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Charting Complex, Dynamic and Extra-orbital Space Operations

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Historically, space operations, and consequently the catalogs of space objects, have been largely focused on satellite activity around the earth. The picture was only dynamic to the extent that new objects would be added, and occasionally updated, and retired objects would disappear. The picture of debris would expand with each new discovery and better capabilities to spot smaller debris objects. Even the dynamics of that level of space activity is a complex endeavor. With the addition of extra-orbital activity, constellations with autonomous formation management, maneuvers and rendezvous, short-lived cube satellites, and daily space tourist flights the things to be tracked in space will be unimaginably dynamic. This paper addresses, what must be known and how decision science and knowledge management can be leveraged to create the catalog of the future that addresses the increasing dynamic space environment. It begins by reviewing the types of interactions and behaviors that will require monitoring and decisions. Using the decisions, we shape what must be known by others and the information exchanges to represent more complex space operations. A more dynamic catalog will also need to include the relationships between objects and the function of objects in terms of transmission and maneuver. Adding dynamics and relationships will extend the catalog from a static record to a playbook that will foster collaboration on changing operations across all classes of operations and performance in orbit and beyond.

I. Introduction

The most prominent issue before the global space community is "the nature of a space catalog for use in delivering fundamental Space Traffic Safety operational products and services" [1]. It must be more than a vehicle registry, simply listing objects that have gone into orbit or beyond. The nature of the catalog must transform to inform independent operators' decisions that would expose others to risk prior to performing those operations. It must reflect forthcoming actions and on-going changes in progress.

Capturing additional information when registering space objects contributes to the long-term sustainability of outer space activities. Nations should consider providing additional information on space objects, their operation, and their status as part of their registry [2]. As new missions are expected to extend to lunar operations and inter-planetary travel the catalog must also stretch to those non-orbit regimes. The information needs and the depth of the space environment characterization simply increases with the complexity of the operation (e.g., objects that can separate or rejoin).

The control environment is changing where more dynamic missions routinely intersect. Information will need to support decisions on time scales that vary from autonomous vehicle reactions to strategic decisions with humans in the loop. Each operator needs information to determine their individual course of action. This type of distributed decision making requires shared situational understanding, where the implications for one's own decisions are understood in the context of potential decisions by others who are actively managing their operations and actions [3].

The vision is open data to the extent possible for broader awareness to furnish a deeper characterization of space objects and their operational environment to support safe, stable, and sustainable space activities. The dynamics and relationships may drive the information needs to near-real time. The details do not have to be routine content in the catalog. The added information could be held by the operator in a discoverable form until requested for direct collaboration by another operator. Space traffic management becomes distributed control with the means to access the collective information of the space community for improving fundamental, real-time knowledge of the space environment to guide individual operator actions.

We contend the next catalog should be dynamic, should extend beyond simple orbital operations to cover a range of cis-lunar operations, should be federated across public and private sources, and should provide an understanding of active operations including a playbook for coordinating common actions. This paper identifies the knowledge needed, the time scales for transient information in the dynamic catalog, the discoverability of additional information to inform tactical decisions, and services to support routine emerging complex extra-orbital space operations. Beyond the product and services needs this assessment identifies a need for the development of technically informed norms in operation which address the routine actions, or "plays," for most commercial space operators.

II. Changing Environment Expands the Catalog Needs

Today, the United States Space Command catalog of objects in earth orbit provides basic knowledge of man-made objects and debris for an incrementally changing environment. Through outreach such the Strategic Command commercial integration cell, the government provides basic data and answers commercial operators requests for standard analyses. Present services from that catalog are limited to daily high accuracy catalog screening for collision avoidance (COLA) with close approach notifications or conjunction data messages issued periodically depending on the likelihood of the events. Space-Track.org allows operators to pull some of the catalog data for their own analysis purposes. Operators who are part of the Space Situational Awareness Sharing Agreement may furnish ephemeris and request advanced Conjunction Assessments. With the National Space Traffic Management Policy, the government is pivoting toward an expanded civilian catalog and commercial set of services to meet emerging needs. [4]

Space environmental dynamics are changing exponentially with the addition of constellations that mark a 10-fold increase in objects on orbit. The deployment and future decommissioning of these vehicles ensure a greater pace of change in catalog information with unprecedented number of launches and positioning maneuvers. Some operators plan pools of on-orbit spares to reposition and replace malfunctioning satellites throughout the constellation lifecycle. As the first generation retires several per day will move to a graveyard or de-orbit, while at the same time the next generation is being deployed. The rate of sub-orbital and temporary orbits will also increase with relatively short-lived cube satellites, and nearly daily space tourist flights. The registry of space objects will be constantly changing.

Many of the emerging objects are designed to support routine maneuvers and rendezvous or to change between orbits. Some constellations are controlled by autonomous formation management for mission performance and collision avoidance. Smart constellations manage mission performance by adjusting the relationships between the objects and their placement or behavior. Emerging missions involve transitions between traditional Earth orbits and lunar or planetary operations. The fact that many are to maneuver more often will also increase the pace of catalog change. The purposes and ways in which they can maneuver expand the attributes for the objects in the space catalog.

The number of space faring nations and organizations grow with the decrease in launch cost and increase in ride share opportunities. These developers, experimenters, and application managers may be short-term members of the community. Quickly registering these short-lived operations will be critical in a more dynamic space environment. Differentiating which have full or limited ability to control their operations is also key to understanding what should be treated as space debris or actively controlled. Within a decade, commercial operations will become over 90% of the space activity and a driver of constant change to the catalog. The organizations controlling active space objects must be accessible to each other and their service suppliers. Those who can actively control the features of their operation need to be brought into the community. [5]

Current space operations are largely focused on orbital activity. A nation is only required to register objects in earth orbit, meaning sub-orbital, transients, and extra-orbital objects are not represented. The current two-line element (TLE) format does not accommodate orbits with eccentricity >= 1 (parabolic/hyperbolic orbits) that would be used for interplanetary missions. The new operations require a means to describe where space objects are when in transition between orbits, on lunar orbits, or even when performing lunar landings and takeoffs, or residing on asteroids.

The possibility of long duration transits (with solar sails or ion engines) at slower speeds creates the need to characterize the transition states of objects as part of the catalog. A new reference model is needed to reflect things in motion in and beyond Earth orbit. At the other end of the time spectrum, the short duration of operations for some cube satellites, parabolic tourism operations, the increased launch and re-entry tempo, and other potential missions makes near-real time content necessary. Both extremes push the space catalog closer to a time representation of space status and events.

Understanding the repositioning of service objects to remove and on-orbit spares to replace a malfunctioning satellite, poses a risk if all appear similar. Some constellations contain a large number similar objects, increasing the need for a means to uniquely identify each object. This could include actual unique identification codes or characteristics such as transmit frequencies. The dynamic catalog requires more knowledge of the objects themselves to inform intent. The expansion of space-to-space communications and the overall increase in transmissions may saturate the spectrum, making it necessary to understand transmitter configurations and transmit duty cycles.

Today, a single international space station (ISS) is orbiting and receiving resupply missions. The ISS operates in a special zone, used by the United States to demark different debris risk mitigation expectations for operations below and above its area of operation. The Chinese and Russians plan to deploy and operate on their own stations in the next 5 years. The United Nations has the goal of expanding activities of human space technology, increasing opportunities for emerging space faring nations, and conducting space related activities in a responsible and sustainable manner [6]. These emerging manned flight activities pose a very different risks from current operations and will alter considerations for non-manned operations with regard to human flight safety [7].

The knowledge of debris of smaller sizes inside geosynchronous Earth orbit (GEO) is increasing with each improvement in sensing technology and implementation of additional sensors by space faring nations. Tracking the larger set of debris and organizing the knowledge from independent sources is critical to LEO. Beyond GEO the dynamic catalog reaches into monitoring graveyards and risks to interplanetary travel, lunar operations. Above the layer of orbital debris, space weather and other risks could dominate and require different services from the current space catalog [5]. NASA's Near-Earth Object Program (Spaceguard) tracks thousands of objects with a remote likelihood of impact with earth or transiting inside GEO orbits [8]. The characterization of these risks and phenomena is critical to objects in transition to or from near earth or lunar orbits.

With the variety of new missions, characteristics, and paradigms, the needs for the expanded civilian catalog and commercial set of services will change as summarized in the Table 1.

From	To
Current active and inactive population	10X current for active objects and visible debris
~50/50 government and commercial objects	Likely > 90% commercial, by many organizations
Occasional orbit changes	Constant flow of transitions of short and long duration
Orbital operations	Ranging from sub-orbital to extra-orbital
Daily screening assessments	Near-real time screening assessments
Simple location reference	Transition references and beyond-GEO locations or references for objects not in earth orbit
One space station	Multiple manned operations in different areas of space
Debris risk for orbits	Space weather and near-Earth objects beyond GEO

Table 1 Potential Dynamic Additions to the Space Catalog

III. A Dynamic Catalog: Expanding the Available Knowledge of Space

We begin with the view that maintaining a catalog serves "principally as a data management function, rather than as a task of managing space traffic." [9, p. 3] Expanding the available knowledge of space and allowing creative commercial companies to innovate will best serve the strategic interests of the Nation, and the international space community. With this hypothesis the dynamic catalog must be shaped and guided to meet at least the minimum needs of the future environment described in Section II. The new dynamic catalog has expanded content, a near-real-time view, additional content discoverable by inquiry, and derived services as described in the sections below.

A. Expanding Content

First, the content must expand in terms of the span of operations that are included. Lunar/interplanetary flights and re-entries will become more common, as well as the *birthing* of satellites on-orbit. Sub-orbital and very low earth orbit considerations for cube satellites, parabolic and horizontal launches must be addressed as they are currently not required to be reported in any catalog. Sub-orbital flights are likely to be a growing part of the contention for entry into space. Regarding the space objects characteristics, what must be known to manage risk for each space object?

Risks	Characteristics
Objects in motion	The maneuverability of the object and plans for future maneuvers.
Objects that separate or join with other objects	Uniquely identifying the separate objects and their state of separation, independent flight, or docking with other objects.
Miscoordination on actions by indistinguishable objects	Recommend unique identification beacons for objects.
Transition maneuvers with a long or unknown duration	The maneuverability and transition time estimates and variable factors (e.g. space weather dependent mobility).
Presence of people on-board	Identify manned space objects and risk calculation adjustments.
Debris generation	Expected release of any parts which will become debris during deployment or other phases (including uncontrollable cube-sats).
Radiation hazards	Differentiating those with nuclear power sources.
Blinding events or radio interference	Laser or space to space communications and transmitter configurations that may affect the operation of other objects.

Table 2 Potential Characteristics Relevant to Risk Management

Access to the space object characteristics from Table 2 is necessary to inform distributed decision making. Additionally, operators must also be in contact with each other for shared understanding of how their actions effect the decisions of others [3]. Ownership and contact information are a necessary addition to the catalog to collaboratively resolve any contested operational activities. Equally important is information upon which nations have jurisdiction and oversight of the operation. The status of the owning and operating organizations involved in the control of space objects, including financial solvency or technical difficulties, may also be important.

The space catalog must account for ever increasing knowledge of the space environment, with increased awareness of debris in orbit, other objects, and space weather. The picture of debris and other objects is expanding with each new discovery and better capabilities to spot smaller debris objects. The knowledge of debris and space weather expands as operations move into other environments. Objects in lunar orbits or beyond earth orbit may provide new sources for spotting, sensing, and tracking debris, meteor activity, or solar weather details [10]. Closer to Earth, expanded data sets for everything from launch vehicle performance, gravitational and atmospheric effects and solar weather can give greater insights into the characteristics of uncertainty and the needed margins for dynamic operations.

The increase in controlled actions and radio-frequency interactions between objects, and a more complete picture of the debris fed by multiple sources add to the challenge of characterizing the space environment. The catalog will need the providence of information and uncertainties associated with reported information, due to its age or observation characteristics.

B. Capturing a Time Variant View of Space Objects

The dynamic catalog is more than a registry of present status, it has a time component that extends into the future and retains knowledge of the recent past. Effective coordination and planning for commercial operators requires insights into future projected activity by others. This would include events in motion as well as future scheduled events. These timed events include planned launches, object maneuvers, separations, rendezvous, and reentries across all orbit regimes.

Launching objects will be increasingly difficult to time for entry in a proliferated LEO environment. The United Nations Office for Outer Space Affairs (UNOOSA) guidelines recommend initiating registry pre-launch to aid with scheduling conflicts [2]. Scheduling actions of different operators may benefit from structures, such as launch and re-entry lanes to deconflict the operations from the dozens of new space ports across the globe. The sub-orbital part of the catalog will be driven by many short lived events including cube-satellite maneuvers or re-entries which might conflict with launches. NASA noted the increasing risk of encounters with air vehicles, or high altitude near space objects during launch and reentry may warrant a sub-orbital catalog of temporary space objects and high altitude airborne objects which may remain aloft for hundreds of days at the edges of space and interfere with launch windows [11]. Extra-orbital returns to an Earth orbit from lunar or interplanetary operations add a new flavor of orbital insertion and planning.

These scheduled events may be coordinated over days or even months, giving great depth in time to the future views from the catalog. On a shorter time-scale, the details of object separation or maneuvers to a new orbit may be planned and occur in near-real time. These planned events and active transitions are expressed as a start time and location, arrival time and termination point as part of the catalog dynamics. The catalog of planned events spreads from planned events months in the future to near-real time operations because decision makers will be acting on many different timetables.

A more dynamic space catalog will also need to understand the relationships between objects and the function of objects in terms of transmission and maneuver. When might actions be expected from which vehicles? What are the patterns of life, and what triggers precede action, such as the pre-planned range at which an autonomous vehicle will take a station keeping action? What tolerance is used for maintaining orbits or stations? How will constellations manage mission assurance (in terms of pre or post coordination of changes)? How will inoperable members of a constellation be removed, repaired, or replaced? How will repair ships or spares be moved into place? A time phased catalog could retain patterns of life and expected planning and reaction times to characterize the dynamic environment.

The space catalog may also retain knowledge of the recent past. Oversight and attribution post-incident would require archives of the past states, actions, and coordination during the resolution of conflicting actions. Consideration must be given to what to record for analysis and possible attribution of liability claims.

C. Expanding the Discoverability of Details and Drill-down Views

Sharing intent in advance is a premise for industry lead collaborative decision making (CDM). Understandably, space operators may not want to share details of their plans or operations. The key is sharing enough intent for commercial operators to discover the actions of others that potentially affect them, so they can begin to collaborate. A CDM approach with strategic deconfliction of intent through direct party inquiry to understand sources of concern or uncertainty between the parties should be part of the policy [11]. The near-real time dynamic information need not be a routine part of the space catalog, so long as it is discoverable during CDM by the affected parties.

Once the need to collaborate due to effects of one's actions on others is apparent, the involved parties use the contact information from the catalog to inquire about the details. During the planning stages of an action, operators seek additional information that would help bound their source of uncertainty in their risk calculus. When will an operation start? What is the planned speed of transition? When will it end? Which of these are constraints and which can be adjusted?

Once active maneuvers commence, the drill down shifts toward near-real time information. Similar to what is done through the Space Data Association, commercial operators directly coordinating their actions may exchange ephemeris or other data "on-request" throughout maneuvers. Surveillance of events such as object separation, rendezvous, or passing distances may also be necessary for the coordination. Space-based sensors can provide new prospective to be correlated with other observations. A significant expansion in sensors offers the possibility to bound uncertainty with specific snapshots immediately before acting. Services are under development for integrating events in near-real time from all available sources. This may include additional relative position determinations that can help prevent collision during the rendezvous and maneuvering process given the higher potential risk for collision [12]. Commercial operators can also exchange pre-and post-maneuver information and status. These on-request exchanges could reduce the frequency and effort for manual intervention in catalog maintenance [13].

Inquiries may also be directed at the broader community to better characterize potential encounters with uncontrolled objects. Given their dominance on space operator decisions in low-earth orbit, a shared understanding of debris dynamics and planned avoidance maneuvers is key to avoid cascading effects of potential conjunctions. Individual space objects may build significant understanding of the debris field they routinely transit and their behavior over multiple orbits [10]. The crowd sourced information available "on-request" could include space weather information and other phenomena important to those operating above the debris field, concerned with the safety of manned flight, or effectiveness of propulsion systems. The increased sources and perspectives offered from ground or space, by public and commercial sensor networks should be discoverable for everyone's benefit.

Awareness must include uncertainty around projected phenomena. General inquires could be issued to the larger community to understand where information does not easily reconcile. This uncertainty may be the presence of non-participating entities and malicious actors [11]. It could include suspect communications or information indicative of a potential cyber-attack. Malicious non-compliance or other actions that would not align with the shared understanding could be detected my different members of the community. A drill down on details and cross-validation with secondary sources will be essential to spotting these events and seeking to bound the uncertainty for the whole community.

D. Expanding the Services and Applications to Support New Operations

The crowd sourced information is layered, with an ability to drill down and inquire about conditions that might affect. That also enables service providers to offer solutions for specific needs. With more than 90% of operational control decisions belonging to commercial operators and a significant growth in proximity missions for commercial purposes, the services will also become commercial in nature. There is a call to decouple space situational awareness (SSA) from any one national government [14] entity, and foster the marketspace for the commercial sector to fulfill many of the emerging needs of a dynamic space catalog [15] [13] [16] [17].

Service suppliers will support many of the basic decisions concerning transitions of space objects as details in Table 3. Services for increased knowledge of debris or on-demand active sensing or monitoring of near objects can be crowd sourced a better picture from numerous independent observations as described in section C. The conjunction assessment service and process must scale to account for more objects in active transition and more known obstacles.

1. Environmental factor assessments (or space object risk models) – Risk assessments are an ongoing service that could eventually inform norms and performance-based safety regulations [2]. Integrated model takes data from all disparate sources to create a single picture with uncertainty characterizations of debris, space weather and other relevant factors requested by an operator.
2. Event conjunction assessments – prior to each "start event" (launch, maneuver, orbit return from extra-orbital domain, separation) to understand effects of the timing and speed of action on the potential for conjunctions.
3. Continuous conjunction assessments (CA) – A revised and scalable process for producing CA with uncertainty characterizations for each risk from the object's perspective. A twin of fast time simulations of orbital motion and attitude control used in system development can be extended for use in assessing actual operation project risk to the object along its path with curated inputs. [18]

Table 3 Basic Services

These basic services are complemented by collaboration channels for working out scheduled events and speed of transitions with other affected operators. These collaboration services are in the table below.

4. Notification of intent – Services identifying to an operator a potential event with a need to contact the counter party to the risk. This could include maneuvers, space-based communications changes or transmissions which may create radio interference or "blinding" events.
5. Contact and control management – Information on where and how to contact operators to coordinate actions depends on knowledge of the current control management of space objects. The contact information must remain current even with handoffs between control facilities.
6. Drill down request – Support exchanges between operators to provide information that would lower uncertainty bounds (e.g., ephemeris, constant or variable speed).
7. Coordinated actions – Maneuvers to rendezvous, change orbits, or de-orbit are being addressed by the Consortium for the Execution of Rendezvous and Servicing Operations (CONFERS) [15]. The exchange for these events should be coordinated in advance with additional information shared throughout the procedure to aid coordination.
8. Contingency management protocol – Services for coordinating responses following an anomalous event, or the autonomous reaction of a space constellation These may be machine-to-machine exchanges to inform decisions, options, objectives or constraints, and considerations for impact of options of other decision makers. Autonomous collision avoidance practices will likely be developed by operators deploying LEO mega-constellations, as operations of these large groups of satellites will not scale without significant automation [19].

Table 4 Coordination Services

Service suppliers may support individual operators with enhanced techniques for assessing risk. The multi-sourcing functions are enhanced with a variety of observations and perspectives, including sensing from the commercial space objects themselves. Models representing the objectives, concerns, and operations of individual objects can track the risk for mission assurance and safety of each object. Commercial providers may employ surveillance and monitoring services with machine learning or other artificial intelligence methods to provide operators with courses of action options and other specialized services as listed in Table 5.

9. Event surveillance – Services for monitoring an Rendezvous and Proximity Operations (RPO), On-Orbit Servicing (OOS) separation, or other planned event. The provider can harmonize sensor data and processing methods to publish the available information as an integrated picture from the catalog [14].
10. Interference assessments – Service to identify sources of optical or radio interference risk for potential coordination, reports information on radio frequency or optical (laser) angles/intercepts with other space objects to the owner of the transmissions and/or the effected party.
11. Anomalous event reports – Service to notify operators of detected or reported events (separation, engine/motion start, mechanical failure, loss of control, malicious non-compliance, cyber-incidents, …) with proximity to areas of interest or operations.
12. Near-real-time (NRT) status – With NRT status through surveillance, beacon reporting, or company ephemeris status, and control data, the service provider can offer operational status characterization for decision makers [18].
13. Course of Action (COA) options visualization - Real-time scene generation tools created for day in the life testing could be adapted to common operating picture visualization to produce course of action options and metrics and monitoring for decision support [18].

Table 5 Surveillance and Enhanced Situational Awareness Services

The system will always need a warning service independent of commercial services; a backstop authority to catch situations no one else has predicted. The organizations providing warning services will need to be aware of commercial service warnings and on-going collaboration efforts to mitigate events of a more general nature or warnings that have been missed as described in Table 6.

14. Warnings – Notifications of an immediate event (e.g., solar flare, conjunction data message with no intent forewarning) that needs attention, or eminent danger or warnings including notice to non-combatants concerning potential hostile activity in an area.
15. Data curation - detecting spurious data and characterizing uncertainty or disparities in available information from standard and alternative sources. Software-based curation provides robust sensor filtering and validation to support automated and continuous sensor calibration and data characterization for other uses. [17]
16. Suspected data corruption – whether through cyber-attack or anomalous-operating sensors, exchanges to validate what is in error and possibly issue warnings about suspect data.

Table 6 General Community Warnings

One broader community service may be to provide structure in space. Some of the suggested structure can be used to solve different issues with manned flight [20], others see the structure as a way to simplify the conjunction assessment between orbiting objects [21]. Services may need to manage entry and egress lanes and create moving bubbles around manned space flights. What combination of risk zones, orbital structures, and catalog structuring can simplify the computational expense to better manage risk?

IV. Sustainability Relies on Actions and Behaviors

Avoiding the next accident that could accelerate the Kessler effect requires knowledge of risks and effective risk controls distributed across the industry operators and the global community. Starting with a set of distributed decisions necessary to prevent such a catastrophe, we can assemble the collective requirements of the community actions and decisions. The procedures and norms to assist hundreds of independent decision makers in coordinating their actions begin with the knowledge of this set. The norms should support a unified set of regulatory objectives with flexible policies for space sustainability codified in legislation, regulation [22], or perhaps CDM agreements.

Recent efforts to understand how to address the sovereignty or lack of formal authority and the "lawless environment of space, yield to the nearly impossible task of formal agreements." The community looks to the more basic realization that the sustainability of the environment is a global interest. For this reason, the Transparency and Confidence Building Measures (TCBMs) were agreed for generating best practices as part of the mutual understanding and international harmonization of norms [23]. Coordination of actions will reduce the risk of incidents that raise liability concerns or could be considered hostile. Differentiating the decisions, type of intent data required, and opportunity to collaborate will be key to the definition of self-management of equitable, rational, and efficient use of space and spectrum in space. [2]

A. Collaborative Decision Making Between Operators

A distributed decision-making environment involves action taken primarily through CDM. Direct coordination between the interested parties will drill down and manage sources of uncertainty as described in section III.C. Shared understanding will ensure each decision maker knows the interaction or chain reaction effects of their actions on others.

The "plays" for each routine action spell out the timing and exchanges with affected parties to assure shared understanding of a dynamic space catalog. The norms choreograph the necessary collaboration to strategically deconflict independent decision makers' actions and tactically resolve the remaining risks. So, what are those routine actions or "plays" space operators can expect to make with coordination?

Routine Actions or "Plays"
Launch (sub-orbit, orbit, beyond orbit, lunar)
Transition between orbits (pass through other orbits)
Avoidance maneuvers (debris, active objects)
Coordinate rendezvous or servicing operation (dock, undock, propel)
Planned maneuver (deploy, deorbit, reposition, end transition)
Execute contingency plan
Station keeping adjustment
Alter facing or configuration (antennas, solar panels, etc.)
Alter transmitter configuration or use
Debris release or collection
Disposal to the graveyard or deorbit
Tasking sensors to validate data or maintain custody
Ground control station preferences
Deployment of objects (separation into parts)

Table 7 Summary of Common Operator Actions and Plays

The key to creating practices and norms is to identify these routine decisions that require pre-coordination and the shared understanding necessary to make informed decisions so decision makers can engage one another to understand and limit the uncertainty before acting. These plays and behaviors are essential to shaping the dynamic space catalog to fit the purpose of a sustainable, expanded space domain. The playbook complements the dynamic catalog content, by explaining the role of information services in planning and understanding actions in progress across space.

B. Playbook for Coordinated Actions

Each "play" is broken into steps and norms for executing recurring operations as pre-establish information flows and continued engagement. Through further drill down or inquiry, and application of services the operators involved gain a shared understanding before taking any major action. The playbook captures the steps and timing for each action and the discovery process, and the information needs required to assure the operators have the information they need.

This is a negotiation between decision makers with different risks, criteria for mission success and constraints. The challenge is decision making under uncertainty which requires an honest exchange to reduce uncertainty knowing both parties may be at risk. Through the plays, operators should know when to wait for uncertainty to lift, when to ask for clarity, and when to act. A key role of collaboration is the drill down and additional data exchange between affected parties to minimize sources of uncertainty.

The resulting playbook is a matrix of objectives, constraints, and external factors that differentiate the types of maneuvers into specific plays with organized steps and norms for coordination. Ultimately, physics will prevail limiting the playbook options that will need to be coordinated and practiced across industry.

The plays must identify the right-of-way for those already on orbit, station keeping, or in transit. The access priorities must also consider hard constraints for mission success, like windows of opportunity for interplanetary travel, or entry/egress lanes to lunar targets. This requires the exchange of mission objectives and constraints between contending parties to resolve access and sequence issues.

The types of actions which can be taken without prior coordination must be limited to assure the outcomes do not affect other operators. This is similar to the principle of due regard, where the acting operator must be aware without any further coordination of the actions of others and maneuverable enough to take all action necessary for the safety of their own and the operations of others.

There will be autonomous actions such as station keeping adjustments that will not have the benefit of coordination immediately prior to action. The understanding of the object including the range of motion, whether for station keeping, mission assurance, or other reasons, and the amount of forewarning prior to action will be key to the autonomous action "plays."

More complex autonomous actions include pre-planned contingencies to address failures or emergency conditions. These plans, especially for manned flight, may be part of the space catalog with some details communicated in advance, along with other basic information. These emergency "plays" characterize an operation with more complex statements of intent and assume coordination of the emergency maneuver will be real-time.

Ultimately, plays are designed to assure that the distributed decision making informs each party as to the effect of their actions on others. It must do so through the eyes of the counterparty to maintain trust. What indication is there of real threat? Which course of action will reduce the risk? Ultimately the operator must decide when to act; however, what is communicated through an event must be agreed to upfront. The play for each type of routine action must produce behaviors that reduce cascading effects from avoidance maneuvers by sharing the intent to take action to determine how others will react.

V. Conclusions

The goal of this paper has been to characterize dimensions of the dynamic space catalog to enable collaborative decision making. We showed how new environments and operations in space will require different content, different time horizons, and discoverability of operational details held by the operators during coordinated decisions. We presented the additional content needed for each space object in Table 1 Potential Dynamic Additions to the Space Catalog and offered the expanded characterization of the space environment that will be necessary for cis-lunar operations. We showed a set of commercial services which may be beneficial to operator decision making. The space community could build these resources as a public private partnership to leverage the best of all information provider's knowledge and capability.

Both knowledge and decision making will be distributed. Decision makers operate under uncertainty which may include a need for understanding the status, intent, or actions of others. Through discovery and exchange of more detailed information with others, operators can achieve shared understanding and reduce uncertainties as described in Section II.C. The operator may be assisted by commercial or government furnished services that have been outlined in the tables of Section III.

The sustainability of commercial space operations depends on the decisions of an increasing number of space faring operators with the oversight of more space faring nations. A dynamic space catalog and a playbook for that coordination will assure the decision makers have a shared understanding of the effects of their actions on others before acting. The actions listed in Table 7 Summary of Common Operator Actions and Plays must be analyzed to understand the discoverable information needs. The dynamic catalog and accompanying playbook of practices will enable the global community to navigate the 21st century in space.

The alternative is incidents in which the liability is debatable, attribution or reparations fail, and the commercial organizations must bear significant uncertainty about the viability of its long-term operation, and their potential for catastrophic loss. It is against that backdrop, we believe the community must begin to expand the knowledge, discoverability of further information on request, and coordination of routine plays that will make up the future space ecosystem from sub-orbital ventures to extra-orbital operations.

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