Statement of
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to the
Committee on Commerce, Science, and Transportation
Subcommittee on Space, Science, and Competitiveness
United States Senate
on
Reopening the American Frontier: Promoting Partnerships Between Commercial Space and the U.S. Government to Advance Exploration and Settlement
July 13, 2017

Mr. Committee Chairman Thune, Mr. Subcommittee Chairman Cruz, Subcommittee Ranking Member Mr. Markey, and other members of this subcommittee, thank you for the invitation to appear before you today to share my view of some salient issues that affect orbital safety, space traffic, and the future of our nation's space exploration and exploitation program. It is an honor to be seated at this table with some of our world's Space sector giants. My name is Moriba Jah. I'm an engineer, scientist, and a technologist. The views I express today have been shaped through an 18-year aerospace engineering career in government, industry and academia. I started my career as a member of the technical staff of the NASA Jet Propulsion Laboratory. I navigated a variety of spacecraft to Mars and Asteroid Itokawa, and also developed advanced spacecraft navigation algorithms toward autonomy and improved orbital knowledge, beginning with Mars Global Surveyor and ending with the Mars Reconnaissance Orbiter mission. After JPL, I worked as a Civil Servant in the Air Force Research Laboratory, where I led the design, development, and implementation of algorithms that have successfully and autonomously detected, tracked, identified, and characterized man-made objects in space, so called "Resident Space Objects," to include orbital debris. My last position within AFRL was as the Mission Lead for Space Situational Awareness. Amongst my achievements, I was given the highest award that can be earned as an AFRL employee, that of AFRL Fellow. Currently, I am fortunate to serve on the faculty of the Aerospace Engineering and Engineering Mechanics Department, in the Cockrell School of Engineering at the University of Texas at Austin. At UT Austin, I lead a research program called ASTRIA focused on the design, development, and technical transition of astronautical sciences and technologies relevant to Spacecraft Navigation, Space Situational Awareness, and Space Traffic Management. I am a Fellow of several organizations and professional societies and serve as a chair and member of several major space-related national and international technical committees. However, I am here today as an individual and the views I express are mine alone. I'd like to also thank my wife Cassaundra, and children Denali, Inara, and Satyana for lending me to you, today.

Executive Summary

We have laws, regulations, and norms of behavior on our roadways, waterways, and airways. We classify and regulate traffic based upon things like size, maneuverability, weight, hazard potential, and others. An oil tanker is treated very differently than a kayak. A truck carrying hazardous fuel is treated quite differently than a Vespa scooter.

Do we have an equivalent Civil Space Traffic Management (CSTM) System? No. Do we need one? Absolutely. Why? Uncontrolled and unpredictable growth of the use of near Earth space. What form could a CSTM System take? What role should America have in it? This is what I am here to discuss.

To be clear, the question is not, "do we need a Civil Space Traffic Management system" but rather, "What form does such a system involve and how do we design, test, implement, enforce, and maintain the system."

Today, I'm going to address this problem by briefly establishing:

- Why we need such a CSTM system
- What could be the components of a CSTM system
- What are the next steps required to put this into effect

Regarding the "why" of us needing a CSTM System, I'll begin by saying that our Space Domain and Environment is no longer the sparsely-populated state-actor-dominant sphere of activity it was decades ago. Our need to explore and grow has motivated the commercial sector, epitomized by our own people the likes of Mr Jeff Bezos and Elon Musk, to discover the state-of-the-possible and turn that into our state-of-practice. This is exactly what we want to see happen and indeed foster and encourage. However, the U.S. is not the only country with growing activities in space. India, just recently broke the record for the largest number of deployed satellites in a single launch, 104 to be exact. Licenses are currently being sought for the launch and deployment of thousands of satellites, within the next few years. So, who is rigorously and comprehensively analyzing the growth of the Resident Space Object population and how does this affect Orbital Safety of Operations and the Long-Term Sustainability of Space Activities? The view of most space actors and investors is that it is someone else's problem! I vehemently disagree.

The Space Domain and Environment is still much like our Western Frontier of old. It suffers from a lack of monitoring, vast geographical sparsity, potential for "lawlessness", lack of environmental protection, etc. Space Piracy has likely already happened, is happening, and will happen so long as we lack the ability to comprehensively monitor all space activities. This unfortunate human behavior has happened in all other domains and to expect the Space Domain to be an exception is naïve at best. The problem is exacerbated by the fact that our space technology has made access

to space cheaper, which has brought greater numbers of space actors to participate in the space commerce sector, much like what the Transcontinental Railroad did for businesses connecting the East Coast with the Western Frontier.

The United States of America has developed, maintains, and distributes, to the rest of the world, the largest free record of cataloged man-made objects in space, so called "Resident Space Objects". This catalog is owned and operated by the U.S. Department of Defense, specifically our dedicated men and women of the U.S. Strategic Command (USSTRATCOM). Many organizations and entities around the world use these Orbital Safety products on a daily basis. However, for the growing needs and demands of the space community these products have been shown many times to be inadequate. They incur an increasing burden upon the USSTRATCOM primary mission, which is National Defense.

We need a CSTM system because:

- Orbital Debris experts worldwide agree that
    - Compared to what is being tracked in our USSTRATCOM catalog, the number of mission-damaging and debris-generating RSOs (1 centimeter in diameter and larger) is at least 100 times greater.
    - Two-Line-Elements (TLEs), which provide basic orbital information on RSOs, are insufficient to meet growing Orbital Safety needs because the theory is based on averaged motion and they lack any measure of uncertainty.
- We do not fully understand the reasons we cannot track more objects. All untrackable objects pose an unquantified level of threat or hazard to space operations and safety.
- For reasons of National Security, USSTRATCOM cannot be fully transparent in providing knowledge of where all trackable RSOs are located in space. This is at odds with efforts at the United Nations Committee On Peaceful Uses of Outer Space (UN-COPUOS) where we talk about transparency and confidence building measures (TCBMs) for collaboration.
- Russia has suggested the creation of a UN-developed and led effort to perform Space Traffic Management/Control. This is not a view accepted by everyone, but if we do not step up as leaders and provide a meaningful solution for others to join and follow, someone else absolutely will. It's only a matter of time.
- Europe is developing their own Space Situational Awareness (SSA) program and their own catalog of RSOs, as well as many other nations, in part because the USSTRATCOM products do not meet their SSA and STM needs and requirements.
- The number of RSOs is growing at a rate that is outpacing global governance measures for the space domain and environment.

What are the proposed components of a Civil STM System?

The CSTM Mission should:

- Assure the safety of operations in space.
- Maximize, foster, and incentivize the use of commercial capabilities and data sources.
- Provide transparency, advocacy of informed guidelines, and safety services as a public good to preserve the space environment for continued, unhindered, and uncontested access and use of space.

The CSTM Primary Functions would be to:

- **Observe and Monitor:** Space Domain and Traffic Observations, Space Situational Awareness (SSA)
- **Track and Catalog:** Identify, Characterize, and Catalog Objects; Relational Statistics, Catalog Updates, Traffic Attribution, Achieve Track "Custody"
- **Analyze and Inform:** Information Dissemination, Safety Products, Conjunction Data Messages

What are the next steps required to put this into effect?

- Provide the FAA with an adequately funded and resourced mandate to: 1) use their STM Pilot Program to work with the community and provide the first instance of a Civil STM system and 2) begin collecting and exploiting space object (e.g. non-SSN tracking) data for orbital safety purposes, with an eye to do this via a Public-Private-Partnership.
- Create or expand the existing role of NASA to: 1) lead the technical requirements for a robust, effective, and meaningful CSTM System, and 2) to work closely with other government agencies, industry, and academia.
    - Conjunction Analysis concerns itself with predicting close approaches between any two RSOs; it is a growing and changing field, and research into new methods is critical to keep up with the rapidly changing and marginally predictable space environment. NASA already has a research investment in this area (the CARA Program at Goddard Space Flight Center) that can be leveraged along with 30+ years of developing and executing this capability for use by civil space operators. It is government's role to retire risk, invest in Science and Technology (S&T) Research and Development (R&D), and share the results with the community to encourage growth.
- Invest in and expand the role of University Affiliated Research Centers (UARCs) as foundational, dedicated, and focused government-academic partnerships to solidify science and technology (S&T) research and development for critical space-related core technical competencies and technology risk-retirement needed by the U.S. Space Exploration program and Commercial Space Industry.

- Engage and craft mechanisms for Industry to get their investment and participation in a CSTM System:
    - Satellite manufacturers
    - Satellite launch providers
    - Space Insurance Brokers and Providers
    - Commercial Space Situational Awareness Providers
    - Space Angel Investors and Venture Capitalists
    - Space Service Users

Mr. Chairman, in the years since the end of World War II, American Exceptionalism has set standards to which the world has aspired. Right now, today, the world needs leadership in this issue. Implemented effectively, Space Traffic Management will provide secure access to space for our critical national infrastructure. It will guarantee America can lead the world in the commercial exploitation of space, and that America can maintain its lead over the world in space exploration and space science. This committee could provide that leadership, and the opportunity to act is before you.

Narrative

In my vast travels around the globe, speaking to and collaborating with space scientists, engineers, and policymakers, it is evident that "American Exceptionalism" is still invoked and desperately yearned for, by the many. America's leadership in the space domain, underscored by taking on and delivering upon what seemed to be an impossible feat, to send humans to another celestial body and return them safely, has inspired not only our great nation, but an entire planet, and seeded some of the world's most creative and innovative ideas.

Exploration is critical to who we are as a species; it drives our growth and evolution. When our minds and bodies are idle, we tend to self-defeating behaviors. What brings out the best in Americans? Rising to great challenges, and working as a nation to overcome them. What got Americans to the Moon and back, safely and repeatedly? Government, Industry and Academia working seamlessly, together. No one sector could do it by themselves.

The US Strategic Command (USSTRATCOM) currently has over 24,000 records active in its space situational awareness database, commonly referred to as the Department of Defense "catalog." Of these, well over 18,400 records correspond to well-tracked, well-understood RSOs in Earth-centric orbit, roughly 1,300 of which are operational satellites; the rest are so-called "space junk." The remaining records in USSTRATCOM's active space situational awareness database are not as well-tracked or understood, which creates uncertainty when operational satellites are screened against them to identify possible spaceflight safety hazards, or conjunctions. The number of RSOs is increasing given an increase in launches, and on-orbit breakup events (i.e. when one RSO collides with another, a satellite explodes, or breaks on its own

due to space aging and material fatigue and stresses). If we could track every detected object, we could wrap a sensible Space Traffic Management system around that and even develop empirically-based policies and regulations. Unfortunately, it is hypothesized that we can only track a few percent of the total number of RSOs that can cause loss, disruption, or degradation to critical space services, capabilities, and activities. In other words, we have an orbital iceberg equivalent of sorts. The ability to track an object in space depends on two main factors: our ability to detect the object AND our ability to uniquely identify the object. This is to underscore that an object that is detectable does not imply it is trackable, and this is a critical distinction to make moving forward.

Tracking an object means that we know where it was, is, and have some idea of what it is and where it will be. Think of how we track air traffic, where the aircraft is in the custody of someone who monitors its motion and relationship to other aircraft. The following Figure (1) puts into perspective the problem we face in our inability to track more of the objects we can detect. It was generated from real data collected by the U.S. Space Surveillance Telescope, about to be shipped to Exmouth, Australia. It is worth mentioning that while we will soon have a long-awaited Space Fence on Kwajalein, the results are likely to be much like with the Space Surveillance Telescope, as seen in Figure 1. When one has an exquisite sensor and it's unique, you'll get very accurate observations during a very small part of the total orbit and you'll be observing things that other sensors will not or cannot. Think of a hula-hoop. An exquisite sensor is having one hand on this hoop. Think about the variety of ways in which the hula-hoop can rotate if you only grab it with one hand. This is like the ambiguity you will have with a unique and exquisite sensor. It will help but you'll have a large number of objects that you can detect but will be unable to track.

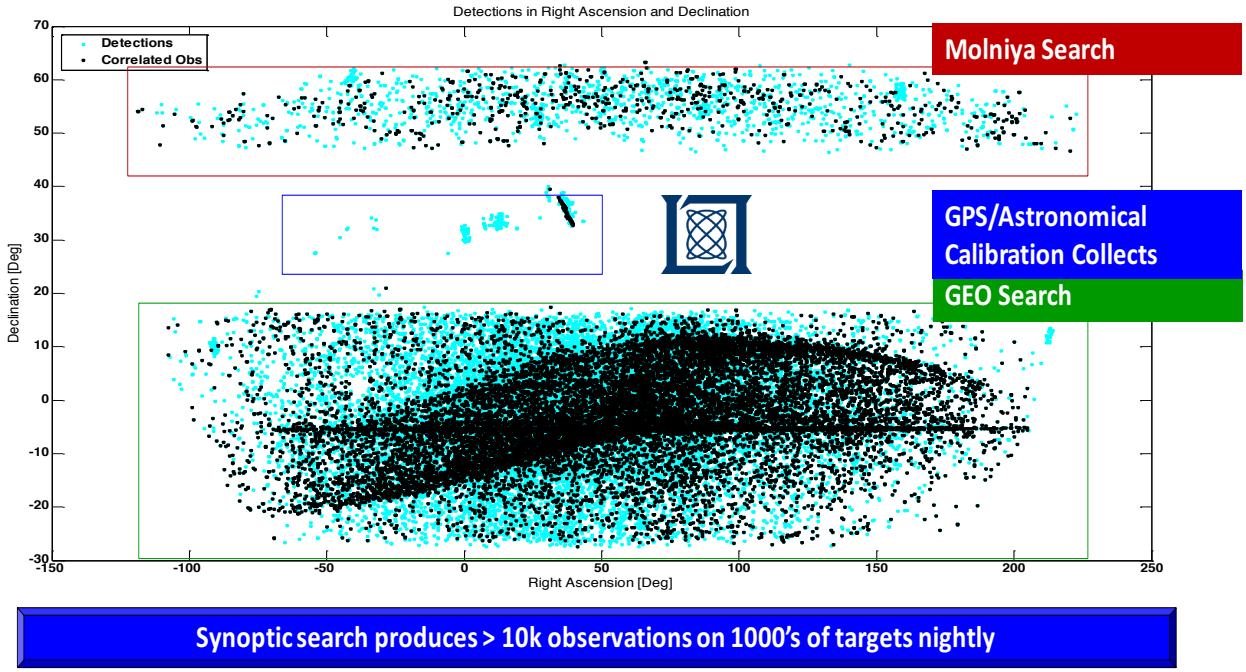

Figure 1. A Single Night's Worth of Resident Space Object (RSO Detections (for various orbital regions) from the U.S. Space Surveillance Telescope (SST) in New Mexico. Detections (dots) that are Black are those believed to be from known (cataloged) RSOs. All else (Cyan) are Detectable but Untrackable RSOs.

So, what prevents us from doing better at tracking objects in space? First, we don't have ubiquitous observations, meaning we don't persistently detect all objects all of the time. In fact, we generally have very sparse observations on any given object in space. Globally, we do not share observational data as a community. This lack of data sharing is perhaps the single most problem in us having a more robust space traffic monitoring and management capability. Secondly, every single object in the world's largest space object catalog (that of our DoD) is represented and modeled as a sphere, a cannonball in space! Needless to say, there aren't many man-made cannonball-shaped objects in space. Only those space objects whose motion is not significantly different from that of a sphere in between observations, are ones we can "track." Gravity is what I call an equal opportunity accelerator: just tell me where you are and I will tell you your acceleration due to gravity, regardless of your size, shape, material constitution, orientation, etc. However, there are non-gravitational forces experienced by objects and all of these depend on the object's physical characteristics. Thus, the lack of a rigorous object characterization and classification scheme is a strong contributor to our inability to track more objects in space. When we wish to understand any population of things, we first "tag" individuals in that population and then "track" these individuals through time, space, frequencies, and evaluate their interaction with other individuals and their environment. We formulate hypotheses, test them, and draw conclusions based upon evidence. We do not do this, rigorously and scientifically, for space objects. If we wish to someday have a Code of Conduct for Outer Space, we will need to know how many classes or species of space objects

there are, and how each class moves, behaves, is influenced by the local environment, etc. Trucks carrying hazardous fuel are regulated differently than Vespa scooters, Oil Tankers on our seas are regulated differently than kayaks and canoes. So, why would we treat all things in space as the same thing…cannonballs? The following figure (2) is a cartoon to show the difference between the limitations imposed by assuming space objects to be cannonball-like versus what they actually are like.

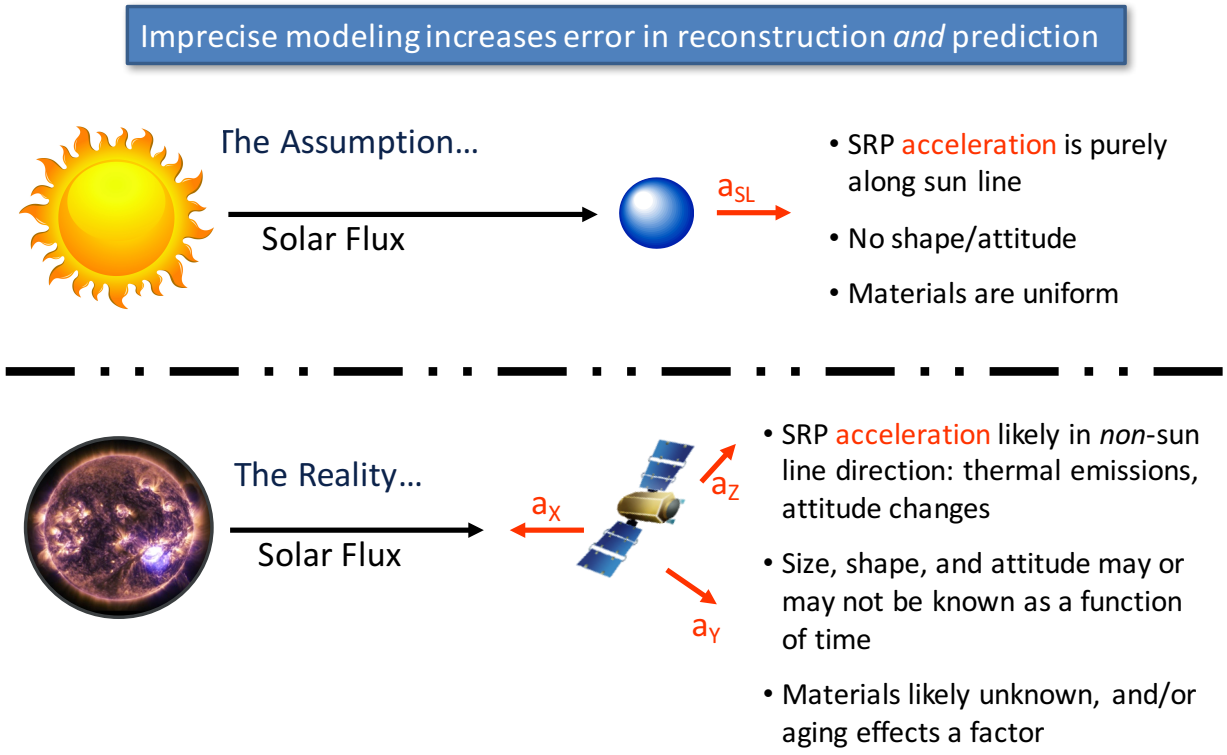

Figure 2. Difference between the motion experienced by a spherical (cannonball-like) space object and a satellite with realistic size, shape, orientation, and material properties. For the sphere, the acceleration due to the sun's effects are unidirectional. In reality, our tracking data informs us that objects experience accelerations due to the Sun's effects in 3-dimensional space (multi-directional).

Lastly, regarding our inability to track more objects in space, are the mathematics and physics we use to process the observed data and infer physical quantities regarding these objects. It really matters…call these our algorithms. Our representation of uncertainties is demonstrably and inarguably oftentimes flawed, unrealistic, and inconsistent amongst our software and tools. The following figure (3) shows a picture our current problem with having multiple detections at multiple times and having to find clever methods of uniquely identifying objects in order to make them go from detectable to trackable. Most RSOs are defunct and therefore do not self-report their identities.

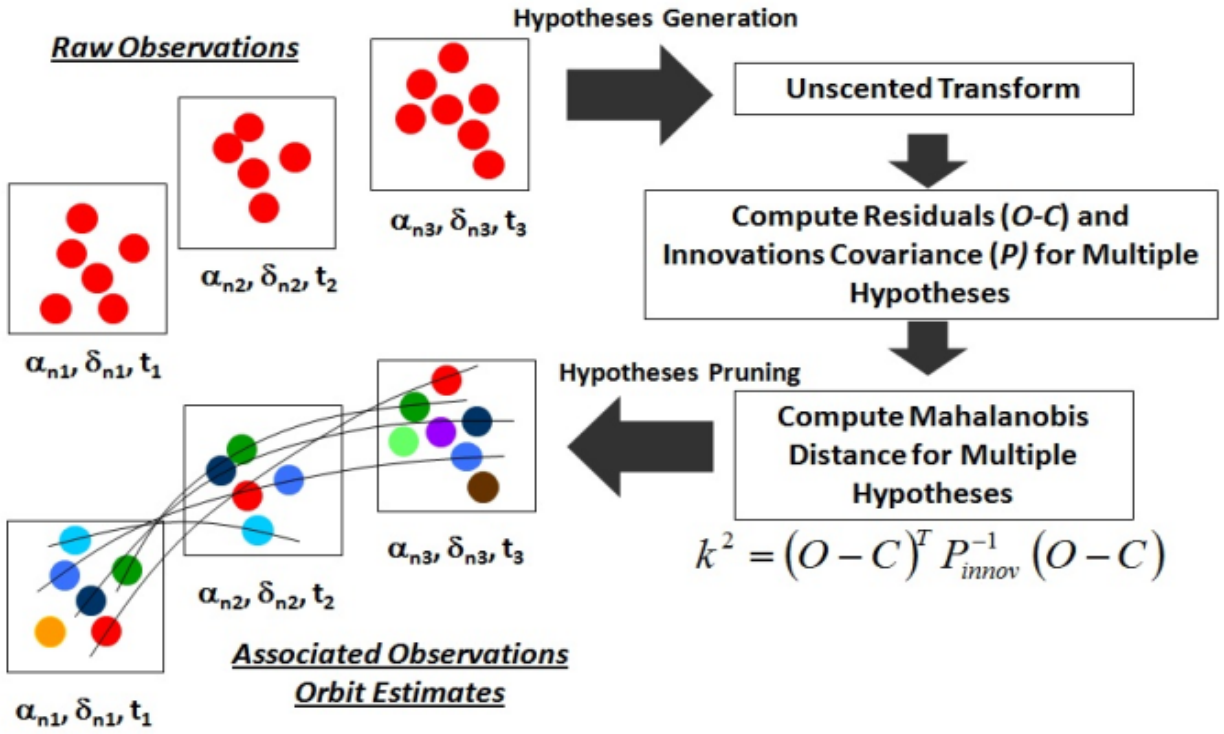

Figure 3. How to Uniquely Identify Space Objects from a Set of Unidentified Detected Objects in Order to Make Detectable Objects, Trackable. The method shown here is one of Multiple Hypothesis Testing as a mechanism to decide which detections should be paired to which objects.

If the RSO population was held constant, I'd say we'd have more time on our hands to figure this all out. However, our global space environment is on a path of suffering a *Tragedy of the Commons* given that our Geospace belongs to all humans and that many space actors behave according to their own self-interests without full consideration of the impact of their space operations and activities on the whole environment…our Space Commons!

As the cost of access to space is decreasing, the number of space actors is increasing. It's like what the Transcontinental Railroad did for helping businesses explode, connecting the East Coast and Western Frontier. Just a few months ago, we saw a record-braking 104 satellites being deployed by India's PSLV space capabilities. Unfortunately, while they did assess potential collisions amongst these 104 satellites, no one performed analyses of potential collisions between those 104 newly deployed satellites and the remainder of the current RSO population. OneWeb just recently received the "green light" from the FCC to equip LEO with over a thousand satellites that will aim to provide global internet. SpaceX will surely be soon to follow with a planned ~4000 satellites.

As experienced in the Western Frontier of old, the environmental impact of runaway mining and prospecting was harsh and detrimental in many instances. Examples are mercury poisoning, silt in our water sources, etc. Our space environment is becoming much more commercially driven and

populated. Many "New Space" companies or start-ups are getting significant investment from Angel Investors and Venture Capitalists who are focused on getting a Return On Investment (ROI) within a few years, believing Space Traffic and Orbital Safety to be someone else's problem. I have personally found an absence of space operations expertise amongst the workforce driving some of these "New Space" ventures, causing me further concern regarding orbital safety and long-term sustainability of space activities. There is a mentality of "take risks and fail often." While this worked well for software companies in Silicon Valley, we can't afford to have this exact mentality in space.

Existing orbital safety methods, information, and processes are not designed to handle the current space traffic conditions let alone the planned activities with larger satellite constellations. There are no standard "rules of the road" for space operations and activities, and we should avoid creating these in a vacuum, absent informed science and technology. While USSTRATCOM provides orbital safety products to the world for free on behalf of the U.S. government, for very good reasons it cannot simultaneously be fully open and transparent and this is a self-evident obstacle to meaningful international collaboration and partnership due to its defensive responsibilities. I'm in full agreement with Gen Hyten, Gen Raymond, Rep Bridenstine, Rep Babin, and others in that a Civil Space Traffic Management (CSTM) system makes good sense to enabling more innovative U.S. space operations into the future.

A government-only solution makes no sense given that transparency, open sharing, ease of working with international partners, etc. is a strenuous situation for the U.S. government at best. The government also lack the full spectrum of expertise required to do this job exceptionally well. A commercial-only solution makes no sense because no single entity has the solution to such a multi-disciplinary problem, nor does it have all the expertise required. Moreover, funding a company or consortium of companies to do this is likely to result in an inability for external input to be well received and incorporated. I've witnessed and experienced this, many times, as a Civil Servant.

Therefore, I propose that the best solution moving forward would be to create a Non-profit Civil Space Traffic Management (CSTM) Public-Private-Partnership (PPP) that will:

- Accelerate the pace and reduce the costs of CSTM development by modernizing approaches to SSA and STM, with focus on long-term sustainability of space activities, through the creation of new federated data standards, measurement standards, models and ontologies, open source software, and data management and analysis techniques that aid in the scientific evaluation of the efficacy and safety of space operations, and attendant policies.
- Act as a neutral public-private entity that could create consortia of industry, academia, and government for collaboration and sharing of databases, computational techniques, and standards.

- Operate a CSTM system that provides the accuracies and products necessary to safely enable innovative and non-traditional commercial uses of space.

The CSTM Mission should be to:

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The CSTM Primary Functions would be to:

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The Tenants of a Non-Profit CSTM Public Private Partnership (PPP) would be to provide and incentivize:

- **Open observational data** - All collected or acquired data will be made open and available for 3rd party analysis to improve learning and enable high Quality of Service domain analysis.
- **Open catalog of space objects and events** - All derived conclusions from CSTM data will be made open and available for 3rd party verification and peer-review of results and conclusions.
- **Open Safety Advisory Services** - As these services are intended to be a global public good, they will be made available to the world.
- **Open and objective verification of data and analyses** - As the CSTM capabilities and processes improve, impartial feedback will be made available to all service providers in the spirit of achieving increasingly effective Quality of Service.
- **Open Market** - It is not the role of the FAA to define the economics of the data and/or analysis marketplace. The intent of the CSTM PPP is to empower industry to stay involved in the provision of service to all space domain actors.
- **Open Workforce Development** - It is to the benefit of all for the specialized skills required of effective space traffic managers to proliferate globally. To this end this CSTM PPP will support mechanisms which result in the education of additional skilled space traffic managers and analysts.

The Benefits of a CSTM PPP are that it would:

- Provide standard and benchmark data sets that enable quantifiably consistent comparative analyses between competing tools, techniques, and algorithms.
- Provide the government with a transparent mechanism to guide and exploit CSTM activities and capabilities AND a sustained/focused investment in STEM education.
- Provide industry with a free foundational CSTM service and a marketplace of focused, cost-shared and openly available sciences and technologies that it can "pick up" and operationalize/commercialize for its own profit.
- Provide academia with a sustained scientific and technological CSTM research and educational investment, to ensure that the U.S. is stocked with capable and skilled workforce to handle the scientific and technological problems of tomorrow.

How does industry profit from such an activity, financially? It can easily wrap profit-making services around the foundational "for public good" layer of orbital safety services and products. It lowers the bar for entry for new space initiatives as they don't need to shoulder the burden of self-providing of these orbital safety services. It's like the benefit of the U.S. developed, owned, and operated Global Positioning System (GPS)! Think of not only the paradigm-changing science but explosion of commerce that has resulted from this U.S. Government investment and service. Many companies have developed profit-making applications which exploit the layer of foundational service provided by GPS.

I also propose that the FAA's Center of Excellence in Commercial Space Transportation be leveraged as an existing mechanism under which a larger academic consortium could be assembled, invested in, and properly leveraged for Space Traffic Management. The current FAA CoE CST membership would need to be expanded upon and increased but focused funding would need to be appropriated and delivered to the CoE with a strategic roadmap on how the S&T is developed and transitioned to both government and industry. Several University Affiliated Research Centers (UARCs) should also be invoked, invested in, and leveraged, to be foundational partners in this STM research and development effort. The UARCs could provide foundational capabilities and sciences to the FAA CoE CST and those CoE academic members could then focus them uniquely on STM needs and requirements, working closely with the government and commercial communities.

Two remaining points for me to make are (1) our society has become too risk averse. We say that we want to push the boundary of exploration except that we are intolerant to failure. This is a gross inconsistency. You can't have leading edge exploration with zero failure. Failure should be calculated but embraced as a necessity of pushing the limits of our science and technology. We maintain a leading edge by assuming and embracing risk. We would have never gotten man to the moon and back, safely, without taking risks! Had we not achieved this lunar exploration first and convincingly, our world would be quite different today, and I'm not sure it would be for the better.

(2) I have been asked if the U.S. government should take great strides in providing security clearances to as many academics as possible. My answer is, "no." Instead, put the effort in declassifying material that should have never been classified to begin with and material that no longer requires it. In other words, make as much information available to the largest pool of smart and passionate people as possible, without sacrificing national security needs, and our country will emerge victorious!

The motto of my research program at UT Austin, ASTRIA, is:

Ex Coelestis, Scientia…Nihil Arcanum Est! This loosely translates to, "from the heavens, knowledge…nothing hides!"

As Ever,

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