Conceptual Development of a Civil[1] Space Traffic Management System Capability

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CONFERENCE PAPER

In support of a possible transition of the space safety aspects of space situational awareness activities from the US Department of Defense to a US civil agency, The Aerospace Corporation has been working to develop a possible test bed of space traffic management concepts. As a starting point, we have considered an enumerated set of "guiding principles" for a civil space traffic management system with the ability to provide state-of-the-art space flight safety services to commercial and foreign satellite operators as a public good. The considered concept, a system of systems, would be innovative and maximize the use of existing and new commercial offerings for data, analysis and operations. Open and transparent by design, the "learning" organization would allow for rapid upgrade cycles of technology. Operating cooperatively with existing and potentially new space situational awareness architectures, both foreign and domestic, the system resources would ensure the protection of sensitive information.

1. INTRODUCTION

The topic of "Space Traffic Management" (STM) is currently being widely discussed at various international events.[2] [3] [4] [5] But what is it? Various definitions abound.[6] [7] We suggest a more operational definition emphasizing its activities, especially in comparison with the related topics of Space Situational Awareness (SSA) and Space Surveillance and Tracking (SST).

As seen in Fig. 1, STM in red shares many of the elements of SSA in blue, but when differentiating between STM and SSA, the focus is shifted from being about understanding the potential threat or "intent" of a space object to tracking positions along orbits – knowing where objects in space are located and where they are going. The objective is to enhance space safety by making accurate measurements of space object trajectories and predicting their future positions to avoid collisions when possible. Enhancing space safety includes tracking not just objects already in-orbit, but also objects scheduled to be launched and those re-entering the atmosphere. The focus is on safety of flight for space objects.

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[1] Here we define "civil" as a civilian US agency, overseeing the space activities of US-flagged commercial entities, and possibly other civilian US agencies' space activities.

[2] https://events.ph.ed.ac.uk/space-traffic2, accessed 12/1/17

[3] http://www.iafastro.org/events/iac/iac-2017/plenary-programme/space-traffic-management-global-challenge-to-protect-the-strategic-domain-of-space/, accessed 12/1/17

[4] http://iaassconference2017.space-safety.org/programme-overview/, accessed 12/1/17

[5] https://swfound.org/news/all-news/2017/09/swf-leads-discussions-on-commercial-ssa-and-space-traffic-management-at-2017-amos-conference, accessed 12/1/17

[6] International Academy of Astronautics (IAA) Cosmic Study on Space Traffic Management. Edited by Corinne Contant-Jorgenson, Petr Lála, Kai-Uwe Schrogl. Published by the International Academy of Astronautics (IAA) BP 1268-16. https://iaaweb.org/iaa/Studies/spacetraffic.pdf, accessed 11/13/17

[7] *Space Traffic Management*, W. Ailor, in Handbook of Space Security Policies, Applications and Programs. Schrogl, K.-U., Hays, P.L., Robinson, J., Moura, D., Giannopapa, C. (Eds.), Springer-Verlag, 2015, pp. 231-255

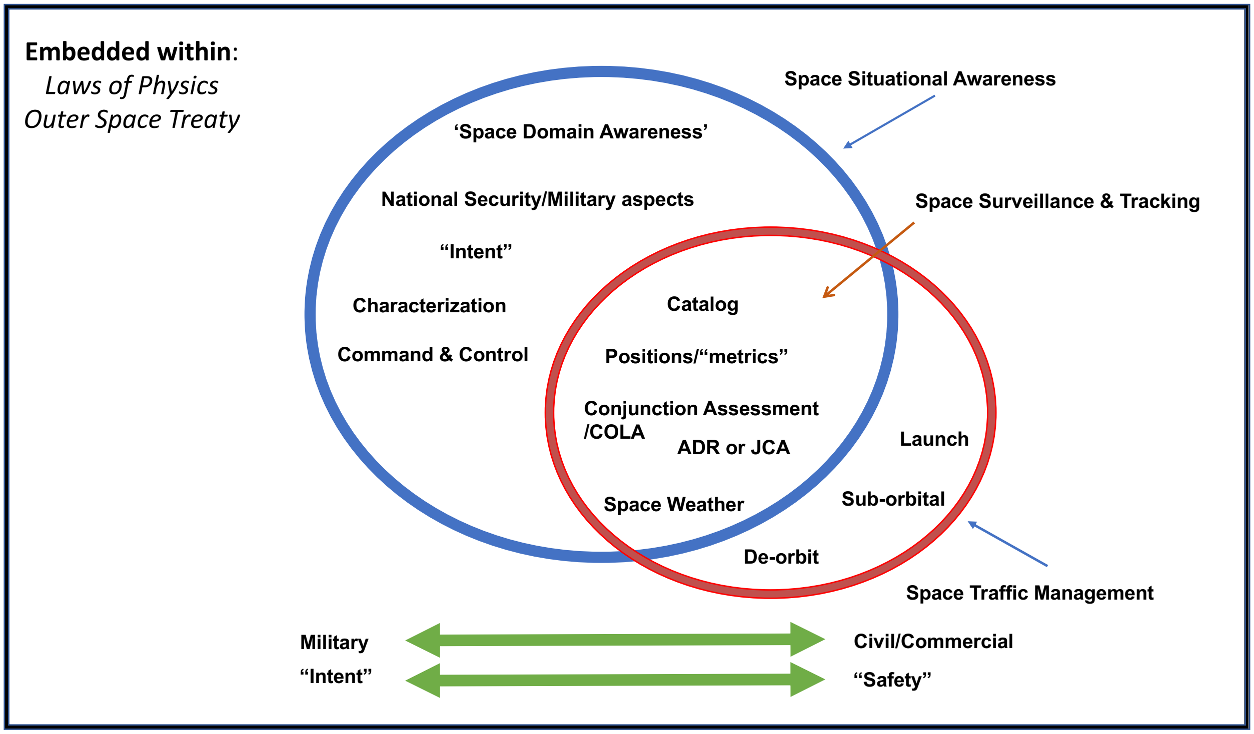

Fig. 1 compares and contrasts space situational awareness, space surveillance and tracking and space traffic management from the point of view of a practitioner, based on constituent elements[8]. While launch/sub-orbital/de-orbit activities are of interest to the military, they do not necessarily fall under the rubric of SSA, but the boundaries can be indistinct.

2. GUIDING PRINCIPLES

The Federal Aviation Administration Office of Commercial Space Transportation[9] (FAA AST) has studied and contemplated possible needs of a civil STM system. FAA AST has espoused a set of "Guiding Principles"[10] for how STM activities might be organized and conducted at a civilian agency ("CSTM"). A recent rendition of the guiding principles is listed below:

- Provide state-of-the-art services to commercial and foreign satellite operators that are accurate, timely and meet the needs of the user community
- Assure all data acquired by the CSTM system is accessible by the US Federal Government throughout the CSTM development and beyond
- Protect classified or sensitive U.S. space data and operations
- Operate cooperatively with existing Space Situational Awareness architectures, while maintaining the ability to function independently
- Maintain transparency with partnering nations and data users on data sharing, data security, services and long-term plans
- Provide an open architecture to enable observations from multiple sources, interchangeable software modules for processing and alternate approaches to predict and analyze potential conjunctions
- Maximize the use of data and services provided by non-government and commercial entities

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[8] Active Debris Removal (ADR); Just-in-time Collision Avoidance (JCA)
[9] https://www.faa.gov/about/office_org/headquarters_offices/ast/about/, accessed 12/1/17
[10] https://www.faa.gov/about/office_org/headquarters_offices/ast/media/6_space_traffic_management_plans.pdf, accessed 11/14/17. Although recent developments have the US Depart of Commerce responsible for CSTM, the guiding principles still have utility.

- Encourage innovation and incorporate improved capabilities and new technologies from both private industry and academia
- Provide safety products and services as a public good – the CSTM system will not levy fees for the products and services it provides

Unstated principles may also come into play, such as alignment with the U.S. National Space Policy[11] and existing international commitments (e.g., the Outer Space Treaty (OST)[12]) and bi-lateral data sharing agreements, as well as considerations regarding the cost of setting up and running the system.

3. A PROPOSED ARCHITECTURE

Let us take the stated, as well as unstated, Guiding Principles, and treat them as a set of 'requirements' or 'design guides' to be used to develop a concept for a civil space traffic management capability. Focusing on the highest levels of our system of systems, they may guide us in setting up a test-bed architecture to explore system efficacy and perform various system trades. Our goal is not to replicate legacy systems that may have a different mission from our stated guiding principles, but to custom design a new system that directly aligns with these guiding principles.

Fig. 2 shows a potential architecture for a Civil Space Traffic Management system. The foundation for the system is a basic *safety loop*, that seeks to acquire the best measurements of the positions of space objects from multiple sources, validate and process these measurements into trajectories, predict future positions of objects and provide warnings of potential collisions as necessary, all with multiple avenues for feedback into the process. Outputs would include observation sharing with other SSA and STM centers, including a catalog of space objects' trajectories, warnings to satellite operators and other interested parties, and quality and situational reports to the international space community.

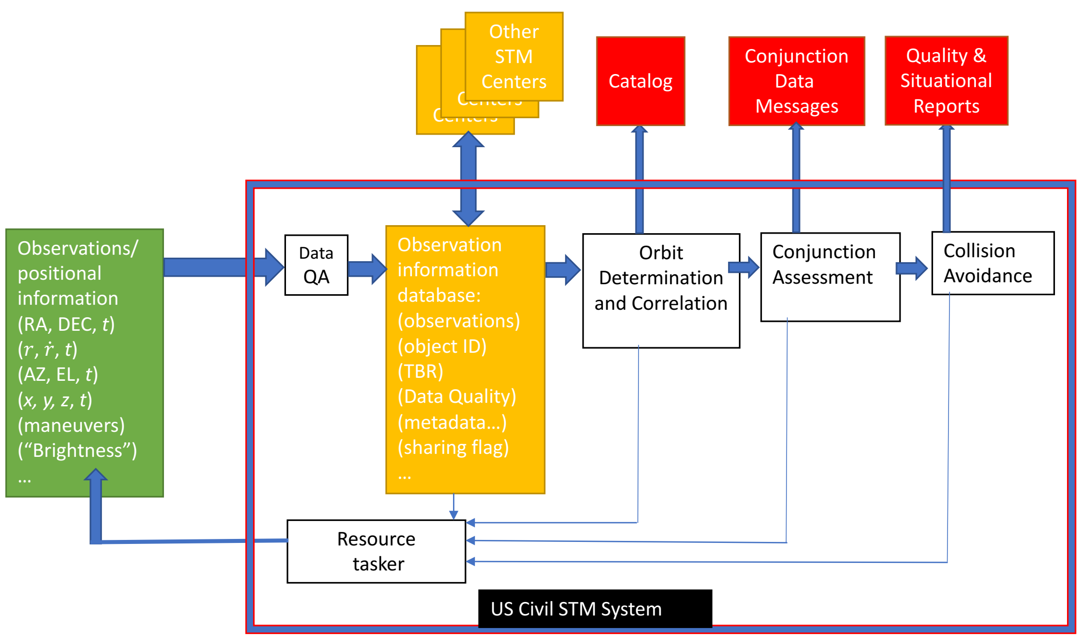

Fig. 2 shows a potential architecture for a Civil Space Traffic Management system. Green boxes represent an 'input,' red an 'output' and yellow both input and output[13]. Not shown are any DoD SSA elements; this system could potentially operate independently of DoD systems.

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[11] http://www.space.commerce.gov/policy/national-space-policy/, accessed 12/1/17

[12] http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html, accessed 12/1/17

[13] Data quality assurance (QA) occurs at almost every stage of input, output, and processing. For clarity of the graphic, these QA steps have been suppressed.

Accurate observations of space objects are fundamental to ensuring space safety. Observations "measure" the orbit of a space object, and generally the more measurements we have, especially high-quality measurements, the better we can describe the orbit. These measurements may originate from various distributed sensors (e.g., optical telescopes or radars), or be reported by satellite operators, with the information coming from radio-frequency (RF) ranging, or from on-board satellite Global Positioning System (GPS) receivers. Measurements may come from disparate sources such as CSTM-dedicated sensors that can be tasked by the CSTM System, and those that only contribute– perhaps from the US Department of Defense, universities, amateurs ("Citizen Scientists," who provide meteorological field measurements to NOAA[14]) or other entities. Operators may also provide their satellite maneuver plans, which may be useful when forming and maintaining satellite trajectories. Observations will also come via sharing with other SSA/STM centers that have their own independent sources of data.

To assure the quality of the observations, information sources and the data they provide must be vetted prior to being used or distributed. A quality assessment of the data should be performed based on various modalities (e.g., measured and estimated biases and uncertainties of the data source), and the data tagged with a quality assessment estimate. Data quality may be assured via a two-layered system. The first layer is to require that incoming data also include measurements of standard "calibration satellites," (or by other means[15], as appropriate). These are satellites that have very accurate published orbits against which a data source can be checked. These satellites include the Wide Area Augmentation System (WAAS)[16] satellites over North America, precision navigation and timing (PNT) satellites – GPS satellites, and other satellites that have suitably accurate orbital information available. Collections against one or more of these satellites should be part of a sensor's regular operations.

The second layer of assurance is to examine the data and uncertainties from a sensor against collections by other sensors of the same space objects, to look for outlying data. A large effort to develop this area was carried out by the Defense Advanced Research Projects Administration (DARPA) "OrbitOutlook" program.[17] Discussions with DARPA[18] have indicated that the techniques developed by OrbitOutlook would be freely available to a US civil agency for Space Traffic Management applications.

Upon vetting for quality, the observations (time-tagged positional measurements of a space object) would be entered into a database of observations, along with various metadata pertaining to the observation. These metadata may include the source of the measurement, any potential identifier of the space object, an assessment of the quality of the data, and potentially an indication as to how the particular measurement may or may not be shared with others. Additionally, sensitive information could be protected by implementing 'enclaves' that limit access to certain data.

We envision the project's database of measurements could at all times remain under direct program control. Yet to act cooperatively with other SSA/STM centers (foreign or domestic), it will be necessary to share measurements with these centers, consistent with national security needs, to allow for a "common operating picture." Rather than a centralized "hub and spoke" architecture, we envision, as one possible option, a distributed, multi-lateral "peer-to-peer" sharing architecture. An existing functional candidate we are investigating is the NASA/NSF-developed "International Virtual Observatory"[19] schema. It is important that this CSTM center be open and transparent regarding how it vets contributed and tasked observational data prior to inclusion in the shared database. Following the philosophy of "trust but verify," it is also crucial that the CSTM center have insight and knowledge of the quality assessment procedures for the sources of the externally shared data.

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[14] http://www.noaa.gov/office-education/citizen-science-crowdsourcing, accessed 12/1/17

[15] *Physics and Human-based Information Fusion for Improved Resident Space Object Tracking*, E. Delande, J. Houssineau, M. Jah, preprint submitted to Advances in Space Research, 22 February, 2018

[16] https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/, accessed 12/1/17

[17] https://www.darpa.mil/program/orbitoutlook, accessed 11/16/2017

[18] DARPA OrbitOutlook program manager, Lt Col Jeremy Raley, private communication, 4/13/17

[19] http://www.usvao.org/about-vao/index.html, accessed 12/1/17

One potential action that results from assessing the quality and the completeness of the observations and entering them in the shared data base is to determine which objects need additional observational measurement, using the sensors that are under the control of the project and can be commanded to make custom observations. This is a basic part of the safety cycle feedback loop, and would be a function of a "resource tasker" to help adjudicate between data needs and resource constraints. An important consideration is that the CSTM system have a set of sensors that can be tasked by the system to collect data as needed, for objects in all orbital regimes. The most likely source for tasked observations is the nascent commercial SSA services provider sector.[20]

With accurate observations in hand – collected, verified, contributed and shared, one can begin to create orbits for objects, and associate new observations with existing orbits. This allows for the creation and update of a catalog[21] of tracked objects, containing orbital elements and uncertainty "covariance" information. For transparency, one can also provide additional information such as how the orbit was calculated, and perhaps some indication as to the provenance of the data included in calculating the orbit. As the goal of CSTM is primarily space safety, the catalog contents may be limited to mainly orbital information, which could be in an international standard description.[22] We would also expect to include a set of lower fidelity orbit information, the so-called two-line element set (TLE), for continued support of legacy software that uses TLEs. An action of the orbit determination process could be to discern what additional observations from the tasked sensors would enhance orbit knowledge, either from a separate site for geographic diversity or at different phases in an orbit, and feed these requests to the resource tasker.

The penultimate step in the safety cycle, with orbital information on a set of objects in hand, is to begin to perform conjunction screening and assessment. This entails propagating the orbits for the various objects in the catalog forward in time, to calculate their future positions and uncertainties, to see if there is a point of closest approach (POCA) between two objects' orbits that fall within certain criteria, such as some measure of the estimated positional uncertainties. As a result of screening, warnings of potential collisions will alert satellite operators. These conjunction data messages[23] will go to other interested parties as well if the conjunction involves only non-maneuverable space objects. In addition to notifications, an important action from this step is the tasking of additional observations to reduce the uncertainties of the orbital information of the two objects, which may lead to either a rescission of the warning, or its continuation.

The final step in the proposed safety cycle is to evaluate the accuracy of the conjunctions our system predicted, and what, if any, collision avoidance occurred on the part of the maneuverable object. This entails further tasked observations of the two objects as they move through the predicted POCA. This allows a quality feedback of the prediction accuracy, and any behavior patterns in maneuverable objects (e.g., Was there a maneuver? When did it occur? In what direction?). An important output of this stage for transparency and confidence building in the CSTM system are summary reports that may be published for the benefit of the international space community, including frequency and location of close approaches, statistics on the quality of predictions, analysis methods employed, etc.

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[20] The astronomical research community is also a source of space object observations, as data on satellites and space debris 'pollute' the observations of astronomers, and are considered 'by-catch'. Additionally, some astronomical telescopes are utilized to collect SSA data by university researchers, but their efforts are to further research objectives, and their work paradigm is generally at-odds with collecting tasked observations for a CSTM system. Prof. Thomas Schildknecht, University of Bern, private communication, 31 January 2018

[21] Logically, it makes sense to create a "catalog", or summarized output of tracked space objects, at this point in the data flow, and it would be useful to the internal safety cycle. However, a recent US government policy directive (Space Policy Directive 3) instructs the DOD to retain the creation and maintenance of the official, released catalog, as a continuation of current practice. Thus would this 'catalog' actually be characterized more appropriately as an unofficial, unreleased internal work product. National Space Policy Directive-3, National Space Traffic Management Policy, issued 6/18/2018. https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/, accessed 6/20/2018.

[22] https://public.ccsds.org/Pubs/502x0b2c1.pdf#search=orbit, accessed 12/1/17

[23] The Consultative Committee for Space Data Systems, "*Recommendation for Space Data Systems Standards: Conjunction Data Messages*," recommended standard CCSDS 508.0-B-1, Blue Book, June 2013

Likely venues for publicizing this information include fora such as the NASA orbital debris quarterly newsletter,[24] as well as presentations[25] made to the UN COPUOS STSC,[26] among others.

The above schema provides for a basic space safety cycle with feedback. It fuses observations, shares data, determines and maintains orbits from the measurements, provides for the publication of a catalog of orbital information on space objects, and provides warnings of possible collisions. But it is also a source of information, a "validated data repository,"[27] for additional value-added space safety applications[28] that could be provided by third parties. For example, in determining the location of a ground-based source of harmful satellite radio-frequency interference, "jamming," whether intentional or not, a standard commercial[29] technique is to use "two satellite geo-location."[30] To reduce the error ellipse of the location on the ground of the jamming source, one needs the most accurate orbital elements for the two satellites. This information could be made available to service providers. Likewise, having accurate current and archival knowledge of a particular space object could help an operator or service provider diagnose an anomaly. Additionally, many useful but at present unknown space safety applications could be developed to take advantage of this information. This support of commercial activities will need to be balanced with national security needs, such as the need to protect sensitive US satellite information.

4. FULFILLING THE GUIDING PRINCIPLES

In section 2 we listed the stated guiding principles, which give us a set of goals for our conceptual system-of-systems architectural design. Our concept's design is compliant with the fulfillment of these goals. Certain goals may only be fully realized via policy, however, such as providing space safety information without user fees.

How well does our concept align with the stated guiding principles?

- *Provide state-of-the-art services to commercial and foreign satellite operators that are accurate, timely and meet the needs of the user community.*
  - State of the art, based on intensive measurements of space objects
  - Incorporates operator data and maneuver plans
  - Interfaces with non-USG users
  - Emphasis on positions and trajectories of all space objects, de-emphasis on their identity
  - Machine-to-machine data sharing
- *Assure all data acquired by the CSTM system is accessible by the US Government throughout the CSTM development and beyond.*

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24 https://orbitaldebris.jsc.nasa.gov/quarterly-news/newsletter.html, accessed 12/1/17

25 http://www.unoosa.org/oosa/en/ourwork/topics/space-debris/index.html, accessed 12/1/17

26 United Nations Committee On the Peaceful Uses of Outer Space, Scientific and Technical Subcommittee, http://www.unoosa.org/oosa/en/ourwork/copuos/comm-subcomms.html, accessed 12/1/17

27 American Institute of Aeronautics and Astronautics (AIAA) Board of Trustees, "Space Traffic Management (STM): Balancing Safety, Innovation, and Growth." An Institute Position Paper, October 2017

28 *Commercial Space Situational Awareness – An investigation of ground-based SSA concepts to support commercial GEO satellite operators SSA*, M.A. Skinner, *et al*., Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, held in Wailea, Maui, Hawaii, September 2013, Ed.: S. Ryan, The Maui Economic Development Board

29 *Interference Geolocation Techniques, Introduction and Basic Requirements*, G. Baraglia, ITU Workshop on Harmful Satellite Interference, Limassol, Cyprus, 14-16 April 2014

30 *Application of a Dual Satellite Geolocation System on Locating Sweeping Interference*, M.H. Chan, World Academy of Science, Engineering and Technology, International Journal of Geomatics and Civil Engineering, Vol. 6, No. 9, 2012, pp. 1029-1034

        - Virtual Observatory (or similar) interface allows easy access to shared data by other US Government stakeholders
- *Protect classified and/or sensitive US space data and space operations.*
    - System designed to operate in a non-classified fashion, neither accepting nor generating classified information
    - Data being handled would be non-classified space safety data from multiple sources
    - Observations of sensitive US space operations could be excluded from the data base during the tasking and QA phases of operation, via spatial filtering
- *Operate cooperatively with existing Space Situational Awareness architectures, while maintaining the ability to function independently.*
    - Designed to be independent, via ability to task dedicated sensors and process own data
    - Virtual Observatory interface robust to presence or absence of connected architectures
- *Maintain transparency with partnering nations and data users on data sharing, data security, services and long-term plans.*
    - Non-classified design allows transparency
    - Periodic presentation of Quality and Situational reports
- *Provide an open architecture to enable observations from multiple sources, interchangeable software modules for processing, and alternate approaches to predict and analyze potential conjunctions.*
    - Designed to function using observational data allows mixing of multiple source information
    - System-of-systems allows upgrades of components on regular basis
    - Transparent and open design
- *Maximize the use of data and services provided by non-government and commercial entities.*
    - Assumes tasked data purchased from commercial entities
    - Designed to function using observational data allows mixing of multiple source information, tasked/purchased and contributed
    - Agnostic to business model (public private partnership, crown company, government-owned government operated (GOGO), etc.)
    - Built-in interfaces to database allow for future commercially-offered value-added services (anomaly resolution, etc.) above and beyond the planned safety services
- *Encourage innovation and incorporate improved capabilities and new technologies from both private industry and academia.*
    - System-of-systems architecture allows for component-level refresh
    - Periodic quality and situational reports provide transparency as to future needs of the system
- *Provide safety products and services as a public good (USG will not levy fees for the products and services it provides).*
    - Designed to easily produce basic actionable safety information, catalogs of space object trajectories and warnings to operators
    - Designed to be automated and machine-to-machine to reduce expensive "touch labor"

5. CONCLUSION

The US Civil STM system, as envisioned here, is an example of how the US Government might produce needed safety information for civil, commercial and foreign space users as part of a civil agency taking on a Space Operations Assurance (SOA)[31] role. It allows for fulfillment of OST obligations regarding the oversight and continuing supervision of US nationals' space operations (as well as others that agree to participate). It is designed to operate in a multi-lateral fashion with other space traffic management and space situational awareness centers, using existing internationally agreed-upon standards for information interchange. It is open and transparent by design. It is conceived to utilize various available sources of relevant information, but can also operate robustly in a

[31] McKnight, Darren, "Space Traffic Management (STM) As part of Space Operations Assurance (SOA), Perspectives and Definitions," AIAA workshop on Space Traffic Management, Kissimmee FL, January 12, 2018

stand-alone manner, having its own independent sources of space object measurements. By sharing observational data, it enables a common operating picture. It can serve as a model for other entities wishing to stand up their own STM center yet does not dictate their design. This transparent STM public service encourages the nascent commercial SSA data and services industry by being a cornerstone consumer for their products and services, as well as an enabler for new space safety applications.