Space Surveillance, Tracking, and Information Fusion for Space Domain Awareness

M. Jah
The University of Arizona
College of Engineering
Tucson, AZ 85721
UNITED STATES OF AMERICA

moribajah@email.arizona.edu

ABSTRACT

As the spacefaring community is well aware, the increasingly rapid proliferation of man-made objects in space, whether active satellites or debris, threatens the safe and secure operation of spacecraft and requires that we change the way we conduct business in space. The introduction of appropriate protocols and procedures to regulate the use of space is predicated on the availability of quantifiable and timely information regarding the behavior of resident space objects (RSO): the basis of space domain awareness (SDA). Yet despite five decades of space operations, and a growing global dependence on the services provided by space-based platforms, the population of Earth orbiting space objects is still neither rigorously nor comprehensively quantified, and the behaviors of these objects, whether directed by human agency or governed by interaction with the space environment, are inadequately characterized.

Key goals of advanced SDA are to develop a capability to predict RSO behavior, extending SDA beyond its present paradigm of catalog maintenance and forensic analysis, and to arrive at a comprehensive physical understanding of all of the inputs that affect the motion of RSOs. Solutions to these problems require multi-disciplinary engagement that combines space surveillance data with other information, including space object databases and space environmental data, to help decision-making processes predict, detect, and quantify threatening and hazardous space domain activity.

1.0 INTRODUCTION

This document presents an introductory overview of space surveillance, tracking, and information fusion for SDA. A relevant activity is the NATO Science and Technology Organization's Task Group (SCI-279-TG) is addressing the technical considerations for enabling a NATO-Centric Space Domain Common Operating Picture (COP). The impetus for this effort is the growing dependence by NATO and its member nations on space capabilities to achieve its mission responsibilities as well as the growing role that space, as an operational domain in its own right, is playing in matters concerning global security. NATO has recognized this important reality and increased the Alliance's collective attention on ensuring NATO operations maximize their leverage of space while ensuring the space capabilities provided by its member nations are preserved to the maximum extent possible. A critical element of ensuring the availability and efficacy of these space capabilities is the availability of a common operational perspective or picture of the space domain throughout the Alliance and its partners.

The presumption is that NATO forces will be more efficient, protected and successful in their future missions if a common operational perspective can be achieved across all operational domains in which NATO must operate; air, land, sea, cyber AND space. The corollary is, without a common Alliance perspective of the space domain, serious operational weaknesses may result when space services and capabilities are degraded or denied to NATO forces by either natural or manmade causes. With the rapid assimilation of information technology globally and associated applications to the modern battle-space, it becomes imperative that NATO maximizes its total battle-space awareness to include the space domain.

A foundational role of the NATO Science and Technology Organization's (STO) collaborative technical activities is providing critical perspectives across the Alliance on the contributions (and threats) that emerging technologies will have on future NATO mission operations. Over the last several years STO has critically examined enabling technology developments and applications related to the ever-growing importance of space to the Alliance. One of the cornerstones of the Alliance has been pervasive interoperability in its materiel and non-materiel resources, assets and operational art. It is apparent from those activities that, for NATO to sustain its strength through interoperability, then interoperability in the space domain must be considered as well. One of the intents of the NATO STO focus on space has been to identify intersections among plausible future NATO operational environments and emergent science and technology developments that can be leveraged to ensure NATO's success. This is the basis upon which STO has undertaken an examination of the enabling considerations necessary for a NATO-common space domain Common Operating Picture (COP).

Space capabilities and services have been essential supporting utilities underpinning much of the command and control infrastructure throughout NATO for many years. However, the threats to those capabilities and services, along with the consequences of their loss or degradation, have only recently become a NATO concern given the proliferation of plausible threats and the growing dependence upon space throughout the Alliance. NATO has no space assets of its own – all space capabilities and services are of individual national origin. The protection of space systems (satellites and controlling ground infrastructure) that provide the capabilities and services to NATO is a singularly sovereign responsibility. In fact, not only the operation of those systems, but the collection/acquisition and dissemination of information on and about the space domain is also inherently sovereign in nature. Since space has become more important as a war fighting domain, this increasingly poses a dilemma for achieving the NATO objective of maximizing the interoperability and integration of force capabilities.

Historically, two of the more pervasive challenges of integrating multi-nationally-sourced data and information that contributes to space domain awareness are (a) overcoming the national sensitivities of data sharing and (b) the accurate technical fusion of such data. Those challenges extend to the effective achievement of space domain awareness within NATO. For the purposes of the SCI-279-TG effort, a deliberate decision was made to NOT address the current and future policy remedies that will be necessary to deal with the sovereign sensitivity issues that must be overcome before a NATO-common set of data and information can be compiled. However, it is posited that the following three types of data and information may be more likely to be shared than other more sensitive information (e.g., space-related intelligence):

1) Space surveillance and tracking;
2) Space environment; and
3) Radio frequency interference experienced by space communication links.

Thus, these three areas of space domain awareness are used within the SCI-279-TG effort as the exemplars for characterizing a likely initial NATO-centric space domain awareness picture.

Since there is currently neither the capability for a NATO-centric common space domain awareness picture, nor an established NATO requirement for one, the question of whom within NATO would be the future customers/ consumers of such insight arises. For the purposes of the SCI-279-TG effort, the following two primary customer/consumer groups were postulated in a future NATO mission environment. The first are the NATO operational command elements which, having joint forces command responsibilities, are presumed to likely have some future need for insight into the space domain in order to effectively consider the alliance space capabilities as well as to develop a proper appreciation of possible threats to them. A comprehensive and current space domain awareness is required in all phases of military planning through to mission execution. Providing the most comprehensive space domain awareness picture available to NATO commanders and operators is the objective in this case. The second are the national command elements of individual member nations providing national forces and resources to the NATO operational environment. In this case, providing a common space domain awareness (SDA) picture across all participants in a NATO operation enables maximum common insight for individual command and control decisions by the nations involved. The overall objective is to enable a shared space domain awareness to maximize deployment of mission resources and afford maximum use and protection of space capabilities and services throughout the Alliance. Ultimately, the customers/consumers of SDA will shape their requirements and manifest them in appropriate doctrine, tradecraft and standards.

This SCI-292-LS was developed as a result of the SCI-279-TG. At this point, it is useful to provide the definition of the space domain and space domain awareness as used as a reference for this effort. These definitions will be refined through various official national and NATO processes.

The space domain can be defined as all conditions, areas, activities and things terrestrially relating to space, adjacent to, within, or bordering outer space, including all space-related activities, infrastructure, people, cargo, and space capable craft that can operate to, in, through and from space.

Space domain awareness, in the NATO context, can similarly be defined as the effective understanding of anything associated with the space domain that could impact the security, safety, economy or environment of space systems or activities within the NATO Alliance. The definition acknowledges the supportive activities and threats related to land, maritime, air and cyber regimes relevant to space operations. It requires the combination of space situational awareness foundations of detecting, tracking and environmental monitoring, along with space intelligence foundations of characterizing normal behavior and sensitivity, to detecting change to know when something has or is predicted to occur. A purpose of SDA is to provide decision-making processes with a timely and actionable body of evidence of behavior(s) [predicted, imminent, and/or forensic] attributable to specific space domain threats and hazards.

Comprehensive operational awareness of the space domain is essential to the achievement of the NATO Long Term Aspect requirement for NATO Space Capability Preservation[1] (as identified by the SCI-238 Specialists Meeting, March 2013)[2]. To ensure that NATO forces, space planners and operators can maximize their deployment and protection of the space capabilities brought to the Alliance through its member nations, a shared, Common Operating Picture (COP) of the space domain will be essential (within the limits of those members to share and contribute space domain awareness data and products). Due to the multi-dimensional technical scope of the involved data and product streams along with associated variations in data protocols, sensor attributes and other technical variables, it will be necessary to evolve a common integrated environment within the NATO space planning and operational domains to ensure the timely exploitation of those data and products. Although there are no limits on what constitutes space domain awareness data, it is essential to initially address, at a minimum, space weather and environmental reporting, space object tracking and characterization/classification, as well as radio frequency interference characterizations and attributions against satellite control links and communication services.

[1] Excerpt from Final Report: Long-Term Requirements Study Enclosure 1 to 1500/SHJ5CMD/08-205478 5000 TC-70 TT-3425/Serial: NU0059 Dated: 23 Oct 2008.

[2] Report of SCI-238-SM Specialists Meeting on NATO Space Dependencies (AC/323(SCI-238)TP/544); published January 2014.

Within the NATO organizations and agencies, little attention has been paid to space domain awareness (SDA) requirements in the past since, as mentioned above, this has been the sovereign purview of the member nations. The NATO Centre of Excellence (COE) organization, the Joint Air Power Competence Centre (JAPCC) has published a few articles on SSA[3] [4] and the BiSC Space Working Group has addressed SSA in its report on NATO space dependencies[5]. The NATO STO activity SCI-229 task group addressed the role of space weather in NATO space situational awareness and concepts for operator tools for detection and interpretation of potential space weather effects on NATO operations[6]. The SCI-238-SM[7] (Specialists' Meeting on NATO space dependencies) and the SCI-268-SM[8] (Specialist's meeting on NATO future space S&T needs) also highlighted the need for NATO to have the ability for comprehensive space domain awareness.

A similar data and information integration challenge has been faced within the NATO ISR community. As a consequence of the disparate types and sources of ISR data being provided to NATO from the member nations, a collaborative group was established to develop guidelines, common processes and ultimately standards to enable the integrated collection, fusion and dissemination of ISR data and information within NATO. The work of the Joint Capabilities Group for Intelligence, Surveillance and Reconnaissance (JCGISR) offers a potential model for collaboration on standards, architectures and interoperability with respect to integrating national-sourced space information and data. The SCI-279-TG activity has attempted to leverage some of the lessons learned from the JCGISR experience to guide some of the thinking on how to approach the space data challenge within NATO.

To date, SDA has lacked credible scientific and technical rigor to quantify, assess, and predict space domain threats and hazards. The current state-of-the-art suffers from a number of inadequacies: there are no standard definitions of elements in the space domain; descriptions of space objects and events are limited; no standard method of calibrating sensors and information sources has been developed; tasking is addressed to individual sensors for specific data rather than to a comprehensive system for information required to address needs and requirements; there exists no rigorous understanding of space environment effects and impacts on space objects; there is no framework that encourages and enables big data analysis, and supports an investigative "from data to discovery" paradigm; we lack a consistent method to understand all of the causes and effects relating space objects and events.

The need to address these concerns has never been greater. On-orbit collisions, natural or intentional, are a global concern that threatens the long-term sustainability of our space activities and environment, and worsens the impact of the space debris population growth in critical mission-dependent orbital regimes. It accounts for an increase in the useless space object population of about 1% annually (with isolated events contributing spikes upwards of 20% population growth) and jeopardizes the livelihoods of tens of millions of people who depend on critical space capabilities and services.

---

[3] JAPCC Journal Edition 20, Spring/Summer 2015; A Model of the Space Debris Environment, C. Wiedmann, Pg 46.

[4] JAPCC Journal Edition 20, Spring/Summer 2015; Space, S. Neumann, Pg 22.

[5] BiSC Space Working Group report on NATO space dependencies to the NATO Military Committee, 2014.

[6] SCI-229-TG final report reference.

[7] **NATO Space Capability Preservation (A Day Without Space)**, Proceedings of SCI-238 Specialists Meeting, NATO Science and Technology Organization, AC/323(SCI-238)TP/544, 2013.

[8] **NATO Space: S&T Developments to Enhance Resiliency and Effectiveness of NATO Operations**, Final Report of Specialist's Meeting SCI-268-SM, NATO Science and Technology Organization, STO-MP-SCI-268, June 2014.

Traditionally, efforts to develop and maintain awareness of all trackable space objects have relied upon the USSTRATCOM's Space Surveillance Network (SSN). But these sensors are often prohibitively expensive for even the richest of nations, and the space domain is too vast for traditional space surveillance, ground or space based, to be truly effective by itself. Protecting important space assets, especially those that provide critical services and capabilities such as communication, weather, bank routing, position, navigation, and timing, requires a new approach encompassing 21st-century technology and a fundamental understanding of the processes governing the behavior of objects in space.

It is in this context that the following sections in this document are given and seek to place the characterization and behavior of space objects on a rigorous scientific footing. Until now, the global approach to space operations has been largely reactive, following the latest commercial exigency or governmental demand signal of the day. By contrast, the fundamental work required should lead to new ways to understand, measure and predict behavior in space. In turn, that work will underpin the development of best practices in space traffic management, and inform efforts to improve mission assurance and mitigate the effects of space debris hazards.

2.0 SPACE DOMAIN AWARENESS GOALS AND OBJECTIVES

Space Domain Awareness (SDA) is the actionable knowledge required to predict, avoid, deter, operate through, recover from, and/or attribute cause to the loss and/or degradation of space capabilities and services. The main purpose for SDA is to provide decision-making processes with a quantifiable and timely body of evidence of behavior(s) attributable to specific space threats and/or hazards. SDA encompasses all activities of information tasking, collection, fusion, exploitation, quantification, and extraction to end in credible threat and hazard identification and prediction. Understanding the synergy between the space environment, the interaction of this space environment with objects (astrodynamics), the effects of this space environment on objects (operational and not), and the available sensors and sources of information, are critical to meaningful SDA. Included in the SDA purview is collecting raw observables, identifying physical states and parameters (e.g., orbit, attitude, size, shape), determining functional characteristics (e.g., active vs. passive, thrust capacity, payloads), inferring mission objectives (e.g., communications, weather), identifying behaviors, and predicting specific credible threats and hazards. Intuitively, SDA is a natural 'big data' problem, drawing from a surfeit of existing and potential metadata and data sources. The problem at hand is a) how these articulated needs can be rigorously addressed using first-principles, b) what methods, techniques, and technologies must be leveraged from other fields or targeted for development, and c) what sensors, phenomenology, sensor tasking, or additional data are needed to support the SDA mission.

Existing research and technology focuses largely on collecting observables, identification of physical states and parameters, and determining functional characteristics. Advances include extracting observations & new information from non-traditional sensors, improving track association and initiation using admissible regions, using Finite Set Statistics methods to improve detection & tracking, and classifying space objects using ontology and taxonomy approaches.

The intent of any operational component is to predict Resident Space Object (RSO) behavior with quantified uncertainty in order to provide decision makers with timely warnings of specific hazards and threats. Behavior prediction must take into account the behavior of other RSOs, physics, and indirect information gleaned from non-standard sources.

3.0 SPACE DOMAIN INFORMATION FUSION

Data on the space environment and objects in it, imported into SDA-DMS, come from a disparate variety of sources and sensors. To maximally exploit the information we must in some sense fuse the data. In this context, the concept of 'data fusion', which is so often only vaguely defined, means that we seek quantitative answers to specific questions with the lowest uncertainty permitted by all the available data. For example, "Where will this object be next Tuesday at 3 o'clock?" or, "What is the likelihood that my on-orbit network capability will be disrupted by space debris within the next two years?" To address this challenge, we have defined a Space Domain Information Fusion (SDIF) model, illustrated in Figure 1, which exploits the techniques of task-specific information (TSI).

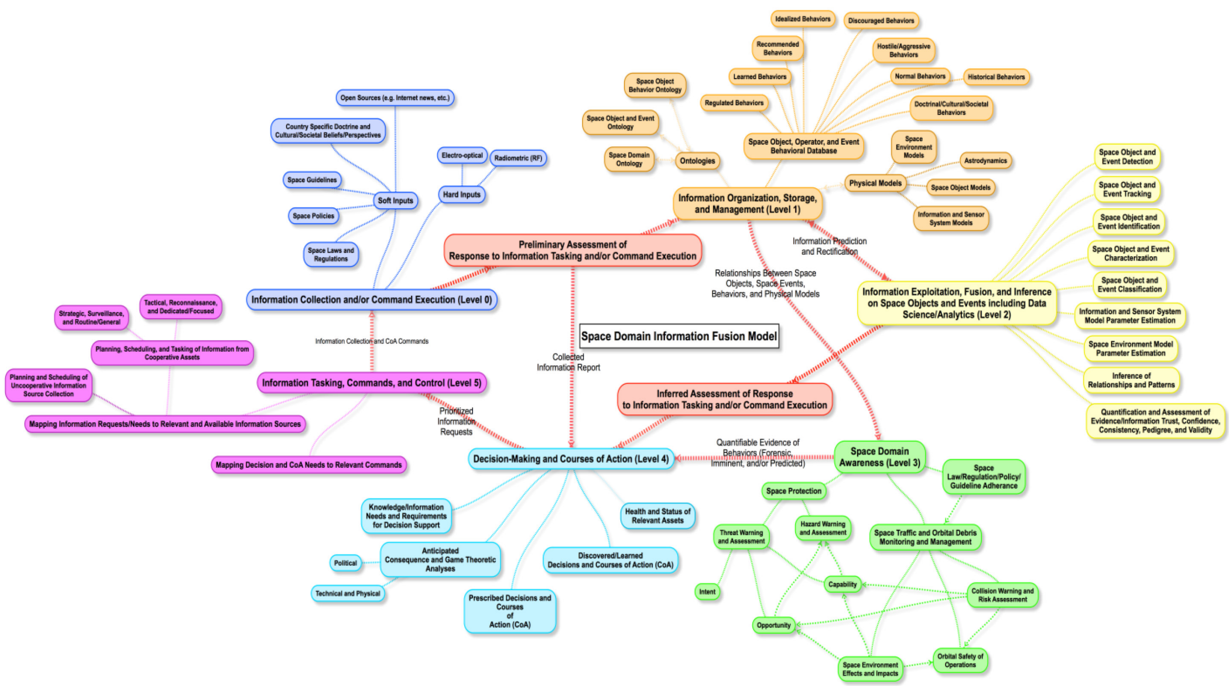

Figure 1: Overview of the Space Domain Information Fusion Model.

TSI is a paradigm for the exploration/discovery of information-optimal solutions to quantifiable estimation and classification tasks. TSI emerges from a rigorous application of traditional Shannon information theory and produces a mathematical formalism capable of quantifying the fundamental limits on task-specific sensor system performance. [1], [2] Of equal importance, the method also informs appropriate data collections and enables the design of sensor systems that optimize task performance in the presence of known device characteristics and system constraints. The key insight of the TSI approach is that task-specific performance is optimized by maximizing the mutual information between the data and the measurement outcome. Note that this is very different from a conventional data processing approach, which seeks to make the output (e.g. an image) "look like" the scene. A caveat is that arriving at an equivalent measure of information for soft inputs such as opinions, is still a tremendous challenge.

The SDIF model is designed to demonstrate a system of systems that accomplishes a series of tasks:

- Facilitate the gathering of information from a system, driven by the specific needs of a given user.
- Autonomously determine how to weigh, trust, and process new information and evidence into the system.
- Provide a rigorous and physically and semantically consistent picture of the space domain via hard and soft input information fusion.
- Discover previously unknown elements of space objects and events via the leveraging of Object Based Production and ontological frameworks.
- Provide space object behavior and event predictive capabilities that are probabilistically quantifiable.
- Demonstrate the art of the possible in terms of decision-making processes and enabling command and control products and services.

The SDIF model provides a closed-loop information framework that can satisfy a variety of user needs, with a broad range of operational concerns, where the knowledge of the space domain is the same. The framework provides a common operating picture that is consistent for all users. The model consists of six main levels as shown in Figure 1 and described in summary as follows.

Level 0

Here, raw data enter the system. These data sources include hard inputs from a variety of sensors and historical surveys, as well as soft inputs such as United Nations guidelines, European Union codes of conduct, country-specific doctrine and cultural beliefs, press announcements, and other open source literature. Both are important in predicting, quantifying, and assessing space object behaviour including space threats and hazards. The focus should not be constrained to information that may only seem to be relevant to the space domain, but all information, as numerous and as disparate as possible. The reason for this is that the Space Domain Information Fusion model, coupled to the exploitation of Object Based Production and ontologies, will see to discover things regarding the behaviour of space objects and events via correlations with any seemingly unrelated information. For instance, what if there is movement of certain space objects prior to each G7 summit? One would never know this unless these events could be easily linked and correlated. The following are examples of information sources:

- Information relevant to space object operational status:
  - Owner/operator telemetry.
- Information relevant to space object and event behavior and dynamic models:
  - Thruster activity.
  - Thermal profile (radiation and energy balance).
  - Solar/Earth Radiation and Earth Albedo.
  - Outgassing.
- Information relevant to non-dynamic models:
  - Sensor performance (noise, biases, and latencies).
  - Sensor locations and Earth Orientation Parameters (EOPs).

- Media corrections (atmospheric refraction, signal delays, etc.).

- Space Object and Event background, context, and sensor/meta-data:
  - JSpOC or country mission catalogs: TLEs, VCMs, state vectors, conjunction assessments.
  - Observations from ground or space based sensors.
  - Commercial data providers (e.g.: AGI, GMV, ISON, Airbus, Zodiac Systems).

- Space Object and Event historical and country-specific behavior:
  - Known break-up events.
  - Known anti-satellite (ASAT) weapon tests.

- World history, news, and geopolitical information:
  - Councils, Summits, Wars/Armed Conflicts, etc.
  - Financial trends, events, etc.

Level 1

This forms the heart of the system: it is the foundational piece that must be correct. The space domain is described through Object Based Production with inter and intra relationships between objects that reside in it as well as external influences described by a dynamic ontology. A behavioral database, models of the physics, and other information about the space domain 'universe' are at this level. This is where all incoming information and evidence is stored, before and after processing, and where past, current, and predicted knowledge and beliefs about our universe reside. The fundamental function of this level is to go "from data to discovery": it is designed to leverage big data science and analytic methods. Whenever anyone wants to know something regarding space objects and events, this is where that information will be drawn from and if absent, will generate an information request that will be sought to be achieved. This graph-based database also contains and maintains various representations of uncertainty and ambiguity associated with the data. At this level, no judgements are made regarding the behaviour of space objects and events. Here are examples of categories and mechanisms of information to be stored and managed:

- Object Based Production and Ontologies:
  - Consistent and rich representation of space objects and events that facilitates linking of large and disparate sources of information.

- Behavioral Context and History:
  - Cultural/societal perspectives.
  - Known past behavior and events.
  - Geopolitical positions.

- Physics Based Models:
  - Space Environment.
  - Space Objects.
  - Astrodynamics.

    - Sensor and Information Systems.
- Information Storage and Management:
    - Dynamic nature.
    - Concurrent access and sharing.

Level 2

This is where our beliefs and knowledge in Level 1 are subjected to critical scrutiny. Here also we assess the degree to which any new evidence can be trusted, and if the evidence indicates that our beliefs should change, to what extent we allow that change to be made or our confidence in our belief to be adjusted. What do we do when evidence seems to conflict each other? How do we quantify, incorporate, and fuse the information we might find in someone's opinion? So far, no specific questions have been asked of the information; the intent is simply to update knowledge of the universe as described to the extent possible given the evidence provided. No judgments are made.

Once our beliefs have been rectified (confirmed, changed, or neither because any new evidence was unrelated) any changes are propagated back to Level 1 to bring our knowledge up to date. *This is important to note!*

Level 3

Here is where we ask specific questions about things in our universe and where the tools of TSI are brought to bear to make judgments about those things and their relationships. Users will supply their own questions and decision-making criteria. For example, to one user an object 1 km from a specific space asset may be threatening. Another may be comfortable with a separation as small as 100 m. Level 3 takes the knowledge from Level 1 and assesses it against user-defined criteria.

By keeping Levels 2 and 3 separate from Level 1, users can apply different evidence and judgments to the information without changing how space objects are defined and represented. In this paradigm, the picture of the space domain is consistent regardless of the specific user.

Level 4

At Level 4, decisions are made by addressing questions such as, "Should I do something?", "If I do this, what is the expected effect?", "What other information do I need to decide between these three courses of action?" Some courses of action might be predetermined by the user, and others not. The user may simply be looking for a body of evidence of something occurring in the space domain that concerns them.

A not-so-subtle issue at this level is the notion of confidence. If the user is concerned with having any other space object within 1 kilometre of their own, how accurately must we know the answer? If our answer were, "object X will be within 1 kilometre of object Y tomorrow at noon UCT" the customer will ask, "what's the error on that?" If our reply is, "+/- 10 kilometres" the customer may likely choose to do nothing because the level of uncertainty may not warrant the effort and risk. Thus, it is critical to now only have the customer's criteria for warning or notification, but also the level of knowledge required to enable a decision. This is part of what is meant by providing "actionable" knowledge.

Level 5

Any output from Level 4 that leads to a requirement for further information passes to Level 5 where sensors and information sources are tasked to collect new information. Other non-information gathering actions may also be tasked. A prioritized list of actions is established and executed. The user has a lot of flexibility into what happens at this level.

4.0 SPACE SURVEILLANCE AND TRACKING

As defined by the United States Strategic Command (USSTRATCOM), Space surveillance involves (but is not limited to) detecting, tracking, cataloging and identifying man-made objects orbiting Earth, which include active/inactive satellites, spent rocket bodies, debris, and fragments. Space surveillance accomplishes the following:

- Analyze new space launches and evaluate orbital insertion.
- Detect new man-made objects in space.
- Chart present position of space objects and plot their anticipated orbital paths.
- Produce and maintain current orbital data of man-made space objects in a space catalog.
- Inform NASA and other government entities if objects may interfere with the orbits of the Space Shuttle, the International Space Station, and operational satellite platforms.
- Predict when and where a decaying space object will re-enter the Earth's atmosphere.
- Prevent a returning space object, which to radar looks like a missile, from triggering a false alarm in missile-attack warning sensors of the U.S. and other countries.
- Determine which country owns a re-entering space object.
- Predict surface impacts of re-entering objects and notify the Federal Emergency Management Agency and Public Safety Canada if an object may make landfall in North America or Hawaii.

It is important to note that USSTRATCOM developed and implemented this process and sensor network since the launch of Sputnik. As such it has been improved in an evolutionary process and does not represent the art of the possible in terms of space surveillance capability. If one were to develop a Space Surveillance and Tracking network and system at present, it would probably not look (or operate) like the USSTRATCOM Space Surveillance Network (SSN).

4.1 SSN Sensors (taken directly from a USSTRATCOM Fact Sheet)

The SSN uses a series of sensors to achieve its mission. Below is a brief description of each type of sensor:

Phased-Array Radars can maintain tracks on multiple satellites simultaneously and scan large areas of space in a fraction of a second. These radars have no moving mechanical parts to limit the speed of the radar scan - the radar energy is steered electronically. A detection antenna transmits radar energy into space in the shape of a large fan. When a satellite intersects the fan, energy is reflected back to the detection antenna, where the location of the satellite is computed. Two examples of these radars include Cavalier AFS in North Dakota and Eglin AFB in Florida.

Conventional Radars use moveable tracking antennas or fixed detection and tracking antennas. A tracking antenna steers a narrow beam of energy toward a satellite and uses the returned energy to compute the location of the satellite and to follow the satellite's motion to collect more data. These include radars include the Altair complex at the Reagan Test Site in the Kwajalein Atoll and the Haystack Millstone facility at the Massachusetts Institute of Technology.

Electro-Optical Sensors consist of telescopes linked to video cameras and computers. The video cameras feed their space pictures into a nearby computer that drives a display scope. The image is transposed into electrical impulses and recorded on magnetic tape. This is the same process used by video cameras. Thus, the image can be recorded and analyzed in real-time.

Midcourse Space Experiment (MSX) satellite is a low-earth orbiting satellite system with a payload containing a variety of sensors, from UV to very-long-wave IR. Originally a platform for Ballistic Missile Defense Organization (now known as the Missile Defense Agency), the MSX was moved to the SSN in 1998.

Ground-Based Electro-Optical Deep Space Surveillance sites assigned to Air Force Space Command (AFSPC) play a vital role in tracking deep space objects. Between 2,000 and 2,500 objects, including geostationary communications satellites, are in deep space orbits more than 22,500 miles from Earth.

The SSN sensors are categorized as dedicated (those with the primary mission of performing space surveillance) or contributing and collateral sensors (those with a primary mission other than space surveillance). Combined, these types of sensors take between 300,000 to 400,000 observations each day.

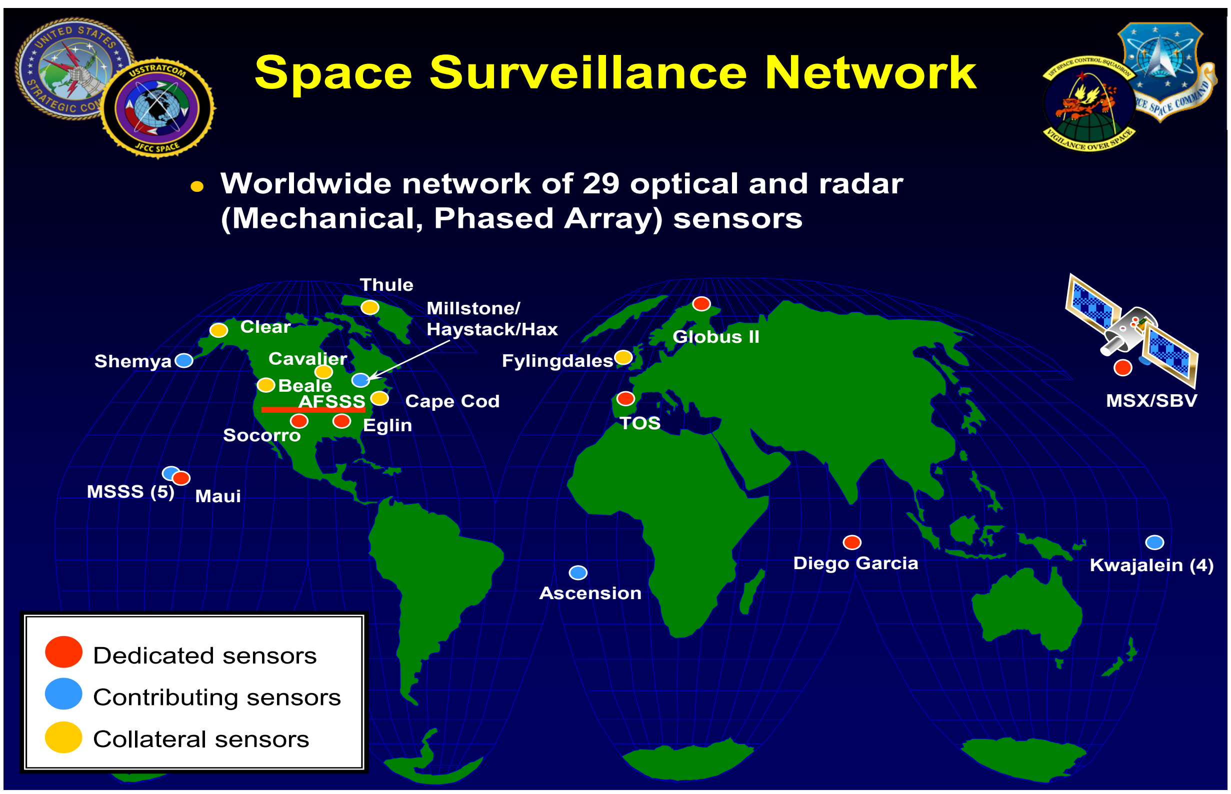

Figure 2: Space Surveillance Network.

4.2 Space Object Tracking

Without loss of generality, tracking an individual in a population implies an ability to “tag” (read uniquely identify) the individual and monitor this individual through time/space/frequency with quantifiable ambiguity or uncertainty, evaluating the interaction of the individual with others and its environment. However, if an individual cannot be physically tagged (or labelled) in a uniquely identifiable way, this poses serious limitations and challenges to space surveillance and tracking, which is indeed the case we face.

Tracking a space object means that one can identify this object with quantifiable and acceptable ambiguity, and reconstruct and predict its behaviour (usually referring to its location or motion). When this is constrained to the object’s trajectory or flight path, this process is more commonly known as orbit determination and prediction as shown schematically in the following figure.

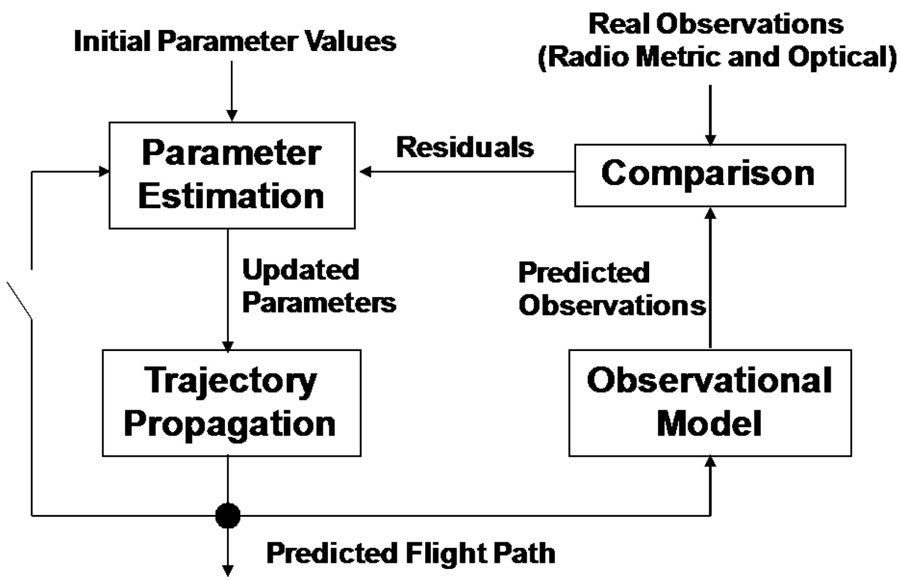

Figure 3: Orbit Determination Process.

Orbit Determination (OD) is the process of adjusting trajectory models to best match the observed tracking data, and quantify the error associated with the trajectory estimated. The collected tracking data are the actual or *Observed* measurements. The trajectory models produce predicted or *Computed* measurements. Then, what are termed Data *Residuals* = *Observed* – *Computed* measurements. The OD method typically aims to minimize the residuals by adjusting the trajectory models. These residuals are minimized in a weighted least-squares sense. The OD process accounts for measurement accuracies and accuracies with which parameters were known before taking measurements (*a-priori uncertainty*). The OD produces (a) an updated trajectory estimate and (b) an estimate of error associated with current trajectory prediction. The various forces influencing the motion of the space object must be understood [8]. An example list of these forces, follows:

- Gravitational forces:
  - Dominant body force (dominant body is treated as spherically symmetric; produces pure Keplerian motion).
  - Non-dominant body forces (third body forces).

  - Dominant body gravity field asymmetries.
  - General relativistic effects.

- Non-gravitational forces:
  - Thruster activity:
    - Trajectory Correction Maneuvers or Orbit Trim Maneuvers.
    - Attitude Control System.
    - Angular Momentum Desaturations (AMDs).
  - Solar radiation pressure and Earth Albedo/Radiation.
  - Thermal radiation.
  - Aerodynamic effects (Drag).
  - Gas leaks (real or compensative):
    - Propulsion system.
    - Outgassing.
    - Unknown/unmodeled accelerations.

OD, especially for uncooperative space objects, requires scientific detective work. Applying the scientific method as an ongoing process is what successful OD requires (refer to Figure 4). The OD process is subjective in that the result is not unique given a variety of assumptions on the space environment models, the astrodynamics models, and the sensor or observation system models. Moreover, the result will also differ depending on what states and parameters are estimated and the assumed prior uncertainty on these. There is a finite amount of information contained within any given set of data and the resulting state estimate greatly depends upon what is asked of the data.

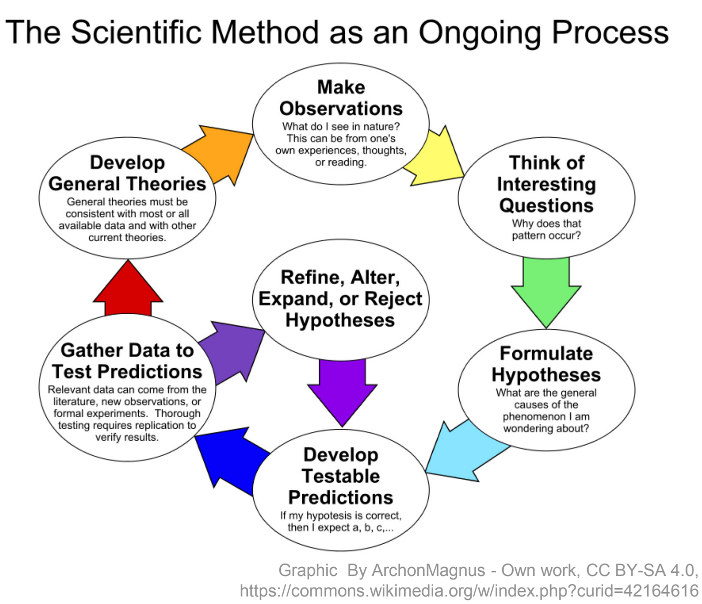

Figure 4: Scientific Method as an Ongoing Process.

Determining a space object's orbit is typically much easier than predicting it. In order to best predict a trajectory, the OD process must attempt to not only reconstruct the trajectory of the space objects but also infer or refine knowledge of key model parameters, dynamic and non-dynamic. The only way to demonstrate that one truly understands the space object's behavior and its interaction with the space environment is via the ability to accurately predict its behavior as corroborated by future observations.

Trajectory Prediction involves accurately modeling and estimating all past forces and events, as well as predicting all forces and future events. This includes the current *Estimated* trajectory error, as well as all future, or non-estimated errors that can also contribute (*Considered* error sources). More specifically, there is a need to consider [4] the error contribution due to any uncertainty in model parameters that cannot be estimated in the OD solution. For maneuvering space objects, future thrusting events are uncertain (even if predicted) and must be included as potential uncertainties that cannot be estimated (i.e. there is a random error in every thrusting event). Many times the orientation, size, and material properties of the space object are unknown and their uncertainty should be considered upon the influence and uncertainty in the predicted trajectory as well.

OD cannot be absolutely validated because the collected data do not have *observability* [9] into all components of state. There are several indicators of solution quality: Regarding quality of fit, are the Data Residuals mean zero with no systematic trends? Regarding estimated parameters, are estimates realistic, within *a-priori* uncertainties? The solution quality can be trended by comparing various solution strategies that are:

a) Data span dependent;

b) Data type dependent;

c) Sensor dependent; and

d) Model assumptions dependent.

One of the most challenging tasks in space surveillance is in associating detections to unique objects. Many studies and analyses regarding space surveillance make two fundamentally flawed assumptions:

1) If the space object is in the sensor field of view, it is detected with a probability of one; and

2) If a space object is detected, it is known which space object generated the detection.

The problem with the first assumption is that the probability of detection is never exactly one; several things contribute to the total probability of detection. The probability of detection is comprised of three components:

1) A sensor-dependent component;

2) A dependence on everything between the sensor and the object; and

3) An object dependent component.

Rarely, if ever, are all three components known with absolute certainty. The problem with the second assumption is that there is always some level of ambiguity in the detection-to-object assignment unless the object is transmitting/transponding a known frequency.

This was the challenge raised earlier in the context of being able to uniquely tag and track individuals in the population. To highlight the extent of this issue please refer to Figure 5 which shows a plot of detections made in a single night by the Space Surveillance Telescope (SST) located near Socorro, New Mexico. Every dot is a detection generated by a space object in various orbital regimes: Molniya (highly eccentric orbits or HEO), Mid Earth Orbit (MEO) with Global Navigation Satellite Systems (GPS, etc.) and the near Geosynchronous regime (GEO). All of the dots that are black are detections that were associated/correlated to unique known objects. All of the other dots are detections generated by space objects that are unknown. At least 50% of all detections are generated by unknown (read untracked) objects. This is a major unresolved issue.

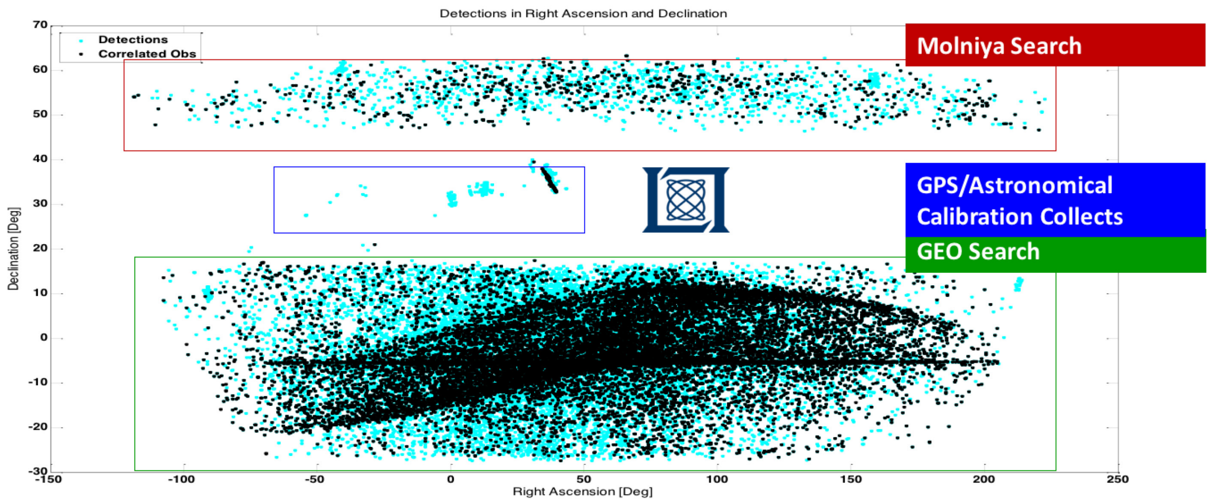

Figure 5: Correlated vs. Uncorrelated Detections from the Space Surveillance Telescope (SST).

In essence, the problem is: given a series of observations (tracking data), determine which detections belong to unique objects and compute their trajectories. One mechanism for performing this is via Joint Probabilistic Data Association (JPDA). A simpler approach is Nearest Neighbor (NN) which is somewhat captured in the schematic that follows, but this simpler approach tends to suffer from higher false positives (i.e. associating data from objects that are not the same, assuming a unique object).

Figure 6 shows a series of unassociated detections at an initial time, then a set of hypotheses are computed from these. These hypotheses are compared to future data, and the hypothesis with the highest likelihood agreement (exploiting the Mahalanobis distance) is assigned to the detection in question. Hypotheses that are the most unlikely tend to be pruned.

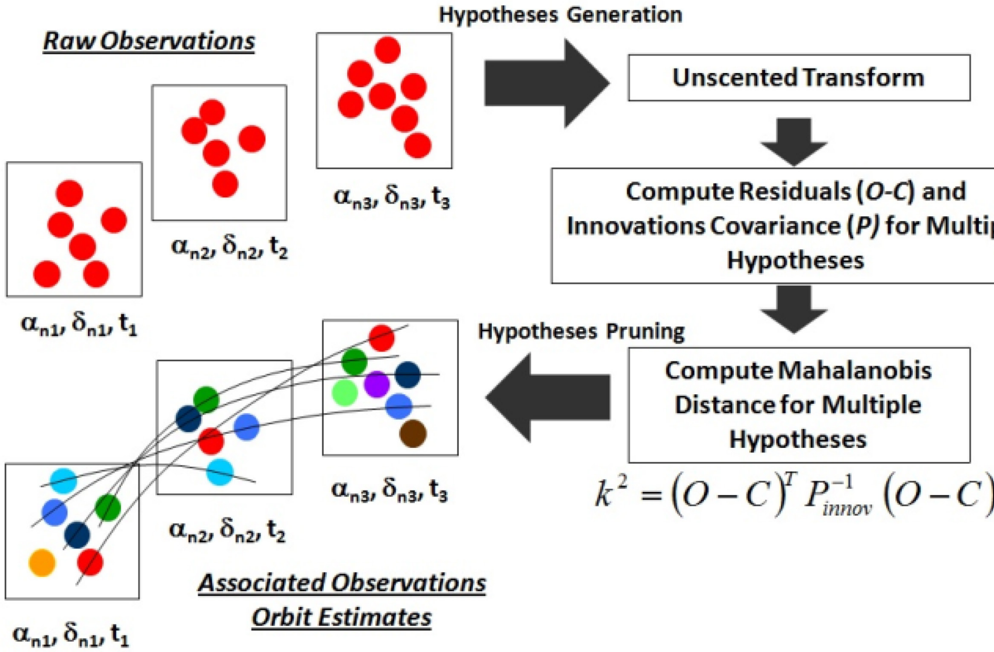

Figure 6: Data Association.

The goal of multiple hypothesis [5] testing is to converge on the correct hypothesis by pursuing an inductive reasoning approach whereby the data are used for their ability to identify and remove the wrong or unlikely hypotheses. Any surviving hypotheses at any given time have a statistical likelihood of explaining past observations. The following provide more insight into the difficulties of data association.

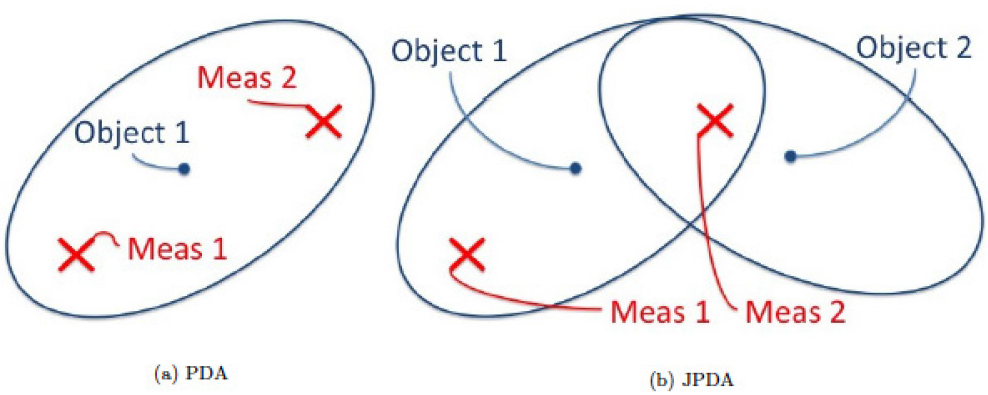

Figure 7: Probabilistic and Joint Probabilistic Data Association.

Let us examine the concept of the JPDA [3]. Assume we have two known space objects that we are tracking and we have just received two detections (measurements) as in Figure 7b. The ellipses surrounding each object represent the object's uncertainty projected (or transformed) into the reference frame where the measurements are represented, assuming that the uncertainty can be represented as a Gaussian probability distribution. There are many occasions when this is not the case and thus care must be taken in considering realistic measures of uncertainty [5], [6]. Figure 8, below, shown a comparison of orbital probability mass distribution against uncertainty represented as a Gaussian assumption versus one that allows the representation to adapt to the underlying propagated errors called AEGIS [5], [6]. It is seen how the Gaussian error ellipses do not conform to the shape or density distribution of error in the orbital plane. All decisions are based upon the assumed uncertainty so if it is grossly inaccurate then only flawed decisions can be the result.

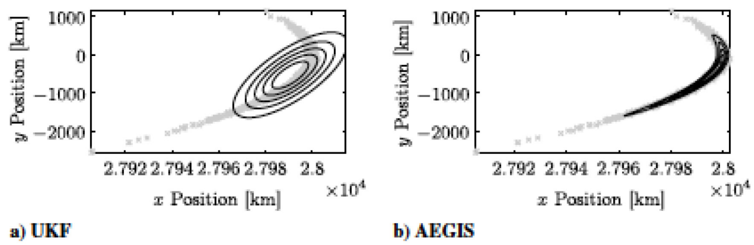

Figure 8: Comparison of Orbital Probability Mass Distribution Against Uncertainty Representation.

What are the possible joint events or hypotheses that could explain the scenario in Figure 7? Table 1, below, enumerates these and all of them could be possible and thus must be considered in the tracking framework. As the number of objects and detections increases, it can be seen that the combinatorics involved invokes the need of computational capacity and efficiency to say the least.

Table 1: JPDA Scenario Example.

Joint Event	Marginal Events	Object# Associated with Measurement: 1	2	Event Description
Θ_1	$\theta_{0,1}, \theta_{0,2}$	0	0	Meas. 1 & 2 from clutter
Θ_2	$\theta_{1,1}, \theta_{0,2}$	1	0	Meas. 1 from Obj. 1, Meas. 2 from clutter
Θ_3	$\theta_{0,1}, \theta_{1,2}$	0	1	Meas. 1 from clutter, Meas. 2 from Obj. 1
Θ_4	$\theta_{0,1}, \theta_{2,2}$	0	2	Meas. 1 from clutter, Meas. 2 from Obj. 2
Θ_5	$\theta_{1,1}, \theta_{2,2}$	1	2	Meas. 1 from Obj. 1, Meas. 2 from Obj. 2

Not considering any of these joint events could lead to errors in the future because we may be missing important information and this could lead to a degraded tracking capability. To this point, there are actually more joint events to consider in the prior scenario that we did not include such as the joint event of measurement 1 having originated from object 2 which performed an unknown (therefore unmodeled) propulsive maneuver. Other domains such as air, ground, etc. may not require an accurate knowledge of the physics because they tend to be data-rich environments (i.e. there are many measurements available). However, the space tracking problem, specifically space surveillance, tends to be data-starved and thus the physics must be relied upon to properly predict the motion in between sparse observations.

5.0 SUMMARY

In order to develop and maintain a database or catalog of space objects and events, and perform space surveillance and tracking successfully, all of the elements presented in this paper must be brought together very skillfully and effectively. Data must be properly collected, transformed, stored, managed, rectified, fused, exploited, disseminated, etc. Great care must be taken in making assumptions and avoiding the temptation to assume more than what the data and information available allow or indicate. Being successful requires an ability to do the proper "detective" work and learn as much as possible from the data for the purpose of improving one's predictability of future behavior. Many people can reconstruct events and trajectories but few can predict them because prediction requires one to know and understand the underlying system. The SDIF model is the framework that drives the entire process and it should be driven by user needs and requirements. Without the SDIF model, the output of the tracking and surveillance will be less useful to user needs or may not satisfy them entirely. Of great importance is the ability to quantify and realistically represent the uncertainty of the system. Most people make the assumption that all of the errors are Gaussian but there is substantive evidence that this assumption is oftentimes flawed, dependent upon the scenario. The focus should be on uncertainty realism versus blindly constraining oneself to Gaussianity. Last but not least, one must understand the data that one is collecting, receiving, and processing. Many errors in what is inferred from the space surveillance activity can be attributed to exploiting measurements under invalid assumptions.

6.0 REFERENCES

[1] Ashok, A., Baheti, P. K., and Neifeld, M. A., "Compressive imaging system design using task-specific information," Applied Optics, **47**, 4457-4471 (2008).

[2] Baheti P. K. and Neifeld, M. A., "Recognition using information-optimal adaptive feature-specific imaging," J. Opt. Soc. Am. A, **26**, 1055-1070 (2009).

[3] J. Stauch, T. Bessell, M. Rutten, J. Baldwin**,** M. Jah, K. Hill, (2016). *"Mutual Application of Joint Probabilistic Data Association, Filtering, and Smoothing Techniques for Robust Multiple Space Object Tracking,"* AIAA Journal of Guidance, Control, and Dynamics, Special Issue on Space Domain Awareness, Submitted (5/16/2016).

[4] Stauch, J., Jah, M., (2015). *Unscented Schmidt-Kalman Filter Algorithm*. AIAA Journal of Guidance, Control, and Dynamics, Vol. 38, No. 1, pp. 117-123.

[5] DeMars, K., Bishop, R., Jah, M., (2013). *Entropy-based Approach for Uncertainty Propagation of Non-linear Dynamical Systems.* AIAA Journal of Guidance, Control, and Dynamics, Journal of Guidance, Control, and Dynamics Vol. 36, No. 4, pp. 1047-1057.

[6] DeMars, K., Jah, M., (2013). *Probabilistic Initial Orbit Determination Using Gaussian Mixture Models.* AIAA Journal of Guidance, Control, and Dynamics, Journal of Guidance, Control, and Dynamics Vol. 36, No. 5, pp. 1324-1335.

[7] DeMars, K., Jah, M., Schumacher, P., Jr., (2012) *Initial Orbit Determination Using Short-arc Angle and Angle-rate Data*. IEEE Transactions on Aerospace and Electronic Systems, 48(3):2628–2637, July.

[8] K. Hill, C. Wetterer, M. Jah, (2014). *"Comparison of Gravitational, Third-Body, and Radiation Pressure Perturbations in Orbit Propagation"* AAS/AIAA Space Flight Mechanics Meeting, Santa Fe, NM, January 26-30, AAS 14-396.

[9] DeMars, K., Jah, M., (2011). *Evaluation of the Information Content of Observations with Application to Sensor Management for Orbit Determination*, AAS Paper 11-606, 2011 AIAA/AAS Astrodynamics Specialists Conference, Girdwood, AK, July 31 – August 4.