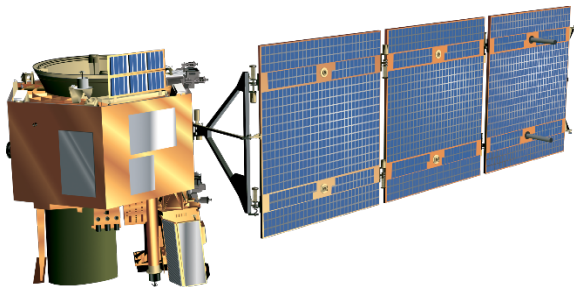


Image source: NASA²⁷

In 2011, EO-1 reached "critical fuel levels and suspended orbital maintenance, beginning a slow decline in orbital altitude. A small fuel reserve was used for debris avoidance maneuvers..."²⁸

Multiple senior review panel's assessed the scientific value and availability of funding for operations²⁹. The 2011 Senior Review panel specifically cited EO-1's instruments as providing a "gap-fill between Landsat 7 and LDCM (Landsat 8), gap-fill for ASTER SWIR bands³⁰" and "prototyping for HypIRI.³¹" The satellite was in good health and "predicted to function through 2015." These parameters ultimately led to a decommissioning date in late 2016 due to the degraded orbit reducing the value of the science.

On March 30, 2017 EO-1 was "transitioned into a permanently safed configuration with fully emptied propellant tanks and drained batteries. NASA forecasts the satellite's re-entry for 2056..."³²

²⁶ <https://spaceflightnow.com/2017/04/01/pioneering-earth-observation-satellite-retired-by-nasa/>,
https://en.wikipedia.org/wiki/Earth_Observing-1, <https://eosps.nasa.gov/missions/earth-observing-1>,
<https://science.ksc.nasa.gov/payload/missions/eo-1/>

²⁷ <https://science.nasa.gov/get-involved/toolkits/spacecraft-icons>

²⁸ <https://spaceflight101.com/nasa-eo-1-end-of-mission/>

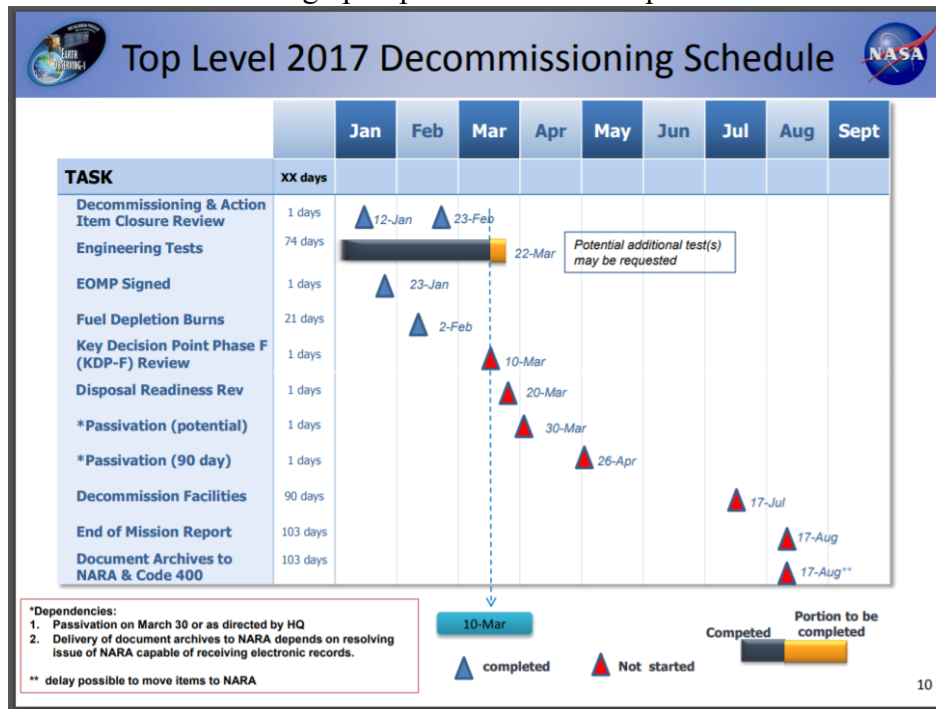
²⁹ Senior Review panels: https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2011-NASA-ESSR-v3-CY-CleanCopy_3x.pdf and https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2015_ESDSeniorReviewReport_FINAL.pdf

³⁰ https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2011-NASA-ESSR-v3-CY-CleanCopy_3x.pdf

³¹ https://science.nasa.gov/science-pink/s3fs-public/atoms/files/2011-NASA-ESSR-v3-CY-CleanCopy_3x.pdf

³² <https://spaceflight101.com/nasa-eo-1-end-of-mission/>

Below is a schedule of tasks leading up to passivation of the spacecraft³³:



How does this relate to the postmission disposal practices? EO-1 will remain in LEO for greater than 25 years beyond mission completion. At the time of design and launch, the solar activity estimates predicted an orbit decay design within the 25 years of postmission completion. However, updated solar cycle information increased the time frame originally estimated³⁴. This information was not known until well into the lifetime of the spacecraft. Estimating the impact of drag (which is influenced by solar activity³⁵) on a LEO satellite is part of the design process³⁶ - something which typically occurs decades in advance of the satellite disposal. In this situation, the updated estimates meant that the satellite would experience less drag than originally expected at the time of design and will remain in orbit longer. Once the new estimate of the decay time frame was known, nothing could be done to accelerate the satellite’s demise. Instead, NASA made the most of the situation by continuing operations for as long as possible. This allowed more science data to be collected and accommodated the need for any collision avoidance maneuvers until passivated.

What’s the take-away from this case study? Space weather is challenging to predict, especially far into the future. Considering the lengthy design, build, and fly process for a satellite, the space weather predictions will have limited accuracy in the crucial design phase. The design of a

³³ <https://ntrs.nasa.gov/api/citations/20170005649/downloads/20170005649.pdf>

³⁴ Discussion with NASA, October 18, 2021,

“A higher solar maximum decreases satellite life and a lower solar maximum extends satellite life.”

<https://www.swpc.noaa.gov/products/solar-cycle-progression>, <https://www.swpc.noaa.gov/impacts/satellite-drag>

³⁵ <https://ntrs.nasa.gov/api/citations/20120008362/downloads/20120008362.pdf?attachment=true>

³⁶ <https://ntrs.nasa.gov/api/citations/20130000278/downloads/20130000278.pdf>

maneuverable (propulsive) satellite involves estimating the fuel necessary to maintain orbit and mission (i.e. science) location, as well as the fuel reserve necessary for postmission disposal. In other words, the low atmospheric drag experienced in LEO requires the occasional reboost of the satellite to maintain the stringent requirements for science needs³⁷. Fuel for collision avoidance maneuvers must also be estimated for the lifetime of the satellite. All of these fuel estimates are based on predicted solar activity levels that can influence the amount of drag experienced by each object in LEO. Further complicating the situation, is the satellite area exposed along the velocity vector influences the amount of drag each object experiences. This means that different objects can experience different levels of drag. As our understanding of space weather improves, the process of designing a satellite and estimating lifetimes will also improve.

Case Study: TRMM

The Tropical Rainfall Measuring Mission (TRMM) was launched in November 1997 from Tanegashima Island on NASDA's H-II rocket³⁸.

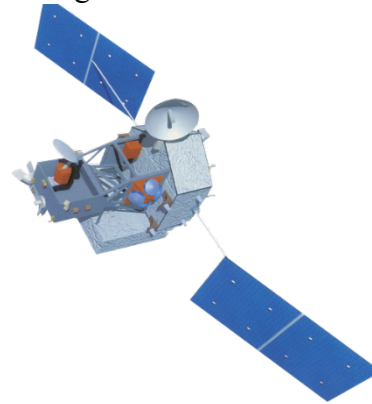


Image source: NASA³⁹

The TRMM mission was known early on to be a valuable data source for disaster efforts. "The data were being heavily used for tropical cyclone monitoring and forecasting," said TRMM Project Scientist Scott Braun at Goddard. "It was being used for flood detection and monitoring. It was also used for drought monitoring, disease monitoring — where diseases are most prevalent in areas of heavy precipitation and flooding.⁴⁰" As a result of the valuable social contribution from the TRMM spacecraft, NASA approved a mission extension in 2001. The mission extension allowed for the orbit to be raised slightly to 402.5 km. This orbit allowed the mission to continue, while minimizing fuel consumption, and extending the mission. In 2005, NASA again reviewed the status of the TRMM mission and determined the spacecraft was healthy, the mission continued to be a valuable social contribution, and operating costs were adequate. The 2005 review resulted in another mission extension until the satellite ran out of fuel⁴¹.

As part of the 2005 review, TRMM's ODMSP compliance was considered. TRMM was in a low 350 km circular orbit where atmospheric drag requires regular reboosts. At this orbit, the spacecraft was low enough to minimize on orbit collision risk. However, the use of the fuel for mission extension meant that an uncontrolled (vs. controlled) reentry was necessary. The TRMM spacecraft had a dry mass of 2630 kg and was estimated to have 12 pieces (with a total mass of 112 kg) survive reentry to the surface of the Earth. The human casualty risk was estimated as 1

³⁷ <https://earthobservatory.nasa.gov/features/OrbitsCatalog>

³⁸ <https://directory.eoportal.org/web/eoportal/satellite-missions/t/trmm>

³⁹ <https://science.nasa.gov/get-involved/toolkits/spacecraft-icons>

⁴⁰ <https://directory.eoportal.org/web/eoportal/satellite-missions/t/trmm>

⁴¹ <https://directory.eoportal.org/web/eoportal/satellite-missions/t/trmm>

in 4200, which is slightly higher than the ODMSP risk. NASA decided to waive the controlled reentry requirement in favor of extending the mission and utilizing an uncontrolled reentry. The issue here was not the amount of time the satellite would take to decay from orbit. At such a low altitude, atmospheric drag provides a natural cleansing process and (solar activity withstanding) will remove the satellite from orbit within a reasonable period of time. In the case of TRMM, NASA needed to consider the risk of an uncontrolled reentry against that of mission extension. The replacement satellite for TRMM was the Global Precipitation Measurement (GPM) mission which was planned to launch in 2010 (at the time of analysis) and ultimately launched in 2014. Thus, NASA was considering the human casualty risk of an uncontrolled reentry against that of the lives saved from TRMM's data (and future GPM data) for disaster support. "Rationale was that TRMM, through its hurricane tracking and other capabilities, had the potential to save lives, out-weighting the risk of human casualty from uncontrolled reentry⁴²"

TRMM represents a situation where the science data provided a social value that was deemed greater than the level of risk exceeding the ODMSP. As the orbit decayed, the satellite's reentry was closely monitored. TRMM ultimately reentered in June 2015 without any issue⁴³.

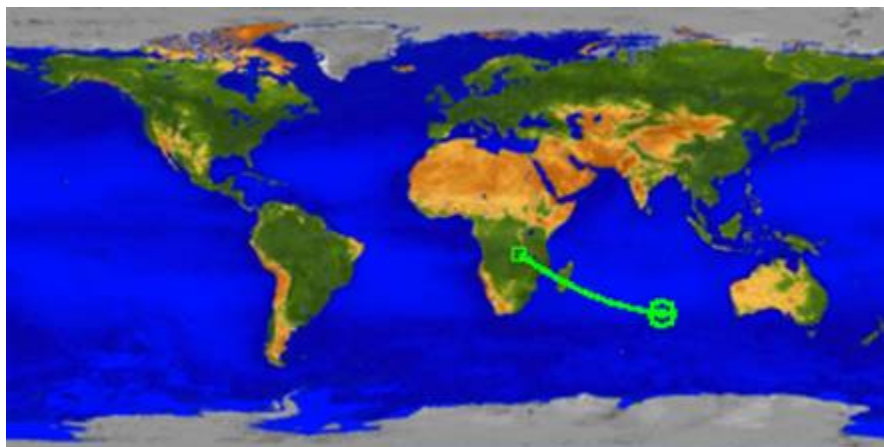


Image source: NASA⁴⁴

⁴² https://trmm.gsfc.nasa.gov/publications_dir/TRMM_Reentry_Risk_Assessment_FINAL_20150604.pdf. A survivability analysis of TRMM assessed that titanium alloy objects would survive. The 12 objects consisted of tanks, flywheels, actuators, etc. and were expected to have a total mass of 112 kg.

⁴³ <https://gpm.nasa.gov/missions/trmm/trmm-spacecraft-re-enters-over-tropics>

⁴⁴ <https://gpm.nasa.gov/missions/trmm/trmm-spacecraft-re-enters-over-tropics>

Case Study: Van Allen Probes

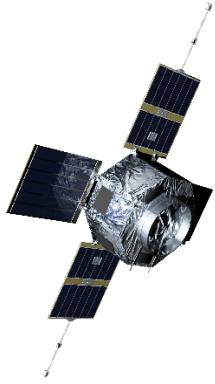


Image source: NASA⁴⁵

NASA's Van Allen Probes were launched in August 2012 from Cape Canaveral Air Force Station⁴⁶. This unique mission consists of two satellites in highly elliptical Earth orbits exploring the Van Allen radiation belts. The mission was extended in 2017⁴⁷ and then ended operations in 2019⁴⁸. In February 2019, shortly before decommissioning, the satellites executed a well-coordinated perigee-lowering campaign intended to decay the orbit of the satellites within 15 years of decommissioning. The campaign was designed around the limited thruster performance capability and consisted of a series of maneuvers over two weeks⁴⁹.

Although complying with the 25-year postmission disposal rule, a recent IG report cites this mission as being an explosive risk due to the inability to disconnect and drain the battery sources. "Originally, the mission planned to reserve sufficient fuel in order to lower the spacecraft to an orbit that would enable reentry within 5 months and in which the spacecraft could be reoriented so that its solar arrays would be away from the Sun preventing recharging of the batteries. However, the subsequent mission extension led to insufficient fuel to lower the spacecraft's orbit per the original plan and disconnect the solar array from the battery. Instead, the batteries will continue to recharge which could eventually result in an explosion and creation of additional orbital debris.⁵⁰" This situation highlights how both postmission disposal and passivation contribute a challenging, but valuable role to sustainment of the orbital environment.

⁴⁵ <https://science.nasa.gov/get-involved/toolkits/spacecraft-icons>

⁴⁶ https://en.wikipedia.org/wiki/Van_Allen_Probes, <https://www.jhuapl.edu/PressRelease/191017>, <https://www.youtube.com/watch?v=Z0aX3n7T0fU>

⁴⁷ <https://science.nasa.gov/science-red/s3fs-public/atoms/files/Heliophysics%20Senior%20Review%202017%20FINAL.pdf>

⁴⁸ <https://www.jhuapl.edu/PressRelease/191017>

⁴⁹ <http://vanallenprobes.jhuapl.edu/News-Center/newsArticles/article.php?id=20190210>

⁵⁰ <https://oig.nasa.gov/docs/IG-21-011.pdf>

Case Study: Terra

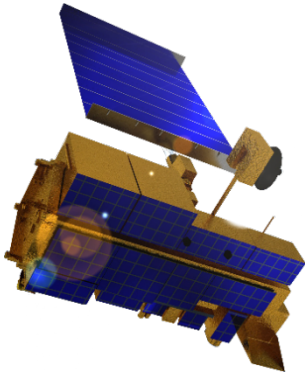


Image source: NASA⁵¹

The Terra mission was launched December 1999 on an Atlas-Centaur IAS launch vehicle from Vandenberg Air Force Base⁵². Terra is a flagship mission that is currently flying an extended mission due to the highly desirable contribution of the mission's science data (discussed below in the Senior Review section). In 2020, Terra performed its last inclination adjust maneuver⁵³; a stationkeeping maneuver that maintains the satellite's mean local time equatorial crossing (for science data quality). The mission is estimated to decommission in 2022⁵⁴

when the satellite will exit the Earth Sciences Constellation and begin lowering the satellite's altitude. Maneuvers will continue for the purpose of avoiding debris. Once all of the fuel is expended, the satellite will passivate and continue an orbital decay to an uncontrolled reentry.

A 2021 IG report expressed concern over the Terra spacecraft ODMSP compliance indicating the "...Terra spacecraft, a 10,000 pound satellite observatory ... is scheduled to be decommissioned in 2026. Terra will not be able to deorbit within 25 years, its batteries cannot be disconnected, and the propellant system cannot be depressurized, increasing the possibility for a debris-generating explosive event. Furthermore, Terra is expected to be in orbit for 50 years after the end of its mission, also increasing the likelihood of collision with other objects in orbit."⁵⁵

The public information available on Terra decommissioning dates varies and suggests uncertainty in orbital lifetime estimates. A variety of presentations exist⁵⁶ that indicate many options were considered for both the ODMSP compliance and the maximization of science. Studies were accomplished to estimate risk during uncontrolled reentry, fuel usage, time remaining on orbit, etc. These presentations demonstrate the dynamic nature of operations and the challenges in precisely estimating time on orbit.

Terra's significant contributions resulted in another mission extension from the most recent 2020 Earth Science Senior Review. The review highlighted the uncertainties surrounding Terra's time on orbit and encouraged more deliberate analysis of the predicted orbit and impacts to science.

⁵¹ <https://science.nasa.gov/get-involved/toolkits/spacecraft-icons>

⁵² <https://eoportal.org/web/eoportal/satellite-missions/t/terra>,
https://www.nasa.gov/mission_pages/terra/overview/index.html,
https://www.nasa.gov/mission_pages/terra/overview/index.html, [https://en.wikipedia.org/wiki/Terra_\(satellite\)](https://en.wikipedia.org/wiki/Terra_(satellite))

⁵³ <https://terra.nasa.gov/about/terra-orbital-drift>

⁵⁴ <https://terra.nasa.gov/about/terra-orbital-drift>

⁵⁵ <https://oig.nasa.gov/docs/IG-21-011.pdf>

⁵⁶ <https://core.ac.uk/download/pdf/42709047.pdf>,
<https://ntrs.nasa.gov/api/citations/20160011554/downloads/20160011554.pdf>,
https://modis.gsfc.nasa.gov/sci_team/meetings/201911/presentations/plenary/wolfe.pdf,
<https://ntrs.nasa.gov/api/citations/20160008917/downloads/20160008917.pdf>

Case Study: QuikSCAT



Image source: NASA⁵⁷

NASA's Quick Scatterometer (QuikSCAT) satellite was launched June 1999 on a Titan II vehicle from Vandenberg Air Force Base⁵⁸. A 2011 Earth Science Senior Review Panel extended the QuikSCAT mission due to the strong national interest of the science data and fulfillment of NASA's ocean winds science objectives⁵⁹. The panel did note concerns about the spacecraft's technical health stating "the QuikSCAT spacecraft is approaching 12 years in operation (design life was three years), has suffered several faults and degraded components, and seems unlikely to survive the next several years without incurring a mission-ending failure. There is no trending data or component health analysis presented to support the assertion that this 12-year old spacecraft is capable of operating through a 2-year mission extension. There is a risk that the spacecraft will be unable to achieve the planned decommissioning orbit."

However, the addendum (included in the report) indicated the benefits outweighed the risks: "Although the QuikSCAT spacecraft has suffered several faults and degraded components (other than scatterometer's antenna spin mechanism) and may incur a mission-ending failure, it is also probable that the spacecraft can operate at this level for the next 2 years; therefore the Senior Review panel feels that this is a worthwhile risk."

QuikSCAT continued to operate until its decommissioning in 2018⁶⁰, many years after the difficult decision made by the 2011 Earth Science Senior Review Panel. According to the 2021 IG report, the spacecraft will significantly exceed the 25-year disposal timeframe and is not fully passivated⁶¹.

Many of the satellites studied were launched shortly before the establishment of ODMSP. However, NASA continues to consider the ODMSP and to pursue efforts to minimize risks to the sustainment of the orbital environment. The predominant challenge appears to be the use of limited fuel capacity for the continuation of science vs. lowering the orbit of the satellite for disposal and reentry. A look at the Senior Review process can provide insight into the assessment of a mission's science value and the decision of whether or not to extend a mission.

NASA's Senior Review Process:

Each of NASA's Science Mission Directorate (SMD) Division's pursue a Senior Review process. This process considers whether or not to continue the operations of ongoing missions

⁵⁷ <https://science.nasa.gov/get-involved/toolkits/spacecraft-icons>

⁵⁸ <https://directory.eoportal.org/web/eoportal/satellite-missions/q/quikscat>

⁵⁹ https://science.nasa.gov/files/science-red/s3fs-public/atoms/files/2011-NASA-ESSR-v3-CY-CleanCopy_3x.pdf,

<https://directory.eoportal.org/web/eoportal/satellite-missions/q/quikscat>

⁶⁰ <https://directory.eoportal.org/web/eoportal/satellite-missions/q/quikscat>, <https://oig.nasa.gov/docs/IG-21-011.pdf>

⁶¹ <https://oig.nasa.gov/docs/IG-21-011.pdf>

that have reached the end of their primary mission. The process is done in response to the NASA Authorization Act which requires biennial reviews of each of SMD's divisions "to assess the cost and benefits of extending missions that have exceeded their planned operational lives."⁶² The results of the Senior Review are publicly available and describe the parameters considered and the reasoning for the decisions concluded upon.



Image source: NASA's Earth Fleet missions (blue circle) in the 2020 Senior Review⁶³

The Senior Review process of the Earth Sciences missions is available on NASA's website⁶⁴. The Review Panel considers "...the scientific performance of each mission and the continued relevance of each mission to the NASA Science Strategic Plan. Performance factors include scientific merit, national needs, the technical status of the mission, and budget efficiency. Missions that pass the senior review process may then be extended beyond their primary operational phase into an extended operational phase."⁶⁵

Panel members can consist of "respected members of the science and academic communities and may include NASA employees not affiliated with the projects under review and representatives from other Federal, state, and nongovernmental organizations that use NASA data products for operational purposes."⁶⁶ A flow chart describing the overall process for the 2020 review demonstrates the review process (for the Earth Sciences Division).

⁶² https://soma.larc.nasa.gov/2020esd_seniorreview/pdf_files/IG-15-001_FINALreport.pdf

⁶³ https://soma.larc.nasa.gov/2020esd_seniorreview/pdf_files/AGUkickoff2020ESD_SeniorReview.pdf

⁶⁴ https://soma.larc.nasa.gov/2020esd_seniorreview/library.html, <https://science.nasa.gov/earth-science/missions/operating>

⁶⁵ <https://science.nasa.gov/earth-science/missions/operating>

⁶⁶ https://soma.larc.nasa.gov/2020esd_seniorreview/pdf_files/IG-15-001_FINALreport.pdf

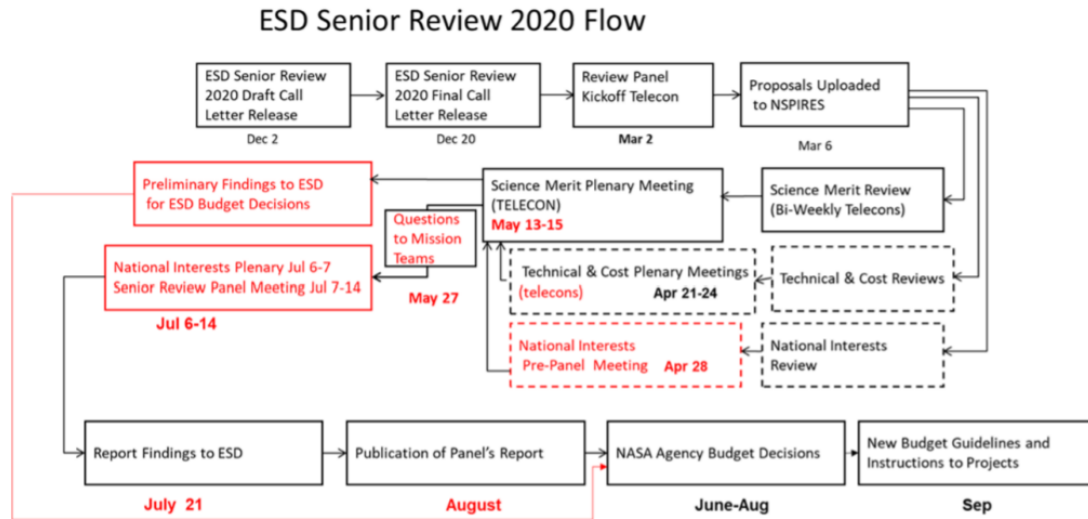
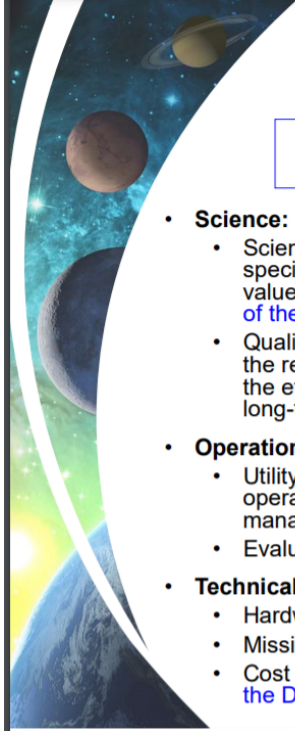


Figure 1 - 2020 Senior Review workflow chart and schedule. (Red highlighting indicates changes to accommodate COVID-19 impacts.)

The 2020 Earth Science Division (ESD) Senior Review Kickoff presentation⁶⁷ (below) provides a summary description for each of the above four parameters, or evaluation criteria, considered: scientific merit, national need, technical status, and budget constraints. The Science criteria evaluates each mission against its relevance to the latest Decadal Survey, which is the 2017 Survey for Earth Science. This criteria also assesses the quality of the data products, particularly the potential impacts that may occur during mission extension. Scientists value the consistency of a dataset and the long-term value that dataset can contribute to research. With these values in mind, the potential impacts of sensor or platform degradation during mission extension are carefully considered.

⁶⁷ https://soma.larc.nasa.gov/2020esd_seniorreview/pdf_files/AGUkickoff2020ESD_SeniorReview.pdf



Evaluation Criteria

ESD's priority for the Mission Teams for the 2020 Review:

➤ *Relevance of the Extended Mission to the 2017 Decadal Survey*

- **Science:**
 - Scientific merit of the mission datasets with the proposed years of additional data collection, with special attention to the science that will be enabled by extension. Merit is based on their intrinsic value in research investigations by the community, [relevance to Decadal Survey](#), and [uniqueness of the data among the global observing resources](#);
 - Quality trends of the standard data products, with a focus on the projected quality for the years of the requested extension, including any change induced by sensor, platform or orbit changes, and the effect of such changes on the overall consistency of the dataset, recognizing the value of long-term data records;
- **Operational and non-research uses:**
 - Utility of the products for "applied and operational uses" that serve national interests, including operational uses, public services, business and economic uses, military operations, government management, policy making, etc.
 - Evaluation factors: intrinsic value, frequency of use, latency.
- **Technical & Cost:**
 - Hardware status and performance, life expectancy.
 - Mission operations plans for health, safety and data collection.
 - Cost realism, [and share of the overall budget projected for the Program of Record as specified in the Decadal Survey](#)

When considering the data products of each mission, the panel also considers how and by whom the data is being used. The table below (also from the 2020 ESD Senior Review⁶⁸) considers the various governmental and non-governmental entities that use each mission. The some-, high-, and very high-utility grades are represented by the purple, blue, and green colors, respectively.

⁶⁸ <https://science.nasa.gov/science-red/s3fs-public/atoms/files/2020-NASA-ESSR-FullReportFINAL.pdf>

Mission / Sensor	Overall Rating	Civil Agencies									Military / Intelligence Community		NGO		
		NOAA NWS	NOAA NOS	FAA	USDA	USGS	CDC	EPA	NPS	USACE	NGA	CI	Microsoft	IGES	
Aqua	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility	
<i>AIRS</i>	High Utility	Very High Utility	High Utility	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	
<i>CERES</i>	Some Utility	Not Applicable	Very High Utility	Not Applicable	Not Applicable	Some Utility	Some Utility	High Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	
<i>MODIS</i>	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility	
Aura	High Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	High Utility	Not Applicable	Very High Utility	High Utility	Not Applicable	Not Applicable	High Utility	
<i>MLS</i>	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	Not Here	Some Utility	Not Applicable	Not Applicable	Not Applicable	
<i>OMI</i>	Very High Utility	Very High Utility	Not Applicable	Not Applicable	Not Applicable	Very High Utility	Very High Utility	High Utility	Not Applicable	Not Here	Very High Utility	Not Applicable	Not Applicable	High Utility	
CALIPSO	High Utility	Some Utility	Not Applicable	High Utility	Not Applicable	High Utility	Some Utility	High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	High Utility	High Utility	
CloudSat	Some Utility	Some Utility	Not Applicable	High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	Some Utility	Not Applicable	High Utility	Some Utility	
CYGNSS	High Utility	Not Applicable	Not Applicable	Not Applicable	Very High Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	Very High Utility	Very High Utility	Not Applicable	High Utility	High Utility	
DSCOVR	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	
<i>EPIC</i>	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	
<i>NISTAR</i>	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Not Applicable	
ECOSTRESS	High Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	Very High Utility	Not Applicable	Not Applicable	Some Utility	Very High Utility	High Utility	Some Utility	Very High Utility	Very High Utility	
GPM	High Utility	High Utility	Very High Utility	Very High Utility	Not Applicable	Some Utility	Some Utility	Not Applicable	Not Applicable	Not Applicable	High Utility	High Utility	Very High Utility	High Utility	
LIS on ISS	Some Utility	Some Utility	Not Applicable	Some Utility	Not Applicable	Some Utility	Some Utility	Some Utility	Not Applicable	Not Applicable	Some Utility	Some Utility	Some Utility	Some Utility	
OCO-2	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	Not Applicable	High Utility	Not Applicable	Some Utility	Some Utility	
SAGE III	High Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Very High Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	High Utility	
SMAP	High Utility	High Utility	High Utility	Some Utility	Very High Utility	High Utility	Some Utility	Not Applicable	High Utility	Very High Utility	High Utility	Some Utility	Very High Utility	High Utility	
Terra	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility	
<i>ASTER</i>	High Utility	Not Applicable	Not Applicable	Some Utility	High Utility	Very High Utility	Some Utility	Not Applicable	Some Utility	Very High Utility	Very High Utility	Some Utility	Not Applicable	High Utility	
<i>CERES</i>	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	High Utility	Some Utility	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	
<i>MISR</i>	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	High Utility	Not Applicable	Not Applicable	Not Applicable	Some Utility	Not Applicable	Not Applicable	Some Utility	
<i>MODIS</i>	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	Very High Utility	High Utility	Very High Utility	Very High Utility	
<i>MOPITT</i>	Some Utility	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Some Utility	Some Utility	High Utility	Not Applicable	Not Applicable	High Utility	Not Applicable	Not Applicable	Some Utility	

Terra and Aqua rank highly amongst all of the entities listed. The U.S. Army Corps of Engineers (USACE) uses Terra for land cover and fire applications. The U.S. Geological Survey (USGS) uses Terra for the mapping of minerals and volcanic hazards. Other entities use Terra data to assess the aerosol emissions, sea ice analysis, monitoring fire growth and fire detection, agricultural changes, carbon monoxide trends, etc. Aqua contributes data to weather prediction models, environmental health applications, monitor drought conditions, ice analyses, snow cover products, croplands for food security, water use assessments, droughts studies, and natural resource assessments⁶⁹. The widespread use of these missions demonstrates great utility and continued contribution to the public, particularly when remembering that the data is provided as part of a free and open data policy.

The remaining two evaluation criteria, technical status and budget, consider the life expectancy of a mission. This assesses how the satellite hardware is performing, as well as the current and predicted health of the mission. The budget necessary to continue operating the mission and the proportion of the budget available is further evaluated.

⁶⁹ <https://science.nasa.gov/science-red/s3fs-public/atoms/files/2020-NASA-ESSR-FullReportFINAL.pdf>

The panel’s summarized assessment of these evaluation criteria for each mission considered during the 2020 review are summarized below⁷⁰. The panel recommended each of the missions for extension. Their scientific merit and relevance to the decadal survey were deemed appropriate for continued operations.

Table 2 - Overview of 2020 Senior Review assessment and mission extension findings.

NASA 2020 Senior Review Extension Findings Summary						
Mission	National Interest Panel	Technical Risk	Cost Risk	Science Overall Findings	Mission Extension	
					FY 2021-2023	FY 2024-2026
Aqua	Very High	Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
Aura	High	Medium-Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
CALIPSO	High	Medium	Medium	Excellent	Extend /Over-guide	N/A /Over-guide
CloudSat	Some	Medium-Low	Medium	Excellent	Extend /Over-guide	Extend /Other
CYGNSS	High	Medium-Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
DSCOVR	Some	Low	Low	Very Good	Extend /In-guide	Extend /In-guide
ECOSTRESS	High	Medium	Medium-Low	Excellent	Extend /Over-guide	Extend /Over-guide
GPM	High	Medium	Medium-Low	Excellent	Extend /Over-guide	Extend /Over-guide
LIS	Some	Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide
OCO-2	Some	Low	Medium-Low	Excellent	Extend /Over-guide	Extend /Over-guide
SAGE III	High	Low	Low	Very Good	Extend /In-guide	Extend /In-guide
SMAP	High	Medium	Medium	Excellent	Extend /Over-guide	Extend /Over-guide
Terra	Very High	Low	Low	Excellent	Extend /Over-guide	Extend /Over-guide

As is the intent, the Senior Review process focuses on the scientific contribution, or the public good, against budget constraints. The Senior Review process does not appear to address ODMSP compliance, however, these details are evaluated as part of the waiver process, if applicable. What happens when a mission is recommended for extension that will lead to non-compliance with ODMSP? The existing process appears to prioritize the continued benefit of the public good

⁷⁰ <https://science.nasa.gov/science-red/s3fs-public/atoms/files/2020-NASA-ESSR-FullReportFINAL.pdf>

(the science data) over the concerns for ODMSP non-compliance. To be fair, NASA carefully assesses all options to compliance and/or minimizing the risk associated with non-compliance. The TRMM mission is a good example of the consideration of the public good against a higher reentry risk. The value of the contribution was considered greater than the increased risk associated with an uncontrolled reentry.

Alternative approaches

The 2021 NASA IG Report expressed concern over the Terra and QuikSCAT missions due to their high mass, extended time in orbit, and explosive concerns. The report indicates that although NASA has done well with debris mitigation efforts, but the agency could benefit from alternative approaches such as debris removal.

At present, NASA's satellites are built to minimize the amount of debris that survives reentry. This approach opens the opportunity for uncontrolled reentries, thereby reducing the dependency upon controlled reentries and valuable fuel resources. The remaining fuel can be used for on orbit collision avoidance maneuvers and mission extension.

NASA may benefit from additional approaches to ODMSP compliance, such as drag deployment devices⁷¹ or active debris removal (ADR). Drag deployment devices are mechanical methods that alter the exposed cross section of the satellite to the velocity vector. In other words, these devices change the shape of the satellite such that more drag is experienced causing the satellite's orbit to decay faster. This approach is effective in LEO where a small amount of atmospheric drag remains. The risk of these deployment devices is accidental deployment. A premature deployment of a drag device is ultimately mission ending, so implementation of these devices will need to ensure reliability of the device and a willingness (or incentive) to accept the risk.

ADR refers to the use of a satellite that intentionally removes defunct satellites from orbit. ADR has been discussed for decades with many creative concepts considered. The technology development is not the reason for lack of implementation. Instead, the cost of access to space remains high. Additionally the uncertainties that come with deploying a new technology create additional concerns. For example, what if the ADR device unintentionally damages the target satellite? This would create more debris in orbit; potentially small, untrackable debris that can prematurely end the missions of nearby satellites. When ADR is eventually employed, the risks of both the new technology and the target satellite will need to be considered. At present, these risks and uncertainties create a disincentive to spending limited resources on removing defunct satellites as opposed to building new satellites for the science community.

Future Studies

Future exploratory efforts could include a review of other government agency satellites (such as NOAA, USGS, and DoD). These reviews could assess the passivation aspect of ODMSP and

⁷¹ https://www.esa.int/Safety_Security/Space_Debris see "Deploying a drag sail", https://www.nasa.gov/spacetechnology/strg/2013_nstrf_long.html

discuss the challenges of passivation. Consideration of the NOAA satellites that experienced multiple explosions of their defunct satellites due to battery issues can contribute to this study.

Similarly, commercial and international satellites could also be reviewed for the ability to meet ODMSP compliance and the obstacles they also encounter. The cost of mitigation efforts in the design phase and the cost of operations could be compared to the cost of active debris removal missions, or even the cost of satellite servicing and refueling missions. Northrop Grumman completed two privately funded satellite servicing missions in 2020⁷². These efforts were in GEO (not LEO), where a designated disposal orbit is used since atmospheric decay is not an option.

- What satellite servicing business cases exist?
- Could these business cases support satellite operations and also encourage sustainment of the environment?
- Could government agencies benefit from satellite servicing to extend the mission of a valuable satellite until a replacement is on orbit, and then properly dispose of the satellite at end of mission?⁷³

Launch vehicle debris is an often overlooked topic. A study of the mass, location, and time in orbit may reveal new opportunities for debris mitigation.

- Where and how much debris is left in orbit with each launch?
- How long does this debris last and whom does the debris impact?
- Can launch vehicles be upgraded to reduce the amount of debris released and at what cost?

Conclusion

The public good benefits of a government satellite will continue to challenge the 25-year disposal rule. Disposal, or debris removal, technologies exist. What remains to be seen is the incentivized application of these debris removal technologies. This is an area where the commercial sector under regulatory incentivization can demonstrate regular application of debris removal capabilities that potentially leads to services. Commercial satellites are not public goods and the benefit of a continued mission is done for profitable purposes. Regulatory incentivization could include reducing the disposal timeframe or creative approaches that support debris removal service business cases. Astroscale, for example, developed a business case on the anticipated failure of satellites in large constellations, such as Starlink and OneWeb⁷⁴. This company is now partnering with the New Zealand government for debris removal⁷⁵ and the UK government to study potential debris removal targets⁷⁶. The private sector and international governments appear

⁷² <https://www.northropgrumman.com/space/space-logistics-services/>

⁷³ NASA is pursuing a Restore-L, now called OSAM-1, mission to refuel Landsat-7. NASA could also consider a satellite servicing mission to support other highly valuable satellites, such as Terra and Aqua.

⁷⁴ <https://www.scientificamerican.com/article/spacexs-starlink-could-cause-cascades-of-space-junk/>, <https://astroscale.com/astroscale-awarded-uk-space-agency-bid-to-study-removal-of-two-defunct-satellites-from-space/>

⁷⁵ <https://spacenews.com/astroscale-and-new-zealand-to-partner-on-space-sustainability-projects/>

⁷⁶ <https://astroscale.com/astroscale-awarded-uk-space-agency-bid-to-study-removal-of-two-defunct-satellites-from-space/>

to be taking the lead in debris removal (and related satellite servicing) services. Last month, the Space Force announced the Orbital Prime program which is an effort to incentivize the development of on orbit servicing, assembly, and manufacturing (OSAM) services⁷⁷. These combined efforts appear to be headed in a direction that encourage the sustainability of the orbital environment.

⁷⁷ <https://spacenews.com/space-force-launches-orbital-prime-program-to-spur-market-for-on-orbit-services/>,
<https://spacenews.com/debris-removal-a-key-goal-in-space-forces-orbital-prime-project/>,
<https://sam.gov/opp/31c4bfe055944ed68abc14f780781564/view>