“Best Practices for the Sustainability of Space Operations”

Date: 20 June 2019

Since the first orbital launch in 1957, the number of artificial objects in Earth orbit has been growing. The corresponding increase in close approaches and collision risk to active space objects from collisions [1, 2] may lead to interruption of crucial space services [3]. Orbital debris population modeling indicates the potential for further increases in collision risk [4, 5, 6, 7, 8]; some of these studies indicate that even in the absence of new space traffic, orbital debris mitigation measures may be insufficient and debris removal remediation may be necessary. Accordingly, mitigation measures are needed to minimize orbital debris and preserve safe access to space in the future. Space industry stakeholders are well aware of these challenges and have achieved key milestones to address them.

In 2002, the Inter-Agency Space Debris Coordination Committee (IADC) assembled a set of guidelines for international space debris mitigation [9], aimed at limiting the generation of debris in the environment in the short-term – through measures typically related to spacecraft design and operation – and the growth of the debris population over the longer-term, by limiting time spent in the low Earth orbit (LEO) region after the end of mission to 25 years. The IADC updated these Space Debris Mitigation Guidelines in 2007 as Revision 1 [10]. The IADC also issued a statement on issues and concerns relevant to planned large LEO constellations [11].

The United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS), drawing largely upon the IADC's initial set of orbital debris mitigation guidelines, developed its own reduced set of consensus Space Debris Mitigation Guidelines [12]. The UN General Assembly endorsed these guidelines in its resolution 62/217.

The International Organization for Standardization (ISO) develops international standards that address space debris mitigation. ISO's top-level space debris mitigation standard is ISO-24113, "Space Systems — Space Debris Mitigation" [13]. This standard and its derivative standards to include [14, 15, 16, 17, 18, 19, 20], incorporate IADC and UN guidelines as well as commercial best practices and expected norms of behavior.

The Consultative Committee for Space Data Systems (CCSDS) is comprised of the major space agencies of the world and develops communications and data systems standards for spaceflight. CCSDS seeks to enhance governmental and commercial interoperability and cross-support, while also reduces risk, development time and project costs, by developing, publishing and freely distributing international standards [21]. The CCSDS international standards for the exchange of orbit, attitude, conjunction, reentry, and event data are particularly relevant to exchanging space data to facilitate safety of flight.

Some spacefaring nations have set up a licensing scheme or national regulatory framework for the space operators in their country. In general, such national regulation reflects a combination of the UN, IADC, and/or ISO-24113, which generally refer to common mitigation measures [22].

Plans to increase our space population with more CubeSats and other small satellites, as well as new, large constellations of satellites, were not envisioned when the above-mentioned guidelines and standards were established. These new planned spacecraft and constellations, coupled with improvements in space situational awareness, space operations, and spacecraft design, all provide an opportunity to expand upon established space operations and orbital debris mitigation guidelines and best practices.

In developing the following best practices, it was recognized that future efforts may be warranted to:

1) Adopt an existing forum or establish new forum(s) to create conditions favorable to the sharing of relevant space information and operator-to-operator coordination of space activities.
2) Address maneuver prioritization in the event that two spacecraft with maneuver capability conjunct. In the meantime, spacecraft operator communications and data sharing will remain the best strategy for avoiding collisions.
3) Address coordination between new large constellation satellite missions and operators existing in the targeted new mission orbit as early as possible to prevent unnecessary co-location or repeating conjunctions once on-orbit.
4) Collaborate with spacecraft manufacturers, governments, and intergovernmental agencies to strive to deorbit all spacecraft after their operational life to achieve ultimate sustainability of the space environment. In particular, relevant facets include the creation of conditions favorable for the development of deorbit servicers, the development of international standards for servicer interfaces and operations, evolution of spacecraft designs to be servicer-friendly, and striving to avoid any spacecraft becoming derelict in an orbit which will not passively decay to reentry within 25 years, and which is not a seldom- used (i.e., graveyard) orbit.

The undersigned space industry stakeholders hereby endorse, and will promote and strive to implement within their respective organizations, the best practices identified and described herein as a valuable advancement towards the sustainability of space operations:

Logo	**Organization**

Best Practices for Sustainability of Space Operations

Respecting,

The 2007 IADC Space Debris Mitigation Guidelines, the 2007 UN COPUOS Space Debris Mitigation Guidelines, and the ISO-24113 "Space Systems — Space Debris Mitigation" standard;

Recalling,

IADC guidelines for international space debris mitigation are designed to limit the generation of debris in all orbital regimes in the short-term and the growth of the debris population over the longer-term, through measures typically related to spacecraft design and operation [23]. These guidelines and other industry best practices were then codified and expanded in ISO's 24113 top-level orbital debris mitigation standard.

Noting,

Most spacefaring nations have established regulations for the space activities of the space operators in their country [22]. In most cases, the national regulation reflects or incorporates the UN, IADC and/or ISO-24113 guidelines.

Recognizing,

That technological innovation and market demands have led to a profusion of pioneering space projects and new systems to provide space services and services from space. This includes innovation in commercial projects that leverage space, spacecraft design and operational advancements, and a number of projects being planned that would deploy large numbers of spacecraft in non-geostationary orbits (NGSOs) to provide broadband connectivity, Earth observation, and other services.

Further Noting,

The IADC and UN guidelines and ISO-24113 standardized practices were formulated on the basis of future space-traffic envisaged at the time they were created. As such, they are not necessarily sufficient in light of recent scenarios that incorporate step increases in commercial space activities, such as the deployment of NGSO constellations with larger numbers of spacecraft than those deployed in previous decades.

Concerned,

About the ability to preserve a safe space environment for future exploration and innovation and the need to limit the creation of new space debris, maximize the information available on both debris and spacecraft, and encourage the development of and adherence to community-wide best practices for all space industry stakeholders.

Urge,

All space actors to promote and adhere to the best practices herein to ensure the safety of current and future space activities, and to preserve the space environment.

The undersigned space industry stakeholders hereby endorse, and will promote and strive to implement within their respective organizations, existing standards and guidelines as published by the IADC [10], UN COPUOS [12] and ISO [13].

In addition, the undersigned space industry stakeholders hereby endorse, and will promote and strive to implement within their respective organizations, the following best practices, regardless of orbital regime:

1. **Spacecraft owners, operators and stakeholders should exchange information relevant to safety-of-flight and collision avoidance.**
   a. Such information should include, at a minimum, operator points-of-contact, ephemerides, ability to maneuver, and maneuver plans.
   b. Typical interfaces include direct operator-to-operator coordination and use of Space Situational Awareness and/or Space Traffic Management entities.
   c. Such exchanges should respect owner/operator intellectual property and proprietary information.
   d. Space industry stakeholders should be protected from legal liability associated with the good faith sharing of information relevant to safety-of-flight
   e. Such exchanges should be in accordance with each operator's country export regulations.

2. **In selecting launch service providers, space operators should consider the sustainability of the space environment.**
   a. Spacecraft operators should include requirements in their launch contracts for LEO missions that upon completion, the launch vehicle upper stages are deorbited through a controlled reentry.
   b. Spacecraft operators should include requirements in their launch contracts for GEO missions that upon completion, the launch vehicle upper stage should be disposed of in such a way that long-term perturbation forces do not cause it to enter the GEO protected region within 100 years of its end of life.
   c. Spacecraft operators should utilize launch vehicle stages for launching their spacecraft that are designed to ensure launch vehicle stage post mission disposal reliability, with a minimum success rate of 90% , and a goal of even higher success rate as technology permits.
   d. Spacecraft operators should utilize launch vehicle stages for launching their spacecraft that are designed to ensure launch vehicle stage post mission passivation

reliability, with a minimum success rate of 90%, and a goal of even higher success rate as technology permits.

e. Spacecraft operators should utilize launch providers who take steps to preclude collisions between deployed spacecraft and any other object that may be within the vicinity of the deployed orbit, including stages of the launch vehicle, active space objects, and inactive space objects, throughout the deployment phase.

3. Mission and constellation designers and spacecraft operators should make space safety a priority when designing architectures and operations concepts for individual spacecraft, constellations and/or fleets of spacecraft.

a. Constellation architectures should include a safety-by-design approach:

   i. Adequate radial separation between large constellations should be maintained to assure a margin of safety under both nominal and anomalous operational conditions.

   ii. Constellation designers should limit the need for active control to mitigate collision risk between their own spacecraft.

   iii. Constellation designers should favor constellation designs which increase the time available to detect a failed spacecraft within their constellation and avoid colliding with it.

b. Precautions should be taken to safeguard the environment from dead-on-arrival (DOA) deployments, particularly when launching spacecraft based on a new design[*]. Such precautions should include one or more of the following:

   i. Rigorous ground-based environmental acceptance testing based upon established acceptance test standards and procedures to include [24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41].

   ii. Qualification-level testing of all protoflight [42] spacecraft, until all critical systems (including those required for maintain spacecraft control and perform active collision avoidance) have been demonstrated on-orbit.

   iii. Launch into and initial operation in orbits that comply with a natural orbit lifetime of less than 25 years;

   iv. Launch into and initial operation in orbits at seldom-used altitudes (see definition of "seldom-used altitude").

4. Spacecraft designers and operators should design spacecraft that meet the following best practices:

a. Spacecraft should strive for a disposal process providing a probability of successful disposal of 95%.

[*] i.e., spacecraft that include elements critical to initial acquisition and control that do not have sufficient heritage to provide confidence in a successful LEOPS campaign.

b. Specific criteria for initiating the disposal of a spacecraft should be developed, included in a disposal plan, evaluated during the mission and, if met, consequent actions should be executed.

c. Spacecraft in orbits with apogee altitude above 400 km should be designed to be capable of performing timely and effective collision avoidance maneuvers sufficient to reduce the probability of collision per conjunction to less than 0.0001.

d. Designers of spacecraft disposed of through atmospheric re-entry should strive to reduce residual casualty risk to less than 1:10,000 per spacecraft and additionally should evaluate casualty risk on a system-wide, annual basis.

e. Spacecraft designers should consider means to improve the reliability of passivation functions, including the ability to complete passivation even after loss of command or loss of contact. Enabling this capability should be at the discretion of the spacecraft operator, i.e., later in mission life, or once the deorbit phase has been initiated.

f. Spacecraft designs should consider including technologies and features that facilitate capture and deorbit in the event that the spacecraft becomes derelict.

g. In order to facilitate the possibility of future servicing and/or removal by an in-orbit service provider, spacecraft operators and designers should maintain information on their spacecraft's inertia tensors, array positioning and other associated spacecraft characteristics.

h. Spacecraft should be designed to be reliably trackable from the ground using passive tracking means (e.g., radar, optical and passive RF). Spacecraft with limited observability should include features that enhance visibility (e.g., laser retro-reflectors and/or radar-cross-section enhancements).

i. Spacecraft operators and designers should consider using methods (e.g., encryption) in spacecraft command and control to maintain positive control of, and avoid unauthorized access to, space asset flight command functions.

5. Spacecraft operators should adopt space operations concepts that enhance sustainability of the space environment.

a. Operators of spacecraft in orbits with apogee altitude above 400 km should conduct active collision avoidance to reduce the probability of collision per conjunction to less than 0.0001, so long as it remains possible for the spacecraft to do so (i.e., until the spacecraft fails or has been passivated).

b. Collision avoidance maneuvers should be coordinated with the other spacecraft operator(s) and implemented as applicable.

c. The condition of a spacecraft should be monitored periodically during its operation to detect and mitigate any anomalies that could either lead to an accidental break-up or prevent successful disposal.

d. In case of mission extension, the capability of a spacecraft (including any mission extension servicer) to perform successful disposal should be reassessed considering the status of the spacecraft (including any mission extension servicer) at the beginning of the mission extension.

e. A spacecraft operating in the GEO protected region with a periodic presence should be disposed of in such a way that long-term perturbation forces do not cause it to enter the GEO protected region within 100 years of its end of life.

f. IADC and ISO guidance is to passivate as soon as is practical. However, with shorter deorbit durations this is not necessarily the best practice. The timing of post mission spacecraft passivation should be based on a tradeoff between the risk of debris generation due to self-break-up versus that due to collision with orbital debris over the passive deorbit period:

   i. GEO spacecraft should be moved into a GEO disposal orbit and should be passivated as soon as practical after the end of its in-service life and completion of its active disposal maneuver.

   ii. LEO spacecraft with long passive deorbit durations (greater than 5 years) should be passivated as soon as practical after the end of its in-service life and completion of its active deorbit maneuvers (if any). Prior to passivation, operators deorbiting LEO spacecraft should strive to place them into a final configuration that maximizes average (uncontrolled) cross-sectional area.

   iii. Spacecraft with short passive deorbit durations (i.e., less than 5 years) should be passivated as late as practical so they may continue to perform collision avoidance maneuvers. Retaining the collision avoidance maneuver capability reduces the risk of collision with orbital debris, and diminishes the need for in-service spacecraft to maneuver.

   iv. Hazardous fluids that are expected to survive reentry should be vented prior to reentry.

g. LEO spacecraft should be disposed of by means of atmospheric re-entry.

h. Operators of spacecraft that use chemical or electric propulsion to deorbit should strive to complete the deorbit phase within 5 years of end-of-mission.

i. Operators of passively deorbited spacecraft that require longer deorbit periods should strive to deorbit their spacecraft as soon as possible after the end of the service life of the spacecraft.

j. Spacecraft operators should strive to maintain current and 48h-predicted positional knowledge of their assets to within 500 m (two-sigma). This accuracy pertains to predicted ephemerides provided under Best Practice 1.(a) above. It is recognized that during orbital maneuvering periods, positional knowledge may be degraded.

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Glossary

For the purposes of this endorsement of best practices document, the following terms and definitions apply:

active collision avoidance
positive action such as an orbital maneuver (through propulsive, differential drag, or other means that is executed in order to reduce the probability of collision with another spacecraft or with orbital debris.

active phase of deorbit
the phase of deorbit during which the spacecraft is performing maneuvers to re-enter the atmosphere more quickly or to relocate it to a seldom-used altitude (e.g., GEO disposal orbit).

break-up
event that completely or partially destroys a space object and generates fragments.

casualty
person who is killed or seriously injured.

NOTE 1 to entry: The medical profession has defined a number of different injury scoring systems to distinguish the severity of an injury. Broadly, a serious injury is one of such severity that hospitalization is required.

casualty risk
probability that one or more casualties occur as a consequence of an event.

NOTE 1 to entry: The re-entry of a spacecraft is an example of an event.

controlled re-entry
type of re-entry where the time of re-entry is sufficiently controlled so that the impact of any surviving debris on the surface of the Earth is confined to a designated area (e.g., an uninhabited region such as an ocean).

derelict spacecraft
a spacecraft that has been abandoned, neglected, or has become nonfunctional but remains in an orbit of any kind in space.

disposal
actions taken by a spacecraft or launch vehicle orbital stage to achieve its required long-term clearance of the protected regions and to permanently reduce the chance that it will fragment.

disposal maneuver
action of moving a spacecraft or launch vehicle orbital stage to a different orbit as part of its disposal.

disposal orbit
orbit in which a spacecraft or launch vehicle orbital stage resides following the completion of its disposal maneuvers.

disposal phase
interval during which a spacecraft or launch vehicle orbital stage completes its disposal.

end of life (EOL)
instant when a spacecraft or launch vehicle orbital stage is permanently turned off, nominally as it completes its disposal phase, or when it re-enters, or when the operator can no longer control it.

end of mission
instant when a spacecraft or launch vehicle orbital stage completes the tasks or functions for which it has been designed, other than its disposal, or when it becomes non-functional or permanently halted because of a failure or because of a voluntary decision.

Geosynchronous Earth orbit (GEO)
Earth orbit whose orbital period is equal to the Earth's sidereal rotation period.

Geostationary Earth orbit (GSO)
Earth orbit having zero inclination and zero eccentricity, whose orbital period is equal to the Earth's sidereal rotation period.

hazardous fluids
Gasses and/or liquids that are generally considered detrimental to the environment, animals and/or humans.

launch vehicle
system designed to transport one or more payloads from the surface of the Earth to outer space.

launch vehicle orbital stage
complete element of a launch vehicle that is designed to deliver a defined thrust during a dedicated phase of the launch vehicle’s operation and achieve orbit.

Low Earth Orbit (LEO)
Earth orbit occupying orbit altitudes below 2000 km.

maneuver
To intentionally steer or manipulate (via either propulsive effects or induced perturbations) a spacecraft’s subsequent position.

mission extension servicer
A spacecraft servicing vehicle designed to extend a spacecraft's mission duration.

Non-Geostationary Orbit (NGSO)
Earth orbit that is not a geostationary Earth orbit (as defined above).

orbit lifetime
elapsed time from when an orbiting space object is at an initial or reference position to when it re-enters the lower atmosphere.

passivation
act of permanently depleting, irreversibly deactivating, or making safe all on-board sources of stored energy, capable of causing an accidental break-up.

NOTE 1 to entry: Passivation is necessary to reduce the chance of an accidental explosion that could generate space debris and the chance of hazardous materials surviving re-entry.

NOTE 2 to entry: Residual propellants, batteries, high-pressure vessels, self-destruct devices, flywheels and momentum wheels are examples of on-board sources of stored energy potentially capable of causing an accidental break-up.

probability of successful disposal
probability that a spacecraft or launch vehicle orbital stage is able to complete all of the actions associated with its disposal.

NOTE 1 to entry: This probability is calculated from the reliabilities of those subsystems that are necessary to enable the disposal. The probability also includes consideration of uncertainties in the availability of resources (e.g., propellant required for the disposal), the probability that the nominal mission will be completed, and considering the probability that the disposal will be precluded by predictable external causes.

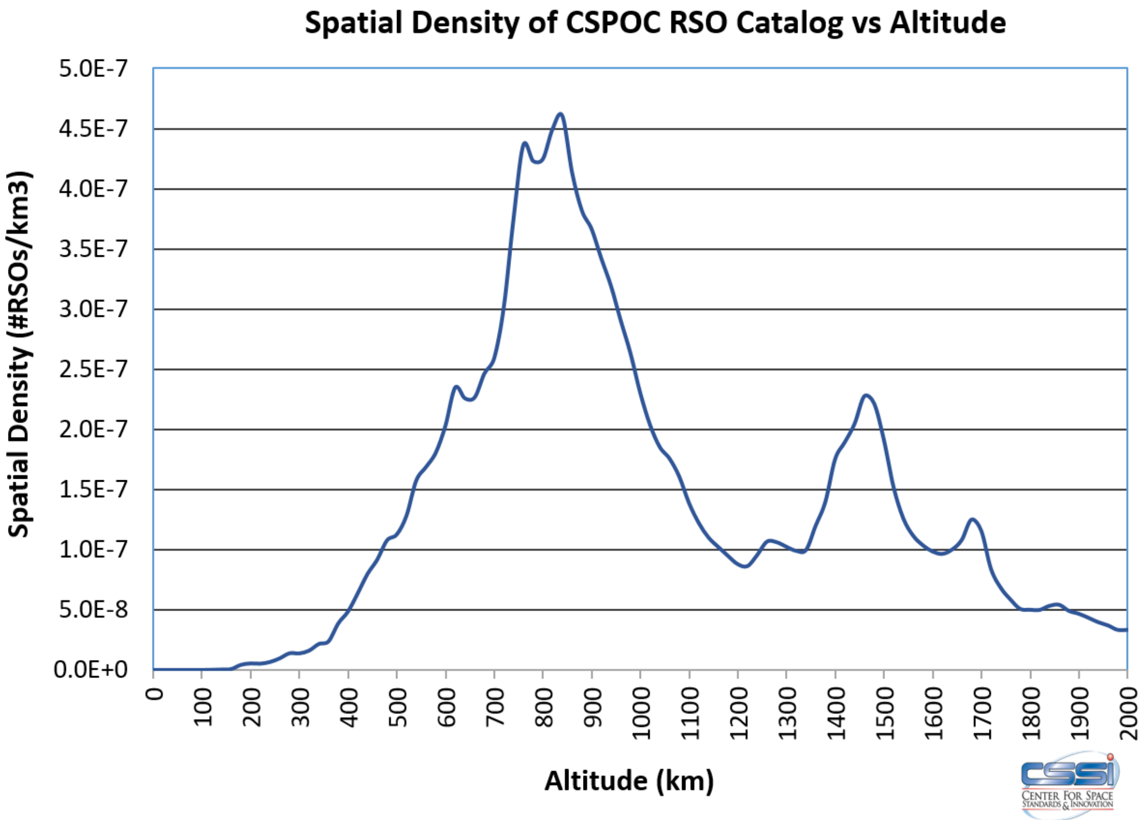
propulsion
the action of driving or pushing forward.

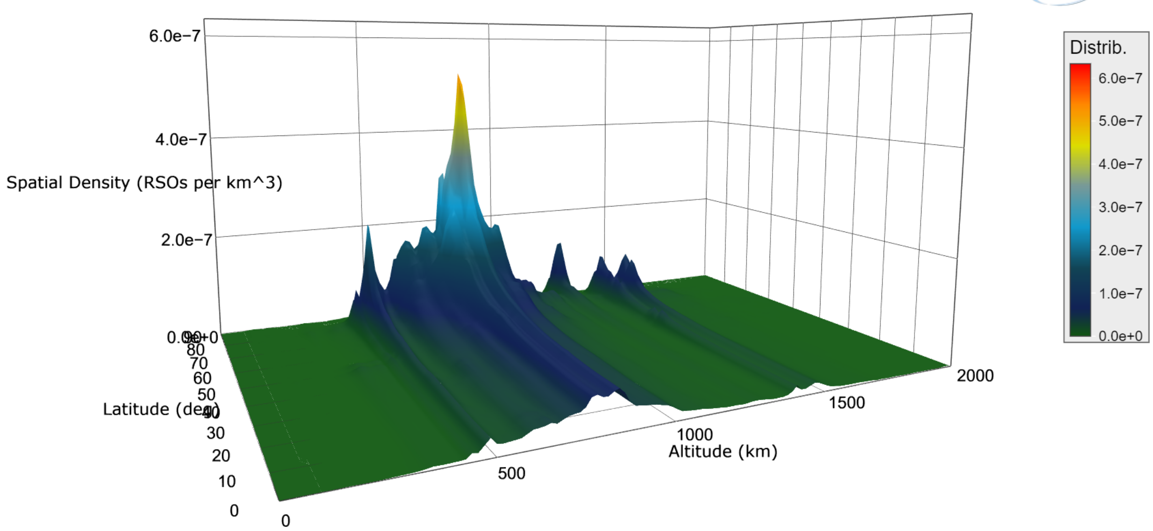
protected region
region in outer space that is protected with regard to the generation of space debris to ensure its safe and sustainable use in the future.

protoflight
As defined by NASA Technical Standard NASA-STD-7002B [42], protoflight refers to flight hardware of a new design which is subject to a qualification test program that combines elements of prototype and flight acceptance verification. A protoflight payload is built, serves to qualify the design and is also the flight article.

re-entry
return of a space object into the Earth's atmosphere.

seldom-used altitude
an altitude that is not an orbit altitude of special significance (e.g. GSO) and that is relatively unpopulated as compared to heavily-used operational spacecraft altitudes and/or crowded debris fragment altitudes (see one-dimensional and two-dimensional depictions below, based upon public space catalog data from 18 July 2018 and 8 September 2017, respectively).





should
something that is seen as being advisable to do but is not binding or mandatory.

space debris (equivalently, orbital debris)
man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.

space object
man-made object which has reached outer space.

spacecraft
system designed to perform specific tasks or functions in outer space, excluding launch vehicles.

SSA
Space Situational Awareness - Comprehensive knowledge and understanding of the space and terrestrial environment, factors, and conditions, to include the status of other space objects, ground and/or space transmitters, and weather, that enables timely, relevant, decision-quality and accurate assessments, in order to successfully protect space assets and properly execute the function(s) for which a spacecraft is designed. (Oltrogge, D., Johnson, T. and D'Uva, A.R., "Sample Evaluation Criteria For Space Traffic Management Systems," 1st IAA Conference on Space Situational Awareness (ICSSA), 13-15 November 2017, Orlando, FL, USA).

STM
Space Traffic Management, defined as the set of technical and regulatory provisions for promoting safe access into outer space, operations in outer space and return from outer space to Earth free from physical or radio-frequency interference (Schrogl, K.U., Jorgenson, C., Robinson, J., and Soucek, A., "The IAA Cosmic Study on Space Traffic Management).

uncontrolled re-entry
type of re-entry where the time and location of re-entry are not controlled.

18SPCS
The United States Air Force 18th Space Control Squadron.