Next Generation Space Operations: Accelerate, Change, Expand Platforms

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Abstract
Next generations space operations will increasingly be performed by private startups providing services customized to customer needs. A growing number of small entrepreneurial startups launch to orbit constellations of hundreds smallsats that in the aggregate execute specific missions. The farther the orbit, satellite operators realize how important it is to build autonomy into the spacecraft. Space computing requires new edge network cache capabilities. And, satellite operations will gradually become digitized for ML-/ AI- enabled autonomy. Space operations will benefit from more accurate forecasts of and/or hardened composite materials to shield from the impact of space weather. The aim of this paper is to explore what opportunities and challenges aerospace professions envision.
Keywords: 5G/6G mobile networking, Mobile Edge Computing (MEC), Smart grids (SG), magnetosphere,

Introduction

The high cost of space mission operations has motivated several space agencies to prioritize the development of autonomous spacecraft command and control technologies. At the same time, there is growing interest in the application of artificial intelligence and machine learning techniques to the space domain by both government [1] and commercial actors. Deep reinforcement learning (DRL) techniques present one promising domain for the creation of autonomous agents for complex, multifaceted operations problems [2]. IoT connectivity technologies are increasingly being combined with computing and large-scale data processing capabilities powered by artificial intelligence (AI) and machine learning (ML) technologies. Space, Air, Ground Integrated Network (SAGIN) is one of the key visions of the fifth/sixth generation (5G/6G) mobile networking technologies [3]. In the past, the exploitation of larger frequency bandwidths and the network densification, namely the deployment of more and more base stations (BSs) to reduce the cell area, were adopted to tackle an ever increasing data throughput demand [4]. Since terrestrial BSs cannot be deployed in off-grid or inaccessible areas such as rural zones, deserts, oceans, the integration of unmanned aerial vehicle (UAV)-assisted wireless communications into 5G systems shows promise.

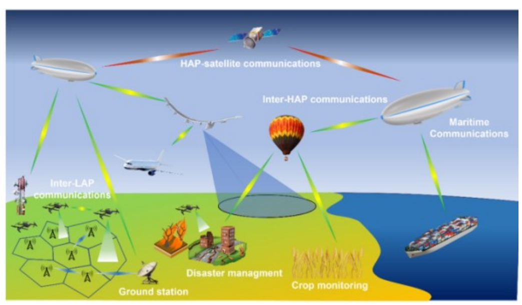


Figure 1. Example of a VHetNet scenario by considering some space, air and ground network components as envisioned in 6G wireless communications.

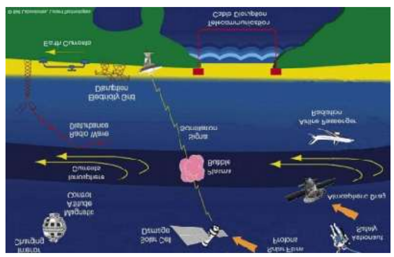
IoT broadly refers to an ecosystem where billions of interconnected physical objects/devices/end-nodes are equipped with communication, sensing, computing and actuating capabilities [6]. Additionally, satellite-based non-terrestrial/terrestrial communications technologies, edge/fog and cloud computing, large-scale data processing are powered by AI/ML. Future 5G and 6G networks aim to provide high-speed access to end devices while traffic load of transit networks and workload of cloud data centers grow.

Edge network cache refers to an in-network storage that contains content request by edge users. The principle of edge computing is to relocate, compute, store (cache) communication services from centralized cloud servers to distributed nodes (users, BSs) located at the edge of the network. Edge computing will continue to proliferate, even in space devices, as individual devices scale up in computational capacities but also among space entities, satellites and devices [8]. Edge computing recognizes that, as high-data rate sensors (e.g. cameras, lidar) proliferate, streaming all data to central cloud systems for processing becomes infeasible.

ISOW 2022 Summary

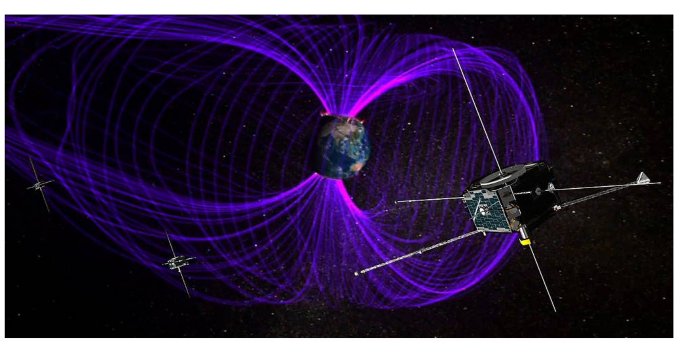
A dedicated Improving Space Operations Workshop 2022 audience appreciated the diversity of voices from leading subject matter experts reporting on varied topics that highlighted trending commercial LEO space operations and what space operations portend for lunar missions. Christopher Kunstadter, global head of AXL's space division, summarized the changing space industry and environment with over 150 yearly launches of about 1800 satellites to orbit. About 5,000 satellites currently crowd an already dense region of space debris at altitude of 700 km above Earth. Robotic in-orbit platforms for space debris removal are being developed. And, solar-wind assisted space-debris technologies are being conceptualized, as described in John Dargin's PRRISM.

Co-founder and CTO Adam London of Astra represents one of many whose startups to develop launch-to-mission platform. His schematic plan described how he was able to shrink the core technologies of launch to develop smaller launch vehicles. He noted entrepreneurial startups provide economic activity from space, typically sensor-embedded spacecraft with cameras and other instruments were launched to orbit so that mission images and data collected are commercially transmitted back on Earth. However, according to Freeman, in case of geomagnetic storms caused by solar flares, their coronal mass ejections occasionally disrupted telecommunications, global positioning services, and electrical systems resulting from damage to spacecraft and radio systems.



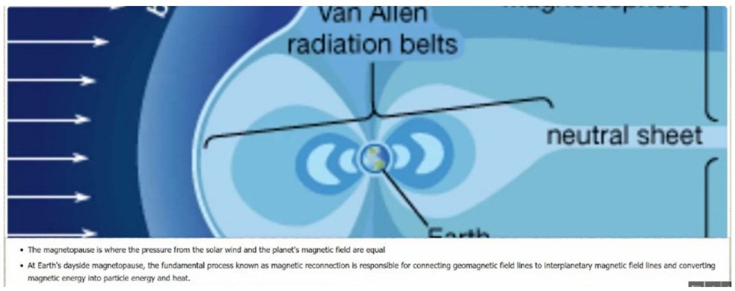
A mitigating strategy would require more accurate space weather forecasts. NOAA's geostationary operational environmental satellites (GOES), solar imaging satellites, and ground magnetometer stations provide near-real-time observational data sets which may be insufficient warning time to prepare for the worst .

Earth's internal magnetism creates a region around the planet known as the magnetosphere. LEO space operations are somewhat protected from geomagnetic storms by a supra-global magnetosphere bubble that deflects solar energetic particles from penetrating the atmosphere and to a lesser degree the International Space Station and other orbiting spacecraft. The boundary between the region dominated by the planet's magnetic field (i.e., the magnetosphere) and the plasma in the interplanetary medium is the magnetopause. Embry-Riddle graduate student, Matthew Chin, described his research on locating magnetopause boundaries per NASA's magnetosphere crossings. An area of weak magnetic field across the magnetopause (or, cusp), suggests an entrance for solar wind particles including outer radiation belt electrons, to pass through the magnetosphere and onwards to the Earth's ionosphere. Monitoring density of ionospheres' total electron count provides one of NOAA's forecast parameters of space weather.



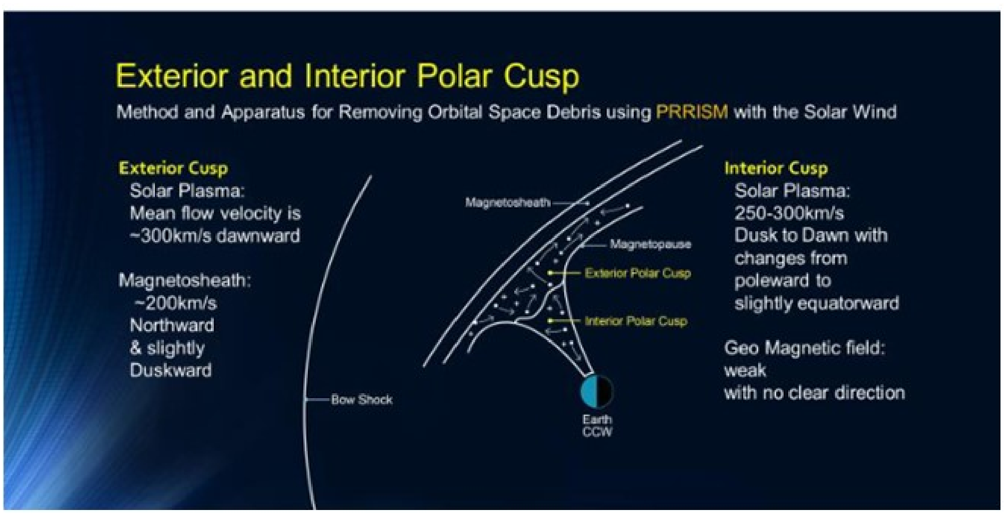
Earth is surrounded by a giant magnetic bubble, called the magnetosphere. Over six years in space, five spacecraft from the THEMIS mission have helped map out this area and improve our ability to predict dynamic space weather events – events that at their worst can impact satellites in space.
Credits: NASA

Observations of the radiation belts and near Earth space have shown that in response to different kinds of activity on the sun, energetic particles can appear almost instantaneously around Earth, while in other cases they can be wiped out completely. Electromagnetic waves course through space as well, kicking particles along, pushing them ever faster, or dumping them into the Earth's atmosphere. Since 2007, THEMIS (Time History of Events and Macroscale Interactions during Substorms) has traveled near Earth through more than 50 solar storms that caused particles in the outer radiation belts to either increase or decrease in number. Electromagnetic waves in space are differentiated based on such things as their frequencies, whether they interact with ions or electrons and cause them to push in the boundaries of the magnetosphere resulting in particle drop outs, or magnetosphere entries. Such information is helpful to those attempting to forecast changes in the radiation belts, which if they swell too much can encompass many of the orbiting spacecraft.



Chin analyzed data of THEMIS E observations to determine velocity, size, and shape of a large bulge moving along the magnetopause described as a hot flow anomaly (HFA). Indicating that the pressure perturbation generated by HFA as the source of the fast compression and expansion of the magnetosphere, the transient deformation of the magnetopause may cause the impending threat of space weather hazards.

ISOW 2022 presentations included novel missions that incorporated innovative technologies. Of particular note, was that polar magnetopause cusps could be utilized as a site for space debris removal. John Dargin conceptualized a model showing how a sufficient force with constructive interference resonates with the electromagnetic field in the polar cusp to reduce turbulence, allowing an increase in the force of the now laminar flow to intercept with the targeted space debris.



The Platform for Redirecting and Removing Inert Space Material (PRRISM) satellite, located in an orbit outside the target orbits, would receive telemetry data from the Solar Plasma Sensor (SPS) and from the Space Debris Sensor (SDS), either onboard or remotely located. The Targeting Computer (TC) on board the PRRISM satellite would receive telemetry data from the SPS regarding plasma polarity, plasma electrical charge, plasma magnetic field strength, electron density, ion density, proton density, flux density, frequency and velocity of the solar plasma. The SDS would send telemetry data to the TC with debris data such as density, size, velocity, and orbit parameters of the debris cloud passing beneath the Polar Cusps. The TC would then determine the required orientation of the PRRISM antenna, the magnitude, frequency and polarization of the electromagnetic wave, along with the timing and power-up sequencing of the PRRISM antenna. This electromagnetic wave antenna would then aim a narrow beam into the Polar Cusp to decrease turbulence and increase the laminar flow of the plasma through the Polar Cusp as the temperature and proton density increased within the plasma. The TC would also provide intercept coordinates and duration for the electromagnetic directed-pressure wave of solar plasma to intercept and move the debris cloud into a decaying orbit. Eventually, the debris would be redirected into the atmosphere to burn up along with other charged plasma to produce the familiar light show, known as the northern and southern lights. The timing and sequencing of the electromagnetic (EM) wave could be pulsed or varied depending on the pressure force required.

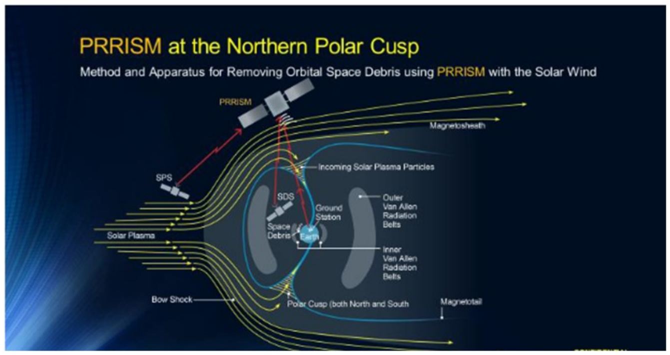
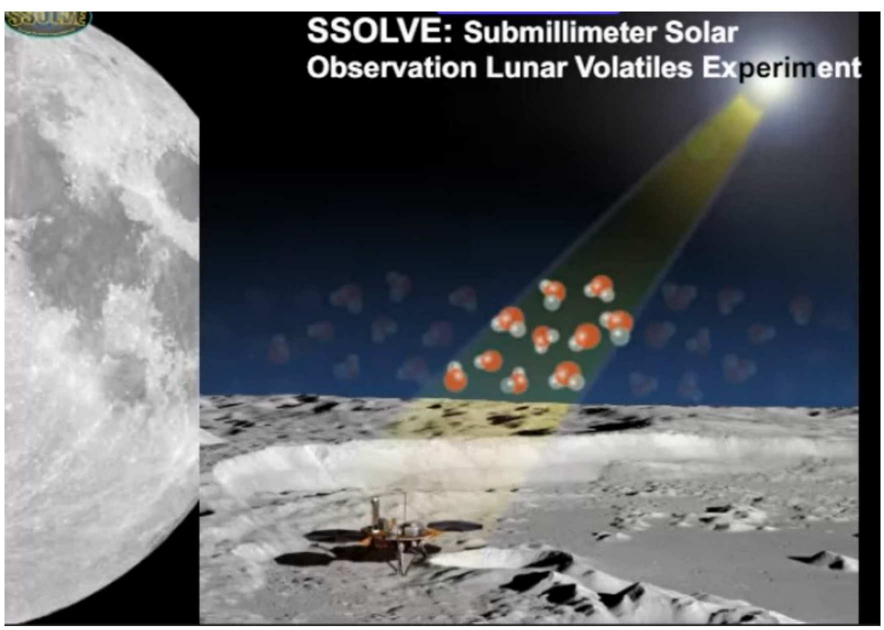


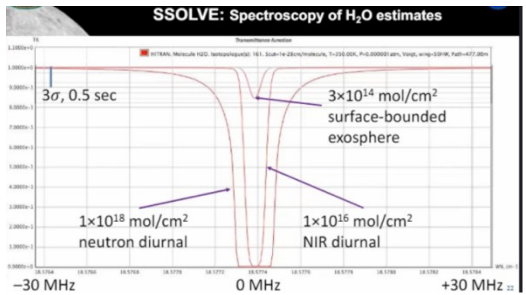
Figure. Force to remove 2 cm debris > 0.059 Newtons. Hence, a force greater than 0.059 Newtons would remove a piece of Space debris 2-cm in diameter from a 500-km orbit. For an orbit of 1000 km, the force is slightly less at 0.051 Newtons.

Lacking consistent protective functions of a magnetosphere, the moon presents a direct target of incident solar winds, galactic cosmic rays. According to Livengood, surveys have estimated water in permanently shadowed region (PSR) and lunar surface water on the Moon. Much less studied is how much water is circulating above the Moon.

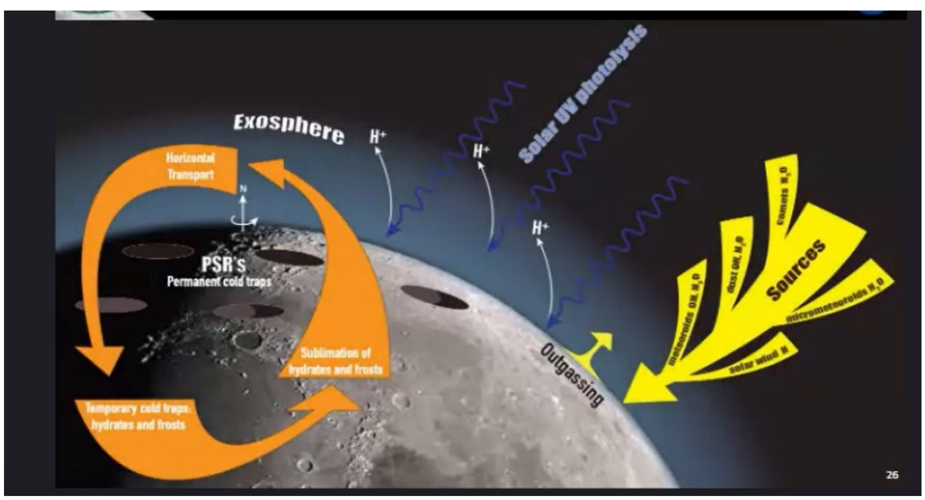
Livengood and his team is currently developing the Submillimeter Solar Observation Lunar Volatiles Experiment **(**SSOLVE) to measure the absolute abundance of water molecules as well as the photolysis product [OH^-], on the line of sight to the Sun within a light beam. SSOLVE telescope will be packaged as a deployable instrument set apart from a crewed lander or delivered by a CLPS lander, which in both cases can be remotely operated from Earth.



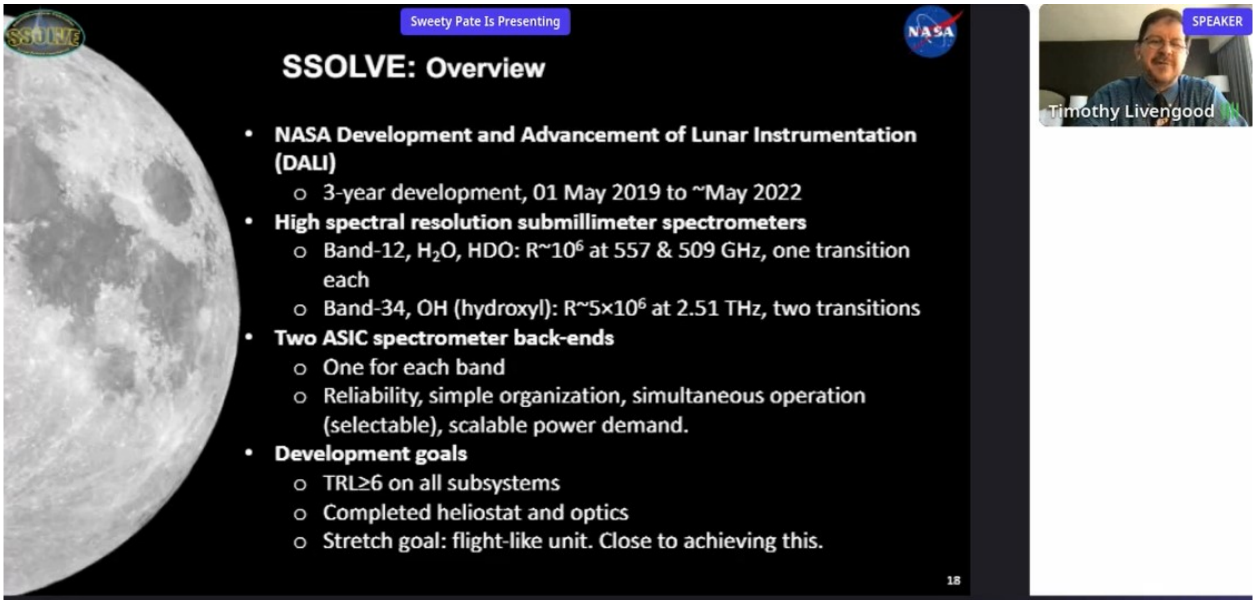
NASA’s GSFC researcher and University of Maryland professor Timothy Livengood discussed how SSOLVE will resolve broad uncertainty in the abundance of water vapor in the tenuous lunar atmosphere and to constrain processes for its supply, removal, and relocation from contaminated lunar sites and thereby constrain the effects of human landings on the lunar environment. A sun tracking scanner (heliostat) will acquire and track the Sun regardless of lander orientation, as well as enabling measurements on dark sky and on calibration targets. Submillimeter spectrometers will use a heliostat to target the Sun and measure the column abundance of H_2O, $[OH^-]$, and HDO in the lunar atmosphere. H_2O and $[OH^-]$ establish the chemical state of water and constrain current photolysis and loss rates, while HDO/H_2O constrains the history of hydrogen loss. Spectral absorption features measure very small quantities of atmospheric water, down to ~1012 mol/cm^2 (~105 mol/cm^3 at surface). Vapor of ~1014 mol/cm^2 or greater can be detected in <10 min.



SSOLVE will measure water vapor to learn which source(s) of water dominates the lunar atmosphere. The global inventory of water in the atmosphere/exosphere is in equilibrium between input sources (yellow) and losses to space and (potentially) permanent cold traps at the poles. Molecules migrate from the warm daylight surface across the terminator to be temporarily trapped on the cold night-time surface until the Moon’s rotation brings the hydrated/frosted surface into daylight to thermally desorb the volatiles into the atmosphere, completing a hydration cycle (orange).



The abundance of water in the tenuous atmosphere immediately above the daytime lunar surface has not been measured, although a wide range of estimates can be derived from measurements on orbit (Benna et al. 2018), remote sensing (Li and Milliken 2017; Livengood et al. 2015; Sunshine et al. 2009; Fig. 3), and equilibrium between assumed supply and loss rates (Table I). These estimates vary by orders of magnitude. The instruments that were deployed by the Apollo missions were unable to measure the neutral atmosphere in daylight due to instrument problems, so neither the total gas pressure nor the composition of volatiles at the surface are known with any certainty (Cook et al. 2013; Stern et al. 2013; Hoffman and Hodges 1975).



Water is challenging to investigate in small quantities due to its presence as a contaminant on instrument surfaces, in sample handling environments, in rocket exhaust, and in any human-occupied environment. SSOLVE is designed to overcome these problems by measuring the total column of H_2O and $[OH^-]$ above the lunar surface, in comparison with calibration measurements that can eliminate local contributions to water vapor in the line of sight. SSOLVE will use high spectral resolution to identify transitions of H_2O, $[OH^-]$, and HDO with certainty, to measure abundance, and to characterize physics in the exosphere using Doppler line width from translational motion.

Table I: SSOLVE will determine the abundance of lunar water vapor – or confirm near-zero abundance

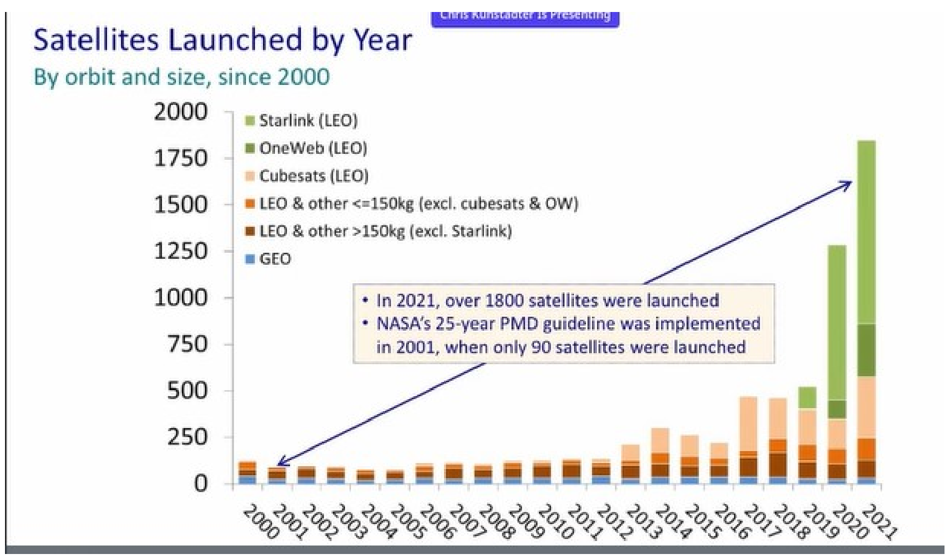
basis		column abundance, H_2O or OH	volume density
Maximum above exobase	collisionless atmosphere	3×10^{14} mol/cm^2	3×10^{7} mol/cm^3
LADEE mass spectrometer	4 km above surface	$\leq 10^{10}$ mol/cm^2	$\leq10^{3}$ mol/cm^3
comparable to or greater than $[H_2]$	$[H_2]$ ~10^9–10^{10} mol/cm^2	10^9–10^{10} mol/cm^2	10^2–10^3 mol/cm^3
micrometeoroid dominated	<100% H_2O	$<10^{12}$ mol/cm^2	$<10^{5}$ mol/cm^3
solar wind dominated	<100% efficiency	$<10^{13}$ mol/cm^2	$<10^{6}$ mol/cm^3
mineral hydrate concentrations	total surface reservoir ~10^{19} H_2O/cm^2	3×10^{16} mol/cm^2	3×10^{9} mol/cm^3

Gray shading indicates abundance less than an estimated H_2O detection threshold of ~3×10^{11} mol/cm^2 in a two week mission.

Volatile species abundance will be evaluated by high resolution (heterodyne) spectroscopy of spectral absorption features against a backlight source. Calibration measurements of the local atmosphere will target an internal source as well as nearby ground or human-made objects.

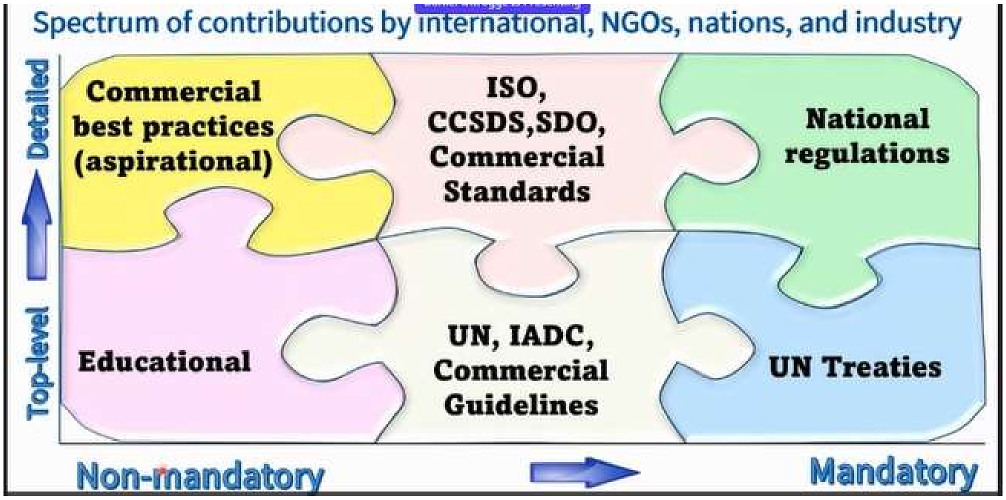
For decades, the International Space Station (ISS) has provided a distinctive platform in low Earth orbit for experimental research. The Dragon spacecraft carried a wide variety of science investigations to the International Space Station on SpaceX's CRS-5. Tobias Niederwieser is a research associate at BioServe Space Technologies within the University of Colorado Boulder where he helps to design, build, and test payloads for scientific research in the space environment. Key projects that have flown on 5 different missions on platforms include: AEM-E - a life support system for the launch of 40 mice onboard the Cygnus spacecraft for 10 days towards the ISS, SABL - three smart life science incubators operating continuously onboard the ISS for the last five years supporting 12+ high-impact science experiments per year, And, PLASM, an automated experiment apparatus currently under development for a yeast radiation study is slated for an onboard Orion mission during the Artemis-1 test flight around the Moon. The Space Automated Bioproduct Lab (SABL) is an EXPRESS locker-sized incubator developed by BioServe Space Technologies for use on the International Space Station (ISS). SABL utilizes the EXPRESS Moderate Temperature Loop (MTL) as a thermal sink for the four thermoelectric coolers (TECs) and avionics. Thermal feedback control and safety monitoring are implemented using a suite of sensors that interface to an NI sbRIO-9636 data acquisition and control computer. Performance of the engineering unit was characterized to verify thermal models of operation, cooling/heating times, and robustness against uneven internal heat loads and off-nominal operation.

Technical papers presented at the Improving Space Operations Workshop 2022 described space platforms which require launch vehicles to deploy into orbit. With much of the aerospace industry being developed and operated by private startups in the commercial sector, constellations of hundreds of smallsats have enabled space operations to be managed at lower costs and with smallsat interoperability such that mission efficiencies are realized.



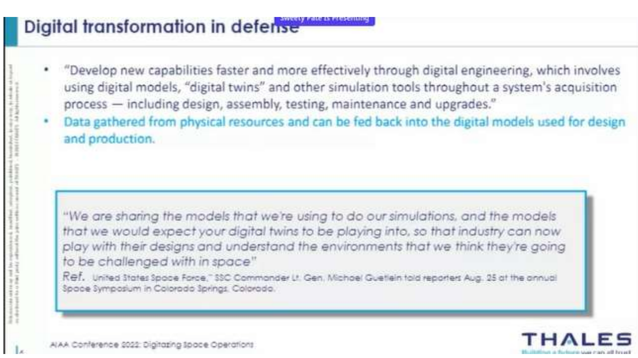
Adam London, founder of Astra, reviewed how his startup recognized a need for smaller launch vehicles to deploy cubesats on orbit. With venture capital support, after three trials and design upgrades Astra is on its way to build space platform for direct services to customers, upload programs and algorithms to orbiting smallsats and integrate sensor technology into the constellation system.

Smallsat interoperability is made more feasible with their COTS availability. At the same time, worldwide satellite operators are the primary managers of space operations, hence the need for their adherence standard best practices. Daniel Oltregge, Director, Integrated Operations and Research, COMSPOC Corporation, illustrated how developing best practices is a collaborative effort of multiple agencies who agree to advance their compliance towards regulation.



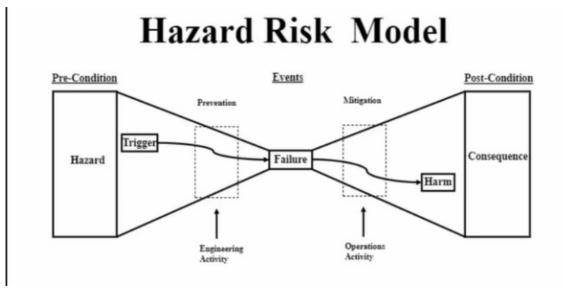
Orbital citizenship is just one of the organizational responsibilities. Operational alignment to national agenda and technology roadmaps are other demands. As space operations expand beyond near-Earth through deep space to the Moon, satellite operations will become increasingly autonomous.

Helene Bachatene, Vice-President, System Key Technologies CTO of Thales (France), spoke of the inevitability of space computers, space submarines. With less reliability on ground station uplinking commands/satellite downlinking data, Bachactene believes the focus should be enhancing satellite autonomy with edge computing. Orbital Edge Computing (OEC) architecture supports edge computing at each camera-equipped nanosatellite so that sensed data may be processed locally when downlinking is not possible. Network cache refers to an in-network storage that contains the content request by or relevant to edge users. In-network storage will require digitizing space operations.



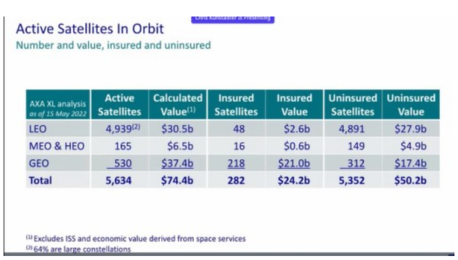
Other presenters noted uncertainties throughout the life cycle of satellites and their operations.

According to Ben Jurewicz performance risk needs management both during engineering activities and operations.



Isaac Passmore referenced the Covid Pandemic most of the ground station was quarantined and mission support to normal space operations prominently was imposed. First, satellite telemetry was managed so that much of what was logged was filtered so that only critical issues would be directed to subject matter experts for problem solving.

There are many operational uncertainties best risk-managed. Christopher Kunstadter, Global Head of Space division, AXA XL, noted the FAA requirement that all launches be insured; on-orbit insurance is optional. Satellite operators can afford to forego insurance since a smallsat loss can have its function easily replaced within the constellation.



Active Satellites In Orbit

Number and value, insured and uninsured

AXA XL analysis as of 15 May 2022	Active Satellites	Calculated Value[1]	Insured Satellites	Insured Value	Uninsured Satellites	Uninsured Value
LEO	4,939[2]	$30.5b	48	$2.6b	4,891	$27.9b
MEO & HEO	165	$6.5b	16	$0.6b	149	$4.9b
GEO	530	$37.4b	218	$21.0b	312	$17.4b
Total	**5,634**	**$74.4b**	**282**	**$24.2b**	**5,352**	**$50.2b**

[1] Excludes ISS and economic value derived from space services
[2] 64% are large constellations

Conclusion

Scaled to size, smallsat constellations have provided an equivalent-valued, affordable option for space missions. Venture capital has afforded startups in the private sector to embark and grow space operations in large numbers. Satellite operators are challenged by LEO being populated with orbital debris and mission uncertainty due to space weather. A conceptualized PRRISM satellite was designed to remove orbital debris. And, space weather risks disruption of global commerce with telecommunications, GPS, and other satellite services. For the most part, the magnetosphere deflects solar wind particles, hence a protective barrier for near-Earth operations. Lunar operations will not be afforded a protective magnetosphere. A SSOLVE satellite under development will study the processes of lunar surface water deposition in an experiment showing H_2O, HDO, $[OH^-]$ from both sun-facing and moon-facing views. As satellite operations increasingly become autonomous, space computing will command on-orbit operations. Digitizing operations will enable the AI/ ML need for greater autonomy.

Risk management of space operational uncertainty may avert hazards, but space insurance helps to leverage the financial liability.

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