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A Future Look at Space Surveillance and Operations

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A Future Look at Space Surveillance and Operations*

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This paper introduces a concept that could support future space surveillance needs, while meeting fiscal constraint during the development. A brief history is included to provide an introduction into the development of some current systems. In particular, we trace the events of the late 20th century that first compelled nations to devote resources to developing space surveillance capabilities. Because space surveillance ultimately relies on the processing of observational data to determine current and future positions for satellites, we include a summary of the major differential correction techniques. The goal is to introduce some of the more common differential correction techniques in use today, with an emphasis on the computational requirements for each technique. The computational aspect is a key area to investigate for any future system. The ***Orbit Determination Interactive Network*** (***ODIN***) concept is then explored as a candidate technique that embraces proven military structure (centralized control and decentralized execution), and combines robust survivability, redundancy, accuracy, scaleability, and fiscal conservatism to provide maximum capability to the military and civilian space users of today and tomorrow. Our focus is on a military solution and use, but we recognize the importance, and foresee the ultimate solution being a combined international resource that will operate much as the *Federal Aviation Administration* (FAA) operates today. A discussion is presented to give the advantages of this type of system, and some tough questions that may be asked. We conclude with a brief discussion of how to implement this type of strategy.

1. Historical Background

The launch of Sputnik caught the West largely “off-guard” with respect to the implementation of algorithms required to determine satellite positional information. Indeed, the mathematical formulation for least squares and propagation had existed for several hundred years, but the intensity of the mathematical relations, and the obvious lack of satellites resulted in a less than rigorous effort to use the techniques. Stars and comets were the primary objects of analysis for several hundred years. Their relatively slow motion permitted a more “casual” approach to a solution—one that often involved months of observation and computational time. Satellites, on the other hand, can cover the entire Earth in an hour or two, significantly decreasing the available time for solution. The advent of the modern computer provided the needed computational power to perform the mathematics. Sputnik was the object to locate.

The development of large-scale space surveillance systems began in the early 1960's. Because *Intercontinental Ballistic Missiles* (ICBMs) were the first practical use for this “fledgling” field, primary emphasis was devoted to warning systems. The tensions of the Cold War helped accelerate the development and we recognize today that the space surveillance system is primarily an artifact from this period. The fact that the systems still exist and function reasonably well is a testament to the ingenuity and vision of the developers in the early 1960's.

In this decade, we've noticed an increase in the commercial use of space. The recent loss of Galaxy 4 on May 19, 1998 from a control processor failure and the ensuing credit card, television, and cellular communication difficulties made national news. The ***International Space Station*** (**ISS**) requires precise knowledge of all objects to avoid costly (and perhaps unnecessary) maneuvers. These trends call for accurate and timely positional information for all satellites, as well as debris.

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2. Introduction

Space surveillance, when it was formed, was self-serving and lacked an external customer focus. The sites fed observations to a centralized location, and the processor fed element sets back to the sites so they could repeat the process. It served itself, not others, although others required help. The early days of space surveillance concentrated only on a general awareness of orbiting satellites—remember the focus was missile warning. Computer and communication resources were very limited, and support to external customers was difficult.

There are some overall concepts that must be understood before addressing the issue of space surveillance. First, the processing of the observations to determine the satellite's state requires some intense mathematical calculations. The overall process is called ***Differential Correction*** (**DC**) because it iterates to find the best orbit to match the observed data using partial derivatives. It really hasn't been until the last two decades that small and personal computers have had enough power to perform the numerical processing we consider in this paper. In fact, existing studies (NORAD, 1975) actively pursued the minimum number of observations and processing to achieve continuous operations due to the limitations of computers and communications systems.

Another important concept is ***propagation***, or moving the satellite position from one time to another. There are three main methods of propagating the data; analytical (fast and inaccurate), numerical (slow and accurate), and semianalytical (variable speed and accuracy). There are trade-offs with each, but historically, the analytical methods have been chosen for their speed and moderate accuracy. Semianalytical techniques, in particular the *Draper Semianalytical Satellite Theory* (DSST), represent the future course in achieving precise and fast analyses. DSST could replace most existing analytical theories and provide significant growth capability should the need arise. Numerical routines would still be the backbone of all space operations.

We've shown an overview of ***orbit determination*** (the combination of DC and propagation) in Fig. 1 [Vallado (1997, 742)]. Notice the interaction between the observations, the processing, and the ability to determine future satellite positions. We define ***dense observations*** as 200-300 observations per satellite pass. The actual number of observations depends on the orbital altitude, time of contact with the sensor, and capability of the sensor to obtain observations. There is a complex trade-space between the density of observations, the number of stations, the force models, etc. We'll address this later.

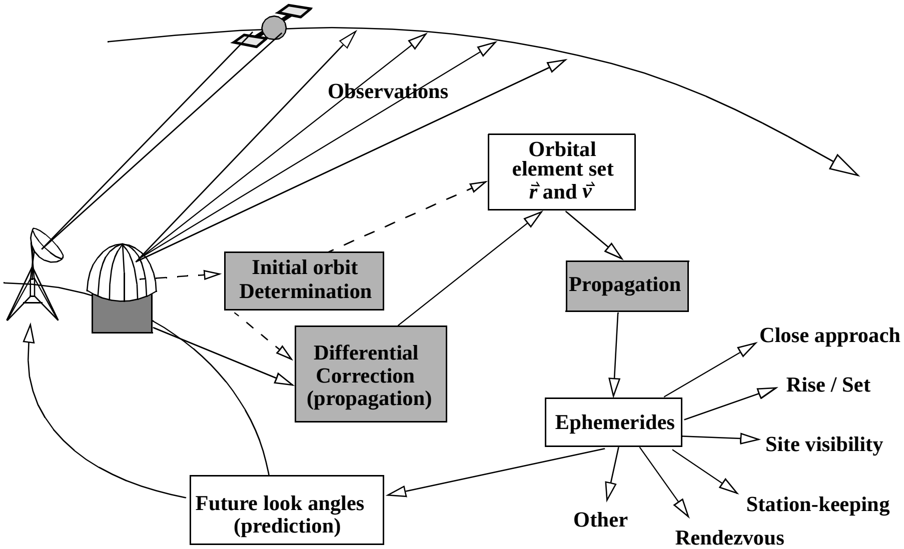

Figure 1. Representation of Orbit Determination. This figure shows the interrelations of initial orbit determination, propagation, and differential correction. Many mission applications, shown at the lower right, require observations, orbital element sets, and ephemerides. Future observations complete the cycle.

Space surveillance is the process by which we observe all objects in orbit. This includes taking observations, processing the data, and distributing and predicting future locations. Space surveillance is the crucial element of effective operations in space, but it's been relegated to the last priority for funding and attention. That's unfortunate because *every* satellite operation relies on this basic data! In addition, every mission relies on precise information about the satellites. The analogy is our thirst to know the location of land, sea, and air forces today—accuracy on the order of several kilometers is not good enough. All source, accurate information dominance will be the central tenent for the future.

Our vision of space surveillance in the 21st century should stress the central importance of space surveillance.

> ***Space surveillance should produce the most accurate product to provide timely support to the users, and to give the owner maximum flexibility in every aspect of operation in the space arena.***

This statement applies to civilian as well as military interests, but it's most likely that the military will be the first implementor as they currently have the majority of the surveillance resources.

2.1 Current Problems

We'll focus much of this paper on a military space surveillance system—the *Space Defense Operations Center* (SPADOC). Although just recently completed, Scientific American (Aug 1997) says *"In 1981 the Pentagon started the Cheyenne Mountain Upgrade (CMU) program to replace the centers' five main computer systems over six years … In 1994 the General Accounting Office reported that the CMU was running 11 years behind schedule and about $1Billion over budget"*. Several additional problems were alluded to at the Space Control Workshop at Lincoln Laboratory (April 1998). Presentations noted deficiencies in the current SPADOC architecture, and it's inability to perform some routine operations. In fact, there were numerous discussions about ad-hoc systems being built and used to supplement SPADOC operations. We feel this is unfortunate for several reasons, the most important of which is the lack of oversight and adequate integration to ensure that replacement systems are truly functional, cost effective, and robust for the future. This situation reminds us of a common occurrence—When do I buy a new car? The answer is when the old one is too expensive, hard to maintain, unreliable, or the features are no longer sufficient. We believe that point is upon us for space surveillance.

Although space surveillance lies at the heart of every operational activity in space (planning, routine and crisis operations, and engagements), use of academic advancements have traditionally lagged within operational systems. From a military perspective, when we consider operating in space, the fundamental principles of war apply—we must always have precise knowledge of the enemy (satellites in this case) over time. Sun Tzu wrote *"what enables the sovereign and the good generals to strike and conquer beyond ordinary men is foreknowledge"*. The fact that many satellites cover the entire Earth in under 100 minutes only magnifies this requirement. From a civilian perspective, we're starting to see the implications of not knowing precise satellite positions. For instance, Telstar 401experienced an electrical discharge on January 11, 1997. Since then, it has been adrift in the *Geosynchronous Earth Orbit* (GEO) belt threatening 19 other satellites. These owners face a decision about maneuvering before each predicted close approach. If they maneuver because the error box is 10km (for instance), but the actual approach is only 350m, precious maneuver fuel is wasted. In fact, it's likely that the attitude control engines could be enough to alter the satellites path to avoid a close approach, given sufficient accuracy. Another example is the crowding of the geosynchronous belt. In January 1998, Telstar 303 and Milstar Flight I were collocated at 120° West longitude. Stationkeeping maneuvers are closely synchronized to keep the satellites at least 20-40 km apart. Future needs may become overly difficult if we continue to rely on a minimal, static performance criteria. More stringent needs exist, but they are often ignored because some current systems can't meet them. It's undesirable and unreasonable to limit space surveillance capabilities because of a decades old system and architectural plan. We need to foster visionary ideas as we strive to lay the foundation for space operations of the future.

Todays number of **uncorrelated targets (UCT**), or satellites that don't match any known satellites is one indication of the larger problem—the accuracy, architecture, and concept of operations of our current space surveillance system. The astrodynamics community has long recognized that we can perform significantly better (at least several orders of magnitude improvement in accuracy) using existing resources (parallel processing, distributed processing, numerical propagation, and dense observations). These ideas were well documented at the PL Astrodynamics Division workshop in December 1993, and the US Naval Observatory in 1993.

We feel that the limited analytical theories used by the military (*Simplified General Perturbation*s, SGP4 and *Position and Partials as functions of Time*, PPT3) have served well for several decades, but must not continue to constrain progress. In addition, the two separate theories (SGP4 and PPT3) are *not* truly compatible, and inconsistencies exist when using datasets of one as inputs for the other. The worldwide astrodynamics community recognizes the need to replace SGP4/PPT3 (April 1997 MIT/LL Space Control Conference, August 1994 AIAA panel discussion), and has developed numerous robust mathematical techniques to solve today's operational deficiencies (capacity, accuracy, timeliness, flexibility, etc.).

The limited analytical theories should be replaced with Special Perturbation (Numerical, SP, or *complete force-model* semianalytical techniques [Draper SST]) for both Differential Correction (DC) and propagation operations. In fact, we are pleased that both services are pursing development of numerical systems today. Real-time Kalman filter systems (like the *Real Time Orbit Determination System*, RTOD, that we'll discuss later) also represent a technique that has extreme potential for space surveillance, and will likely provide all near real-time data in the future. Maximum likelihood estimators also show promise to meet future demands.

Finally, personnel issues are inextricably linked to the process. Although the theoretical foundation is well known, the "man-in-the-loop" still introduces an unknown variability in the final solution. The constant movement of military personnel further exacerbates the problem. Often by the time an operator reaches proficiency, a duty change nullifies the experience gains. Automation alone can't solve this problem.

Correcting these and other problems will not be easy to implement, and will cost some money to fully implement, but we can approach the solution incrementally. We'll consider a scenario using the Navy's new resources to cover an initial transition period. The time of Navy operation allows us to phase-in virtually every aspect. This minimizes a one time system shock, spreads the fiscal burden, but also gives us incrementally improved capability.

2.2 How Accurate?

The accuracy of current sensor systems is often questioned. The discussion often suggests that highly accurate orbit determination isn't possible because of the available data. The facts say otherwise. There are numerous international satellites for which the ephemerides are routinely known to a few meters or less. The *Space Surveillance Network* (SSN) sites that supply SPADOC are capable of producing data that can form orbits to a few tens of meters for *low-Earth orbiting* (LEO) satellites. This fact was demonstrated by Fonte (1994) in the real-world, and numerically validated by Vallado and Carter (1997).

With this in mind, we propose a new set of accuracy standards designed to challenge the current system, but to still be within reach. We distinguish between LEO, and GEO satellites as the orbital processing is slightly different. We intentionally avoid further distinctions as we could get lost in defining accuracies for "all" orbit classes. It's also important to analyze the effects of propagating the state vector, thus we give prediction accuracies over time.

- Under 30m for all LEO satellites including a one day prediction. 200m for a one week prediction on all LEO satellites.
- Under 50m at epoch and for a one day prediction for all highly eccentric orbits (similar to the Molnyia). 350m for two week predictions on all deep space satellites.
- Under 100m at epoch and for a one day prediction for all deep space (past semi-synchronous and including GEO). 600m for two to three week predictions on all deep space satellites.

Once these goals are met, we should plan for even higher accuracy. If the look ahead (in the future) shows we're adequate but need to fix another aspect, we should work in that direction. We can't extract all the benefits of space if we don't examine every aspect of the space surveillance operation.

The processing and data collection must also support these accuracy requirements. We'll consider debris as the primary driver. We must protect our satellites from unanticipated collisions with debris.

2.3 Future Challenges

Future satellite systems will likely stress even the most robust space surveillance systems. The primary driver here is the growth of the Space catalog (Miller, 1998). Low Earth orbiting commercial satellites pose the immediate challenge. As we witness large commercial satellite constellations (like Teledesic at over 200 satellites in low Earth orbit), it's obvious that we don't have the ability to maintain even the existing level of performance. The debris campaigns performed with SPADOC suggest we can surge for an additional 50 objects or so with numerical processing—long term tracking is less likely. The addition of over 200 new satellites will place significant burdens on the current operational system.

An additional concern is the increased risk of collision posed by the increasing use of space. The French Cerise satellite collision on July 24, 1997 highlighted our current inability to predict close approaches in a timely manner. This will only worsen in the future.

Although some integrated approaches try to limit the scope and accuracy of catalogs, this ignores the inevitability of future requirements and normal growth. The current FAA dilemma of aging computer and control systems is an example. Any future architecture for space surveillance should learn from this experience and not repeat it. The size and characteristics of the objects that we need to track directly influences the overall number. The ISS is a perfect example. Much of the ISS analysis suggests that most of the conjunctions come from satellites *not* in similar orbits to the station, but rather in highly eccentric orbits that cross the ISS's path, and many of them are debris. Estimates for total space debris range as high as 30,000-50,000 pieces that are larger than 1 cm. Some approaches consider only functioning satellites for ISS analysis. In fact, a rationale to track all objects is seen in a simple example—a satellite that's crippled by a piece of debris is just as inoperative as one that's hit by another functional satellite!

3. Theoretical Background

It's useful to review the mathematics of differential correction so we can appreciate the foundation behind any upgrade efforts. Ultimately, it is these equations that will enact any plan and concept that is developed for space surveillance. In addition, there are some nuances that are necessary for understanding the concept.

The primary relations to process observational data rely on the statistical processing of the data. The basic linear least squares model gives the underlying mathematics for the answer (Vallado, 1997, 673)

$$\hat{\boldsymbol{X}} = (\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{b} = \boldsymbol{P}\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{b} \tag{1}$$

where $\boldsymbol{X}$ is the satellite vector, $\boldsymbol{A}$ is the partial derivative matrix of the state with respect to the observations, $\boldsymbol{W}$ is the weighting matrix, and $\boldsymbol{b}$ is the residual matrix.

Unfortunately, the satellite problem is highly non-linear, and we use a non-linear form of least squares (Vallado, 1997, 679-680)

$$\delta\hat{\boldsymbol{x}} = (\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{W}\tilde{\boldsymbol{b}} = \boldsymbol{P}\boldsymbol{A}^T\boldsymbol{W}\tilde{\boldsymbol{b}} \tag{2}$$

where for a state-space dimension of 2, with N observations,

$\boldsymbol{A}$ ⇒ partial-derivative matrix ($N \times 2$)
$\boldsymbol{A}^T$ ⇒ $\boldsymbol{A}$ transpose ($2 \times N$)
$\delta\hat{\boldsymbol{x}}$ ⇒ corrections to the state vector(2×1)
$\tilde{\boldsymbol{b}}$ ⇒ residual matrix ($N \times 1$)
$\boldsymbol{W}$ ⇒ weighting matrix ($N \times N$)
$\boldsymbol{P}$ = $(\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}$ ⇒ covariance matrix (2×2)

Notice the difference in that we're now estimating corrections to the state, and not the final answer. This is the primary technique for processing observational data. The residual matrix is now the differences from the nominal state estimate—a reality when using a Taylor series expansion. The nominal state usually comes from prior knowledge, although it can also come from initial orbit determination methods.

Although least squares is a powerful mathematical tool, it's helpless in the face of a poor physical understanding of the problem. In astrodynamics, covariance analysis, sometimes called error analysis, is used to evaluate how the type, amount, quality, and distribution of observation data affect the performance of the estimation process. This is often done as part of mission planning to determine required sensor assets and models to use in data reduction and planning for mission support. Actual data isn't needed—just observation models and partial derivatives, noise characteristics, and assumed tracking schedules and sensor locations.

The covariance matrix $(\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}$ contains the variances and covariances of the solution parameters (state space) and indicates a measure of observability of the parameters from the available data types, as well as the effect of noisy data on the estimated parameters. Again, these statistical values will be accurate *only* if our choice of mathematical models matches reality and the calibration values are correct. Our choice of models depends on our understanding of the *physics of the problem*. It's also significant that the region within which the implicit linearity assumption holds must include the region of uncertainty (i.e., the $\pm 3\sigma$ region). Otherwise, the covariance matrix may not represent the actual errors. In fact, with limited analytical theories and insufficient data, the covariance matrix is generally irrelevant.

However, results of dense observations and numerical processing have shown that the covariance is quite relevant, and can even provide information about the performance of the sensor (Fonte 1994 and Phillips 1995) given adequate data and communication processing. Incidently, this study showed that single station dense observational data could produce a vector that was good to about 12 m after an 18 hr propagation. As we processed the data over a period of time, the covariance became a reliable method of determining the accuracy of the fits—each covariance matrix showed about a 3-5m overall RMS position accuracy. As we processed new data one day, we noticed the covariance settled around 50m. Upon calling the site, we found they were having mechanical difficulties and they were surprised we knew of their difficulties before they notified us!

Vallado and Carter (1997) extended these results to examine how you could process between data collections and still maintain a certain level of accuracy. They showed that one could numerically propagate one week between observations while maintaining better accuracy than daily analytical updates. After presenting the paper, we received a call from NASA who employed the "dense-obs" technique to an interplanetary satellite with stunning success.

To solve the tough satellite orbits of drag or solar radiation pressure, we must know the *Ballistic Coefficient* (the true BC, not a modified parameter), the true solar radiation coefficient, the sensor biases (which can become quite numerous for many sensor sites), etc. Much of this analysis requires precise knowledge of the satellites *attitude*. Each of these parameters, called ***solve-fors***, are estimated during differential correction runs. They are usually treated as static parameters during processing, but some current work is investigating the effect of allowing them to vary with time, and to let them change with subsequent passes. The more parameters you estimate, the more data you need to arrive at a good solution. Unfortunately, the sparse observations that support SGP4/PPT3 do not support numerical processing that requires BC, solar radiation pressure coefficient, etc.

Sequential batch techniques exist that process new data, but still retain the previous epoch, and covariance at the epoch time (Vallado, 1997, 704-705). This technique is often labeled a sequential method, and is often confused with Kalman Filtering techniques. There is a difference between the theory and practice. The main indicator of which technique is used is the treatment of the covariance matrix. If the covariance is not formally moved to the new epoch time through rigorous mathematical relations, it's probably a sequential batch routine. We'll introduce true filtering applications shortly.

To arrive at the traditional sequential batch relations, we substitute the linear least squares relations to give us a new state correction and updated covariance matrix as:

$$\begin{aligned} \delta\hat{\boldsymbol{x}}(0|k+1) &= (\boldsymbol{A}_{new}^T\boldsymbol{W}_{new}\boldsymbol{A}_{new} + \hat{\boldsymbol{P}}_k^{-1})^{-1}(\boldsymbol{A}_{new}^T\boldsymbol{W}_{new}\tilde{\boldsymbol{b}}_{new} + \hat{\boldsymbol{P}}_k^{-1}\delta\hat{\boldsymbol{x}}(0|k)) \\ \hat{\boldsymbol{P}}_{k+n} = \hat{\boldsymbol{P}}(0|k+1) &= (\boldsymbol{A}_{new}^T\boldsymbol{W}_{new}\boldsymbol{A}_{new} + \hat{\boldsymbol{P}}_k^{-1})^{-1} \end{aligned} \tag{3}$$

so $\delta\hat{\boldsymbol{x}}(0|k+1)$ is the improved correction to $\hat{\boldsymbol{X}}(0|k)$ due to additional data through time t_1. But we must not forget to iterate! We still have a nonlinear problem and a linearized solution, however, so we have to be careful when iterating. For example, the nominal estimate resulting from processing 1,000 observations is probably very close to the actual answer.

Unfortunately, the answer is still at the original epoch. Of course, we can propagate the state to a new time, but the problem still remains of how to propagate $\delta\hat{\boldsymbol{x}}$ and $\boldsymbol{P}(0|k)$ to the current time because the state-update estimate is still calculated at the epoch time. The *state-transition matrix* (Φ) is sometimes used to propagate our state update and covariance.

$$\hat{\boldsymbol{P}} \approx \Phi \hat{\boldsymbol{P}}_o \Phi^T$$

The sequential estimation technique [Kalman Filter] is similar, but it also invokes an additional component (process noise) in the formulation. The result of the approximate method (above) is a predicted estimate using the new data. Remember that Φ is a linearized approximation for use in propagating the covariance matrix, and we may introduce unnecessary errors.

The traditional Kalman filtering applications are developed in Vallado (1997, Ch. 9). The *Extended Kalman Filter* (EKF) is often used with satellite problems, but there's also a linearized approximation. The prediction and update for the EKF are

PREDICTION

$$\boldsymbol{PKEPLER}\,(\hat{\boldsymbol{X}}_k, t_{k+1} - t_k \Rightarrow \hat{\boldsymbol{X}}_{k+1}) \qquad \text{Predicted State}$$

$$\delta\bar{\boldsymbol{x}}_{k+1} = 0 \qquad \text{Predicted State Update}$$

$$\bar{\boldsymbol{P}}_{k+1} = \Phi \hat{\boldsymbol{P}}_k \Phi^T + \boldsymbol{Q} \qquad \text{Predicted Error Covariance}$$

UPDATE

$$\boldsymbol{K}_{k+1} = \bar{\boldsymbol{P}}_{k+1} \boldsymbol{H}_{k+1}^T \left[\boldsymbol{H}_{k+1} \bar{\boldsymbol{P}}_{k+1} \boldsymbol{H}_{k+1}^T + \boldsymbol{R}_k\right]^{-1} \qquad \text{Kalman Gain}$$

$$\delta\hat{\boldsymbol{x}}_{k+1} = \boldsymbol{K}_{k+1} \tilde{\boldsymbol{b}}_{k+1} \qquad \text{State Update Estimate}$$

$$\hat{\boldsymbol{P}}_{k+1} = \bar{\boldsymbol{P}}_{k+1} - \boldsymbol{K}_{k+1} \boldsymbol{H}_{k+1} \bar{\boldsymbol{P}}_{k+1} \qquad \text{Error Covariance Estimate}$$

$$\hat{\boldsymbol{X}}_{k+1} = \bar{\boldsymbol{X}}_{k+1} + \delta\hat{\boldsymbol{x}}_{k+1} \qquad \text{State Estimate}$$

where $\boldsymbol{H}$ is the partials of the observations with respect to the state, $\boldsymbol{F}$ is the partial derivative matrix, and $\boldsymbol{K}$ is the Kalman gain. $\boldsymbol{Q}$ is the process noise, and it accounts for the mis-modelled force models.

Note how the prediction of the state uses the previous estimate of the state. Unlike the *LKF*, this filter uses the updated state for subsequent calculations, and the predicted state update, $\delta\bar{\boldsymbol{x}}$, is not used. This technique simplifies the equations but doesn't make the filter run any faster. In fact, an *EKF* will usually run *slower* than an *LKF* because the Φ matrix must be recalculated at each step. In addition, the predicted value of the state must be updated at each step. We can avoid a complex propagation by using a perturbed two-body approach. Except in some time-critical mission situations, increased computer speed has virtually eliminated concern about this additional processing, and the *EKF* enjoys wide popularity for its accuracy and speed. The $\tilde{\boldsymbol{b}}$ matrix is the residual matrix defined for the *LKF* and the nonlinear differential correction. Although no iteration is required, it's still considered differential correction because we're estimating corrections to the previous estimate of the state.

Filters have a persistent reputation of being hard to tune, especially in setting the $\boldsymbol{Q}$ parameters for process noise. But one approach strives to define the process noise as a function of the system's physical processes—the work of Wright (1981, 1994) that is generally known as *Real Time Orbit Determination* (RTOD). Wright recognized that process noise in the orbit problem is a real physical phenomenon that arises from uncertainty in the force models. Wright shows how to derive a generalized process-noise function for the errors in the gravity model, whether due to truncating the model (which we do to save computer time) or to our inability to perfectly model the Earth's gravity. A simple example illustrates the concept. If we model a 4×4 gravity field, the process noise error is the contribution of the gravity field *above* 4×4. If we limit the field to 50×50, we can calculate the process noise "exactly." These physically defined filters don't enjoy wide support, partly because people must know astrodynamics *and* estimation to exploit the concept. However, we feel their place in future space surveillance systems is highly desirable.

4. Discussion of Current Techniques

These equations form the backdrop for analyzing the current system. The nature of iteration is evident in all methods of operation, although some techniques perform these iterations with much greater efficiency. Because of the early history and evolution from missile warning, the current military system is predominantly analytical. There are many sensors, few observations, and approximate results. *Doppler Orbitography and Radio positioning Integrated by Satellite* (DORIS), *Satellite Laser Ranging* (SLR), etc. are newer space surveillance systems using fewer stations, more observations, and numerical processing.

Vallado (1997, 740, #6) presents an interesting question regarding the modification of a sensor network. In reality, the answer is a mix of all the options suggested in the question.

Consider a few simple proverbs:

More data gives a better estimate of the true solution.

A closer first guess is better.

Longer fit spans require better initial guesses, more iteration, but yield longer prediction accuracy.

Batch least squares processing (Eq 3) is the primary workhorse today for most orbit determination applications. A fading memory filter is used to deweight the older data. The idea of covariance matrix and probabilities with the accuracy of the orbit are just beginning to take hold. This isn't surprising because limited analytical theories produce covariance matrices that are of limited usefulness. For example, you can't determine if the orbit is accurate to 50m if your gravity model accepts errors of 200m!

The approximate sequential batch method is used in many applications, although there has been little interest correcting the covariance matrix as limited analytical theories are generally used for the orbit determination.

Depending on which technique is used, the future architecture will vary. We'll consider a planned approach in which batch least squares continues to be the mainstay for operations until a real-time Kalman filter technique can be integrated into operations.

5. Desirable System Features

There are numerous features we would expect (and like) to see in a future space surveillance architecture.

COMPLETE / ROBUST

We must be able to use all forms of data for processing. For instance, a future space surveillance system should be able to accept SSN, *Russian Space Surveillance System* (RSSS), *Doppler Orbitography and Radio Positioning Integrated by Satellite* (DORIS), *Air Force Satellite Control Network* (AFSCN), SLR, *Global Positioning System* (GPS), University, space-based (MSX), bi-static, and other observational data. It should also be able to accept all forms of data (radar, optical, laser, interferometer, *Space Ground Link System* (SGLS), etc.) There should be no program lockouts in the computer software.

There also needs to be true surge capability in the system. Although some references indicate that SPADOC has extra surge capacity for numerical vectors and additional observations, the reality is that it doesn't exist full time. For instance, close approach calculations are performed on only a small fraction of the existing satellites, and they use SGP4 because the computers can't handle all the numerical runs. In fact, virtually every technical operation must first use SGP4 to screen candidates. Admittedly, it's feasible to use simplified techniques to minimize future numerical calculations, but the numerical vectors must be available (and accurate) for that subsequent processing.

The second area of surge capability is the observations. Historically, the Naval fence has produced too much data for SPADOC processing, thus a single triangulated point has been sent to SPADOC, not the individual direction cosines. All data should be used—if it's worth collecting, it's worth using in its raw unadulterated form!

The debris campaigns have shown that we can process about 20,000 additional observations per day (about 20% of the total), but that's with extra crews, and additional attention. Any future system should have the ability to process what we would consider today to be staggering numbers of observations. Many operations are centered around a one-size-fits-all concept in which many sites contribute a few observations and all satellites are updated very often. ODIN, discussed later, processes many observations from a few sites, and uses highly accurate numerical techniques to update the satellites. There is a trade-off between the two approaches, and it’s likely that an intermediate approach is what will finally be implemented.

TIMELY / EFFICIENT

Data must be available in a timely manner. The Internet shows great promise to speed vast quantities of data between worldwide locations, however, its use in the military is often very limited.

The system should also be capable of solving difficult problems using existing data resources, in a minimum amount of time. An example of this is the area of close approach. The Navy has already demonstrated complete satellite catalog (all on all) close approach calculations on their new distributed processing system (Coffey et al, 1998). This was simply a demonstration example, and used brute force techniques for each evaluation. The interesting feature is that the system uses distributed processing, and can therefore integrate almost any type of computer into the architecture. This should not be confused with parallel processing systems which have multiple processors that perform certain sections of an operation at the same time, and on a single type of computer. Alfano (Vallado, 1997, 805-814) has developed a unique splining and blending technique that uses any propagator, larger time-steps, and produces highly accurate determination of the close approach times and instances. In fact, this software has recently been incorporated into Satellite Toolkit (STK) as a state-of the art close approach process.

Efficiency also encompasses the distribution of data. Some systems continue to use an 80 column limit, despite the fact that punch cards (for which the 80-column limit originated) have been obsolete for decades. The Internet offers huge potential for distribution of data. It’s quick, reliable, and redundant. It’s also cheap and readily available.

MAINTAINABLE / STANDARDIZED

Ultimately, the issue of maintainability rests with the specific software implementation, and the computing hardware. We’re becoming accustomed to the modern merger trend. This suggests we be very cautious when implementing new systems, and ensure we can port the existing code to a new system as speed, supply, and requirements dictate.

We can’t over-emphasize the importance of the availability of computer code, test cases, and documentation. The astrodynamics software code must be updated and thoroughly evaluated, tested, and researched by a truly independent analysis, and by other organizations wishing to use the code. Organizations that declare certain codes to be a standard without a truly independent evaluation, miss the opportunity to improve their product by testing, and incorporation of other experience and design lessons. To assume the code is in no need of peer review is questionable. For instance, SPADOC has had recent problems like the mean motion rate and inconsistent gravitational field constants. Many non-DoD efforts exist for highly accurate orbit determination, particularly Logicon/RDA, Draper Laboratory, MIT/LL, UT Austin, JPL, NASA, Aerospace, and so forth. We should leverage these technologies and cooperatively share academic research potential to redefine computer codes and make them truly state-of-the-art. Sharing computer code is not a popular trend because we all know that no computer code is perfect. The acceptance of change is the best indication of true learning. The refusal of review indicates suspected trouble!

Any upgrade should be designed for future growth. The dependence on one type of processing (batch least-squares) is extremely limited. For instance a Kalman Filter approach exists (RTOD by Logicon/RDA and Wright 1981, 1994) that has several uninterrupted operational uses for over a decade. Although specifically tailored to satellite missions, the technique has been shown to process through maneuvers, weeks of no data, and even reentry predictions. This technique could be used for special high interest satellites. This could be an important fix for the UCT problem because it carries a realistic covariance at the current time.

ACCURATE

A very important area which is now receiving attention is the verification of the computer codes with *externally generated ephemerides*. This process usually takes SLR *Precision Orbit Ephemerides* (POE) information for verification. While this accepted community practice is very valuable, a subtlety exists. The SLR community has externally, and internationally agreed upon standards, coordinates, and reference frames. When the POE's are processed by GEODYN, (also available as a module in STK—PODS) for the SLR data, the POE's are the accepted standards. They undergo periodic peer review. It’s also possible to perform independent processing of the SLR data. It would be incorrect to equate these independent orbits to the standard POEs without substantial peer review and validation. In fact, you would likely find significant errors primarily due to the fact that approximate coordinate systems are often used (recall the discussion on standards—see also Vallado, 1997, 534). You *can* compare orbits to your own vectors, but that's not a really independent check because the underlying code is the same. Beware, accurate observational data and inadequate processing may provide precise answers, but not necessarily accurate ones!

The use of *probability* in concert with the operations is also a real benefit. The old paradigm of sparse observations on each pass to support a limited analytical theory (SGP4 and PPT3) must be changed. To keep up with the reality of limited (in quantity) sensors, and ever increasing accuracy requirements, sensor taskings and differential correction processing must fully use the existing data. Additional observations will allow you to obtain a more accurate covariance matrix. This has several uses—close approach prediction, tasking, laser clearinghouse, etc. Tasking the sensors when the covariance matrix "tells" you gives the operator the option of concentrating on problem satellites (maneuvering, etc.), rather than trying to monitor a large and complex tasking algorithm.

The issue of a *realistic covariance matrix* cannot be overemphasized, and in fact, it has received considerable discussion over the last few years. In reality, only two viable approaches exist that have been proven to be effective. First, using a Kalman Filter that incorporates actual model noise equations (RTOD by Logicon/RDA), one can derive realistic covariance matrices. The other approach involves careful differential corrections of dense observational data, with complete force models. The important points here are the dense data (remember it's much more difficult to solve for variables with fewer equations than unknowns), and the complete force models. Some approaches have claimed accurate covariance matrices using limited analytical models, *and* limited force models. You just can't get more accuracy than the assumptions in the development will permit. You might be able to develop an empirical method after analyzing sizable quantities of numerical data, but it's still not the correct solution. A simple review of the mathematics illustrate this result. You can't estimate small bias and solve-for parameters correctly unless you are modeling the underlying dynamics with greater precision than the observations. For example, if your gravity model is truncated and contributes 50-200 m of error, can the covariance possibly detect a bias that's between 50 and 100 m? Even if you could detect the bias, how do you detect the noise which is usually an order of magnitude smaller?

6. ODIN Concept

We introduce the ***Orbit Determination Interactive Network*** as a concept of operations designed to maximize effectiveness of the existing space surveillance resources, and incorporate added flexibility to provide a bridge to the 21st century. A major tenent of the technique is ***centralized control, decentralized execution***. This concept also embraces distributed processing, and is nearly infinitely scalable. Truly tested, documented, and standardized codes will allow for easy transition to additional sites. The actual operation would employ all the items we've discussed so far—dense observations, numerical, semianalytical, and Kalman filter processing, etc. Figure 2 shows the conceptual idea.

This idea is not without its critics. Indeed, Admiral Owens said *"The problem with deep, fast, and rampant innovation is not getting people to accept the new but to surrender the old."* A brief description of the process follows.

Each sensor site would have standardized numerical and differential correction code which would be centrally controlled and maintained by a group of organizations, but available to individual agencies for continual improvement and re-validation. As each site approaches a required tasking, it would download the current state vector and covariance matrix from a web along with existing observations in the fit span. The site would numerically propagate the existing state vector to the expected pass time, take the observations, perform near-real time track verification, and perform a numerical DC to update the orbit. Of course, if the track verification was outside established statistical limits, the results would not be considered valid, and the data would be passed to a central location for further processing. If successful, the site would automatically place the updated state, covariance matrix, and observations on the web, and the next site tasked to observe this satellite would take this updated information, and repeat the process. Anomaly resolution would be handled via existing techniques at a central location, and all observations could be passed via modern electronic communications; i.e. ftp., email, etc.

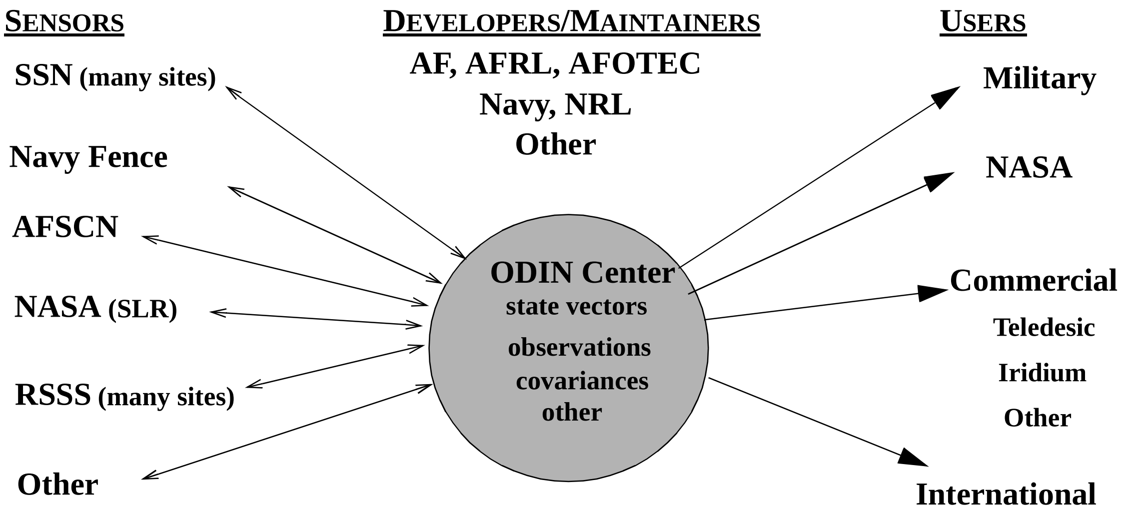

Figure 2. **ODIN Concept of operations.** This chart helps us visualize the interrelations between the sensors, developers, and users of space surveillance data. Although the civilian role is shown to be small, it's growth is unprecedented, and will likely be the driving factor in developing a future space surveillance architecture.

Existing UCT processing would still be accomplished at a central site, but it would be assisted by realistic covariance analyses and the overall improved catalog accuracy. By improving the overall accuracy by over an order of magnitude, the number of UCTs should drop dramatically.

Communication links have witnessed a tremendous change over the last 20 years. Unfortunately, most of the existing communications architecture, based on a sparse observation requirement (3-5 per pass) to drive limited analytical theories, limits the perceived capacity to process the observations. ODIN would be designed around today's high-end high-speed data communications to provide the extra data we need today, and the staggering amounts of data that will exist in the future. Many operations could take advantage of commercial ftp and email services to augment existing operational systems.

The tasking algorithm would have to be completely revised—definitely not a trivial matter. But, if the process were done correctly, the end result could be significantly more efficient and would likely show expanded capability. Because we're using numerical processing with accurate covariance values, the tasking algorithm could numerically propagate the state and covariance to determine when the state would exceed a pre-set level of accuracy. For many objects in “benign” orbits, circular 1000 to 20000 km altitudes for instance, this period could be several weeks before retasking. Note that it might be useful to periodically revisit satellites to ensure they have not inadvertently moved. This could be done quite simply using the Navy’s interferometer fence. Satellites cross through the fence about twice per day, and these observations could be used to signal when an unexpected motion is encountered. The numerically determined orbits would have sufficient accuracy to tighten the acceptable deviations and thereby highlight that motion.

Vallado and Carter (1997) showed a method that could affect this process. They took dense tracks of data for the initial fit span period (5 days). The resulting state vector was numerically propagated for about one week when new dense observations were added (one days worth). This method worked quite well for higher altitude orbits, and reasonably well for lower, drag-perturbed orbits. Significant additional research is needed. Including the direction cosine data from the Navy’s interferometer could likely extend the propagation interval as there would be periodic observations to “assist” the numerical propagation.

7. Benefits:

Although it's hard to quantify the benefits of a future concept, we can speculate on the problem areas of today, and how the ODIN concept, coupled with a general rework of the space surveillance architecture, addresses and solves some of these difficulties.

COMPLETE / ROBUST

In the near term, the military is still the dominant player. Desert Storm showed the immense importance of space control in a wartime situation. The world marveled at the effectiveness of precision guided weapons. To deny that level of accuracy to space surveillance is to miss the points of modern warfare. In fact, if we recall the importance of foreknowledge described by Sun Tzu several thousand years ago, situational awareness and the value of knowing the enemies location was of primary importance. As the rapid growth in civilian requirements continues, we'll need to be able to provide that same accuracy for *all* satellites.

TIMELY / EFFICIENT

We believe more efficient space operations will be possible through creation of a separate Space Force. Ultimately, properly executed space surveillance will enable creation of a ***Space Force*** (**SF**), much like the Air Force evolved from the Army in the 1920's. The rank-and-file have long recognized the need for a separate Space Force. Gen Horner (Ret) even suggested this possibility at a dining-in speech at AFRL in the Spring of 1996.

The civilian counterpart would be a new ***Space Agency*** (**SA**) that would have all the traditional responsibilities of the SPADOC system today, but the charter could also include a dual-use service like the current FAA operations for commercial aviation. The SA would have the tools and resources to perform integrated space operations and control. It should avoid the problems of the current FAA (antique mainframes, lack of standardized and well-written software, not enough accuracy, inability to keep pace with the state-of-the-art, etc.).

Reduced UCTs and more efficient use of our existing resources is another likely outcome of the ODIN concept. This would happen in two ways. First, the improved ephemerides would permit tighter radar beams, less search time, and greater accuracy (from the increased power). Of course, an unknown maneuver would require a wider beam, and less accuracy, but that's the way a search is performed today. Second, the better the orbits are known, the more accurate observation association could be performed. There would be a lower chance of a fake screen occurring because the tolerance on each parameter could be significantly tightened. We have all witnessed the reality of shrinking budgets, but the excess capacity we have in terms of obtaining observational data on the satellites is an opportunity for us to meet budget constraints and increase accuracy.

Because each sensor site would process the data and place the result back on the "web", the information would always be up-to-date. Currently, there are some systems that "post" new information at certain intervals—once a day, twice a day, once per week, and so on. All space surveillance operations would benefit from a continuous, near-real time accuracy.

ACCURATE

On August 31, 1998, North Korea launched what was to have been it's first satellite, Kwangmyungsung 1. The launch followed a path over Japan and caused considerable concern as it was unknown whether it was a missile or a satellite. The accuracy of the initial orbits were limited, and this caused a period of uncertainty.

Order of magnitude improvements to deep space capabilities are possible. Currently, the *Ground Based Electro Optical Deep Space Sensors* (GEODSS) cannot track all their assigned satellites. There are two primary reasons. First, the deep space objects are tasked to be tracked at least once a day, primarily so that the errors introduce by SGP4/PPT3 don't grow so large that the sensors can't reacquire the satellite. In actuality, although the requirement is to obtain daily observations, the system can tolerate about one week between observations. Thus, many of those satellites are actually tracked only once a week or more. However, the interval could be lengthened to several weeks, and the accuracy could be improved using dense observations and an upgraded Navy interferometer fence to provide supplements to the orbits. The other stated reason to track often is that maneuvers can't be detected unless the SSN maintains this kind of coverage. This may be true for some GEO satellites, but other options exist. The Navy fence provides an exceptional opportunity to detect unknown maneuvers to relatively high (semi-synch) altitudes. If we couple our precision orbits idea with this notion, we could eliminate a large number of unnecessary taskings, and concentrate efforts on the maneuvering GEO satellites. Note that even some debris may continue to vent propellent, making it appear to maneuver, thus some minimal form of observations are necessary to make sure the satellite doesn't become lost. Furthermore, by using numerical propagations, we can accurately predict ahead weeks on many dead objects, and still keep the accuracy under 1 km for close-approach determination. This also frees up GEODSS-like resources to look at satellites which truly need updates. The Astrodynamics Division at Phillips Laboratory has demonstrated several important tests in the area of highly accurate angles-only orbit determination using the Raven telescope. This work has grown from initial research at Maui, who have also made significant progress in this area.

MAINTAINABILITY / STANDARDIZATION

ODIN maintains *compatibility* with existing users. A comment is necessary about the transition from SGP4/PPT3. We often hear that everyone has built their systems to accept only SGP4/PPT3. In fact, this isn’t surprising as it has been the only product for a long time. Remember that if the only tool you have is a hammer, then every problem looks like a nail. The simple solution for older systems using SGP4/PPT3 is to perform a simple conversion from the osculating state vector to the standard 2-line mean element set. Although this introduces some error, and the subsequent propagation's aren't as mathematically precise as if all the operations used a numerical technique, the very use of SGP4/PPT3 suggests that many kilometers of error for a LEO satellite, and a few tens of kilometer for a GEO satellite are acceptable for their applications. If additional precision were required in the 2-line element set, a differential correction could be performed on an ephemeris generated by the numerical routine to more accurately determine the mean elements for SGP4/PPT3, although this really defeats the purpose of the numerical technique. Thus, only the high accuracy users would need to make any changes. Most high accuracy users already have numerical routines and would benefit greatly from the increased accuracy of the state vectors and access to the covariance matrices.

The issue of *standards* is often discussed. While SPADOC uses *World Geodetic Survey* WGS-72 (FK4) and WGS-84 (FK5), most of the computer code was developed decades ago when computer programming (and documentation standards) were significantly different than they are today. As a result, while the capability appears “on paper” to switch between coordinate systems and constants, there are many undocumented variables that combine old constants that are virtually impossible to decipher. This is an error that is currently being solved in the latest version of the SPADOC software.

As mentioned at the beginning, it's important to shed the operational constraints that have existed in space surveillance for over 30 years. True standardization will remove *processing differences* like the two separate analytical theories of SGP4 and PPT3. This has been especially difficult for civilian users, and is the source of long-standing mis-trust between the services. We need to have the courage to acknowledge what's happened, correct it, and move on to truly joint and even international operations!

We suggest that all programs should adhere to the *International Earth Rotation Service* (IERS) standards and the efforts directed by the *US Naval Observatory* (USNO) (McCarthy, 1996). An important subtly here is that we use those standards, and not approximate and modify them! Their efforts mark the state-of-the-art in determining constants and conversions for astrodynamics. The JGM-3 model is recognized as a much more accurate gravity field model than WGS-84. JGM-3 is a principal part of the recently released gravity model (EGM-96) of DMA, GEM, JGM, and OSU. All programs should use these systems, and be designed for future update because Earth models are continually being refined.

SPADOC continues to use a true-equator, mean-equinox system. While the original development coincided with limited computational resources, it is now a source of difficulty with interfacing with the world which commonly uses a true-equator, true-equinox system. We need to conform to existing standards, developed by the international community, especially when the new *International Celestial Reference System* (ICRS) is implemented.

Much of the standards work which has been done has been misdirected and duplicative. The IERS committee and the USNO perform valuable work in this area, and have chaired positions for many years. Unfortunately, their work is not embraced by all agencies.

The problem with having operational personnel develop the standards is that they're often limited by their vision of the future and not of the way things could work. Thus, most of the work has been constrained by the limitations of the current system (SGP4, PPT3, sparse observations, etc.) and not on how the system will work (state vectors, covariance matrices, etc.). The opposite problem exists if technical people dominate the process, in that nothing will ever produce an answer in a reasonable amount of time. The solution is to have a mix of operational and technical people to balance the technology against the requirements.

The year 2000 problem (*Y2K* problem) has many people mesmerized. A common solution that is in practice simply puts the problem off for 50, 51, or 57 years. While this is past most of our operational careers, it doesn’t represent the correct approach. The simple solution is to adopt a standard of time used by all major scientific and industry centers—the Julian Date. This is not to be confused with the day of the year (Vallado, 1997, 67, 69). The Julian Date allows accurate incorporation of day-month-year-hour-minute-second information in one variable. It's valid over years, centuries, and even the approaching millennium in 2001. It’s also the standard reference for determining and distributing planetary and luni-solar phenomena. This is also a convenient time to replace the time argument as the 2-digit year in the current two-line element sets. Therefore, we might as well provide a complete fix. In addition, if we fix the timing (year) problem, we should also take the opportunity to show vision and update the communication files, eliminate 80 column character and format constraints, and place more digits into the transmitted data.

8. How to Implement this Strategy?

Implementing ODIN (distributed precision orbit determination and maneuver detection) for a future space surveillance system will have ramifications throughout the community. There are actually two parts. First, we must strive to integrate these new ideas on an incremental basis to accommodate a transfer to a new concept of operations using highly-accurate numerical calculations. Then we can integrate the full idea using decentralized execution. To this end, let us illustrate a brief flow of events that could meet these challenges. Several of these operations may be worked in parallel.

- The Navy would proceed with an interim *full satellite catalog numerical operations.* The AF would continue SGP4 processing. Because the alternate space surveillance center (Navy) would be processing the numerical vectors, routine operations from SPADOC can continue without interruption while the numerical demonstration is completed. The Navy has already completed a one month dry-run (Coffey et al., 1998) and will execute routine processing soon. The AF is also pursuing a numerical demonstration, but it lacks the integration with the current on-line system. The AF should be an integral part of this joint demonstration to ensure commonality among output (source code, coordinate frames, force models, etc.) so we can avoid another era of SGP4/PPT3 operations. In a year or so when the bugs are worked out, Space Command could implement a common, verified, tested numerical operation into the [then] current form of the SPADOC system, and standard operations could revert to the AF. Recent projects at Space Command suggest they are moving away from the mainframe approach of SPADOC, and it would be prudent to wait to incorporate new techniques until the new form is agreed upon. Because the AF process to incorporate new techniques requires more time than the Navy, the trial period of Navy operations would permit the AF to evaluate, influence, and plan for the incorporation into the AF system. It would also be beneficial to set up a backup implementation at Space Command, or the Space Warfare Center to test the validity of any proposed solution technique.
- It would also be wise to incorporate Industry/University concepts into this joint demonstration. In addition to building consensus among the services and industry, the partnership could re-establish the close communications between the civilian and military that have somewhat eroded over the years. The military would end-up with a redundant system that was flexible and accurate enough to entice commercial customers. This could even provide a source of revenue for the services, and become a truly national resource.
- Conduct the Space Warfare Center Battlelab Initiative on *dense observations.* The AF and Navy would obtain data to perform objective analysis of trade space of observations, sensors, and processing. This would enable us to decide how to support the joint numerical operations in the previous step. It would also enable us to determine how to more effectively use existing data and would pave the way to ODIN operations in the future.
- Rewrite the regulations. Currently, Space Command regulations limit the numbers of observations a sensor site can record and send to SPADOC. For SGP4/PPT3 operations, a few data points, taken every day, allow the differential correction programs to find an approximate estimate of the orbit. While numerical processing can slightly improve the accuracy of the differential corrections (as initially demonstrated by PL (Fonte, 1994, and PL, 1995) and later by Vallado and Carter (1997), there is insufficient data in current operations to fully exercise what a numerical propagator can do for you (for instance, solve-for parameters). Thus, the regulations need to be changed to permit the sensor sites to take more

(on the order of 200-300 per pass, not just 10 to 15) observations. The regulation rewrite wouldn't force every site to change their operations, but during routine program updates, the parameters that limit observations today, could be changed to permit more efficient processing in the future. Discussions with operators from the sensor sites themselves suggest that this is feasible even before a regulation rewrite. In fact, our experience with several dense observation experiments suggests it can be done today.

- Form a unified oversight group (AF, Navy, Industry, Other) to fine tune the astrodynamic operations. This includes standardization and would implement the previous discussion of initial demonstrations coupled with joint code and test case development.
- The AF would evaluate how to implement numerical processing in SPADOC. This would complete the move toward the master tenent of Aerospace Power—**centralized control, decentralized execution**. As has been pointed out, decisions made almost a decade ago have tied SPADOC to large mainframe computers. The work of PL and AFRL has demonstrated that high-accuracy orbit determination on a PC is capable of exceeding all mainstream operational techniques. In fact, as mentioned earlier, the trend at the 1998 Space Control Workshop at MIT/LL showed a general departure from mainframe operations, to stand-alone systems. The Navy’s new distributed-processing system at Dahlgren is specifically designed for 21st century concept of operations (numerical processing). The Navy has already presented results of complete SATCAT numerical processing and UCT parallel processing (Papers AAS 97-687 and AAS 98-113). They are currently exploring the near real-time implications of full catalog maintenance and have completed a one-month trial period. Of course, they are only using the standard “sparse” observations, and some of the more difficult orbits (drag, high eccentricity, solar radiation pressure, etc.) do not show the marked improvement one would expect with truly dense observations.
- In the longer term, as the sensor sites become upgraded, the observations could be switched to a distributed processing architecture (ODIN). This would also be accompanied by the organizational shift of operational responsibility.
- Transition to civilian operation with military resources. This could be a long, but important process.

9. Tough Questions

This discussion obviously leads to numerous questions. We’ve tried to anticipate some of those concerns and address them in this section.

- The current system works fine.

While this may seem accurate, it’s really not. this is evidenced by the vast proliferation of off-line systems that are in use, and development today. Unfortunately, the rigorous and competitive aspects of large scale integration are not being practised. To avoid costly upgrades in the future, we must carefully and methodically plan for upgrades today.

For decades, the *minimum approach* was placed into every aspect (regulations, software, operations, etc.) of space surveillance. Admittedly, communication and computer systems were limited 25 years ago. That's not true today. Although system inertia complicates resolution of the problem, [true] visionary leadership and partnership with DoD, Industry/University can correct the problem quickly. An important fact to consider is that solutions to Space Surveillance have always looked at the observations, and not the processing. The rapid technical acceleration of computers and communications require us to re-examine the processing.

The problems with rapidly changing personnel isn’t as easy to solve, especially in light of declining budgets and increasing roles and missions. A portion of the solution rests with civilian positions, but this increases funding requirements. We do not attempt to solve this problem except to pursue as much accuracy as possible to allow a margin for any unexpected results.

- Who really needs numerical processing?

Today, not everyone. But, consider the dollar cost in causing a shuttle launch to delay because the error boxes around the satellites are so large, we can’t accurately predict the intersections. Consider the collision of two dead satellites that are outside the general orbit of the ISS, but cause high velocity debris to penetrate the orbital plane of ISS. The list could go on. As space gets more crowded, each of these become more important. Accuracy is the solution to all these problems.

- Where are the requirements?

It’s been said that what we learn by studying history is that we don’t learn from history and are destined to repeat the same mistakes. General Mitchell lamented his contemporaries reluctance to adopt his new ideas in the 1920’s. His critics argued that airplanes were “only good for observation”, “of no use to the military”, and “there’s not enough money”. We too are seeing the same arguments today with regard to space surveillance. This question is somewhat related to the previous. It’s been argued that the requirements have never really existed for higher accuracy. There’s a subtlety here in that we define requirements as what’s needed for space surveillance to operate. Some centers define requirements as those written documents that have undergone a formal staffing and approval process. We use the former definition throughout this paper. As we watch the growth of the commercial satellite markets, we should see the warning signs that indicate unprecedented change. Accuracy, processing timeliness, and data access will be the required norm in just a few years. A goal of this paper is to address the questions of how do we manage a fundamental shift in thought, and how can current computational and technical advances be used to help this change.

The lack of accuracy requirements argument has been used for decades as a reason not to upgrade the current system—the semantics issue often dominates the discussion. In fact, we suggested full catalog numerical processing at the PL Astrodynamics Division workshop in 1993. The suggestion was soundly rejected by the operational community at the time. Today however, that same community has embraced the idea and is striving to implement full catalog numerical processing!

Consider precision munitions. Do we place a limit on how accurately the cruise missile should hit its target, or do we try and achieve as much accuracy as is possible? While we need to consider requirements, we shouldn't close our eyes to obvious improvements which will come out of the research community. Thus, we must be continually re-evaluating our requirements and be cognizant of research efforts that will significantly change the status quo. We must know where the satellites are. Could we ever operate an airline industry in which we only knew the positions of the airliners to only 50 km?

- Who does the organization?

The military would lead at first, then a national group in the United States, and then international. The management and political considerations would be difficult, but the initial pathfinder approach of the military could significantly ease the process.

- Who gets the data? / Security

The 1CACS Bulletin board concept for distribution of observations and 2-line element sets is a huge step forward, and the proposed unclassified Web site is sorely needed. AIAA formed a special panel to evaluate space-related needs at the 1994 AIAA conference. The idea was to provide a forum for the world astrodynamics community on how to structure their research to assist operational needs in space. Although all the invited organizations didn’t participate, the overall concerns from the audience included the need for standardization, access to computer software and data so they could perform studies, increased accuracy, and leadership and ideas from the operational community to the educational community. By placing some of the software and data on the web, the Military could reap the benefits of having hundreds of additional eyes examine the codes, rederive (and perhaps document!) the codes, for no cost. This would give a greater confidence in the answer generated, and would gather additional customers. Sensitive information could be preserved at dedicated government locations.

Distribution of the data is difficult within the military, will be more difficult with civilian and military combined, and will be especially complex when international cooperation is achieved. Of course, some satellites will be placed on an exception list. A true spirit of cooperation is needed to convince other nations to respect our sensitive satellites while we respect their rights. This is a touchy area because we have little difficulty releasing information on all Russian satellites, and do so routinely. In an era of cooperation, we would have to work closely with other countries to ensure their rights aren't inadvertently infringed upon. However many examples exist where an operation must have access to all information. For instance, if a country wishes to run accurate close-approach determination, all satellite positions must be known. This lends itself to an FAA-like organization for space—we call it the ***Space Agency***.

- How should we distribute the data?

The data should be available through several means to ensure connectivity, and timeliness. Thus, the Internet could pose as an effective vehicle, supplementing existing communication systems.

Whenever data is released, there are important legal considerations which can’t be overemphasized. The fact of future collisions, litigation, determination of who moves, and so forth, will arise. The question we must answer is how a country will be able to respond. Will some nations have limited accuracy and throughput systems? Will there be high accuracy available? Will competitors continue to keep their competitive edge and have better products available for a subset of satellites? These are not easy questions and we won’t try to solve them here. But we are sure that highly accurate orbits will reduce the number of frivolous claims.

- How good does it have to be?

The product must be the best available or users will go elsewhere as they do today. There are numerous sources of existing data with higher fidelity. Many of these don't have the scope of Space Command, but the fact they're more accurate suggests something is missing in the current operational system. An example came to light during the recent *International Astronomical Union* (IAU) conference in the summer of 1996 with the amateur astronomers use of GEO orbits passed via Internet in Europe. Their orbits are so accurate that they use the GEO orbits to calibrate their telescopes, and then perform their main goal, astrometry. This is, and should sound backwards because we usually know the star positions more accurately, and align telescopes based on the stars.

- What should the relationship be with other communities?

Cooperative arrangements should be pursued at all levels and with all participating countries. This is an effective way to leverage scarce resource dollars. As mentioned previously, an interactive spirit with the worldwide astrodynamics communities fosters a cooperative arrangement and spawns new ideas. At the same time, it permits Space Command to retain special interests within proper channels.

- What sort of cooperation should be considered?

At a minimum, computer code should be available to all government organizations, and limited analytical theories should be generally available as the previous SGP4 release was (Hoots et al., 1980). That’s how standardization works effectively. In addition, provisions should be made to permit universities to have access to the material for research and enhancements. Of course, appropriate restrictions on distribution would have to be applied. Observations that are unclassified, as most are, should be readily available to the public. There are enough people interested in space surveillance (communication satellites in particular), that it's very likely that some companies may wish to perform their own orbit determination from the raw observations. This could offset some of the workload on SPADOC as they could simply import the independently produced vectors with basic validation checks.

- The sensors can’t provide the data

As for the sensors, Eglin can perform RCS runs and produce hundreds of observations in a single pass. The FPS-85 systems can track over 100 satellites simultaneously, and perhaps as high as 200. Fylingdales was routinely sending hundreds of observations to SPADOC after they completed an upgrade. Some people have suggested they were showing off, but a quick review of the physics suggests that any radar is capable of producing many more observations than we could ever imagine using. They are computer code limited, but this can be changed. There is also a trade-off between the number of stations and the number of observations, but fiscal reality suggests we use all our data wisely, and develop a robust system that can dynamically adapt to changing structure and environmental variables.

- What capacity and coverage are needed?

Today's current sensors including the SSN radars, Navy fence, GEODSS, and SLR network sensors provide more than adequate coverage and capacity to handle precision orbit determination on all active and inactive satellites. Maneuvering satellites present additional challenges, but the problem is achievable given sufficient sensors, dynamic tasking, and a processing system employing precision ephemerides. Future space-based sensors can fill any gaps inherent from geographical constraints in the current system. This process presupposes that the correct numerical processing, calibration, current atmospheric and solar parameters, and operational insight are used in the orbit determination process.

Clearly, to implement the ideas of the SA discussed previously, there should be global coverage. A mix of the current radars, GEODSS, SLR sites, and Navy fence is an extremely effective resource, although it's not currently used to its fullest potential today. The primary element missing today is the space based portion, although MSX is exploring this alternative. A permanent manned presence in space as well as increased space activity suggests the requirements to track smaller objects, and more objects with greater fidelity, will increase. Also, requirements to track smaller objects could multiply the number of objects to process by several orders of magnitude.

- But the computers and communications can’t handle the load

Today's computers and communication systems can easily overcome the limitations which were in place at the time of older analytical theory development. To say that a 500MHz Pentium II can’t perform significant orbit determination is to ignore reality.

- Who will pay?

The military has the preponderance of facilities. We also acknowledge the millions spent by each service as they duplicate the others research, technical breakthroughs, and operations. This is a lucrative source of dollars. The challenge is to get inter-service cooperation, and joint oversight to force the commonality and standardization. The possibility exists that if the product is good enough, a fee-for-service could be established for the near-term, until the civilian organization is completed. Although the military owns the equipment, there are several proposals currently under review to privatize portions of space surveillance. In the long run, the civilian community will finance much of the operation as they will derive significant gain from its completion.

- How timely should the data be?

The data should be available as soon as possible to any potential user. The ODIN concept ensures this is true as the only delay in the system is the short time of processing the observations. This time should be about 10-15 minutes. New launches should be characterized after the first pass over any SSN site. The dense observations concept should help the process of determining the initial orbit. There should also be data exchange between countries whenever possible, although this is tough legal and political question.

- How will everyone be able to use the data?

Commonality and standardization are the keys. We must adhere to international standards (IERS, IAU, etc.). You can’t truncate and modify standards, you must use the original standards. The *Jet Propulsion Laboratory* (JPL) planetary ephemerides are a prime example. They include documentation, source code, high accuracy and quality.

There must be compatibility with the other organizations, including the Navy. The idea of having separate simplified analytical theories for nearly 40 years is non-productive, especially when today's technology virtually eliminates the need for analytical theories by using numerical techniques.

- What about the ITWAA coupling?

Space Surveillance should be removed from it's coupling with *Integrated Threat Warning and Attack* (ITWAA). While this joint alignment has served well during the cold war period, the future architecture of space control and force application will force a re-definition of this traditional arrangement. Close coupling is still needed because of the relationship with missile warning and space surveillance, however, in a peacetime environment without any major nuclear threats, the role of space surveillance must take center stage.

Although it would be tough to decouple missile warning from space surveillance, the former has driven the requirements and operations picture for many years. Perhaps the solution is to separate the functions, but place an oversight function within USSPACECOM to coordinate activities of both groups. Would it be possible to have one service perform space surveillance, while the other service performs missile warning? With common software and visionary leadership, the communications could be seamless, and efficient! Higher accuracy helps all facets of missile detection from the satellite orbits of monitoring satellites, to the geolocation of signatures.

10. Conclusions

The process of implementing a new concept such as the ODIN concept discussed here should not be taken lightly. However, we all know you should dig a well before you’re thirsty! The implementation could be phased in during a period of time.

Significant progress has been made in space surveillance over the last few years. The Navy has completed checkout of a new distributed-processing center designed to handle the future loads of space surveillance. AFSPC has refined its' procedures and software to process and deliver accurate numerical vectors to specialized customers. These activities lead directly to a plan of updating the current space surveillance operations, give us the opportunity to finally achieve commonality in processing (no more separate and incompatible theories like SGP4 and PPT3), and will ultimately increase the accuracy delivered to all users throughout the world.

For the near future, it makes sense to demonstrate the utility of a full catalog numerical demonstration using the Navy system and facilities while a joint AF/Navy software suite is fine-tuned. ODIN is a concept that could extend this initial operation into a truly joint, and even international venture to locate all satellites.

Bottom Line

To obtain the necessary and accurate information, we must use dense observational data, from all available sources, with well-coded and documented numerical processing. This allows centralized control, and decentralized execution of all space surveillance tasks.

11. References

Coffey, Shannon L. et al. 1998. Demonstration of a Special Perturbations Based Catalog in the Naval Space Command System. Paper AAS 98-113 presented at the AAS/AIAA Astrodynamics Specialist Conference. Monterey, CA.

Fonte, Daniel J. Jr. 1994. PC Based Orbit Determination. Paper AIAA 94-3776 presented at the AIAA/AAS Astrodynamics Conference, Scottsdale AZ.

Fonte, Daniel J. Jr. 1994. Evaluation of Orbit Propagators for the HI-CLASS Program. Technical Report PL-94-1017. Kirtland Air Force Base, NM: Phillips Laboratory.

Hoots, Felix R., and Ronald L. Roehrich. 1980. *Models for Propagation of NORAD Element Sets.* Spacetrack Report #3. U.S. Air Force: Aerospace Defense Command.

McCarthy, Dennis. 1996. *IERS Technical Note #21.* U.S. Naval Observatory.

Miller, J. G. Tasking and Maintenance of Deep Space Satellites. Paper presented at the Space Control Workshop. MIT/LL. 14-16 Apr, 1998.

Neal, Harold L., Shannon L. Coffey, and Steve Knowles. 1997. Maintaining the Space Object Catalog with Special Perturbations. Paper AAS 97-687 presented at the AAS/AIAA Astrodynamics Specialist Conference. Sun Valley, ID.

NORAD, Feb 1975. Tasking Improvement Project Implementation Team Phase I Documentation. Colorado Springs, CO.

ODIN Brief to USSPACECOM/J3 and CMOC/CC. 1996.

Phillips Laboratory. 1995. 1995 *Success Stories*. Kirtland Air Force Base, NM: Phillips Laboratory History Office.

Seidelmann, Kenneth P. and Bernard Kaufman. *Artificial Satellite Theory Workshop*. Proceedings, USNO. Nov 8-9, 1993.

Schumacher, Paul W. Jr, et al. 1998. Design for Operational Calibration of the Naval Space Surveillance System. Paper AAS 98-116 presented at the AAS/AIAA Astrodynamics Specialist Conference. Monterey, CA.

Scientific American. Command and Control. August 1997. pg. 33-34.

Tzu, Sun. The Art of War. Air Command and Staff College Reading.

Vallado, David A. 1997. *Fundamentals of Astrodynamics and Applications*. New York: McGraw-Hill.

Vallado, David A. and Scott S. Carter. 1997. Accurate Orbit Determination from Short-arc Dense Observational Data. Paper AAS 97-704 presented at the AAS/AIAA Astrodynamics Specialist Conference. Sun Valley, ID.

Wright, James R. 1981. Sequential Orbit Determination with Auto-Correlated Gravity Modeling Errors. *AIAA Journal of Guidance and Control*. 4(2): 304.

Wright, James R. 1994a. Orbit Determination Solution to Non-Markov Gravity Error Problem. Paper AAS-94-176 presented at the AAS/AIAA Spaceflight Mechanics Meeting. Cocoa Beach, FL.

Wright, James R. 1994b. Analytical Expressions for Orbit Covariance due to Gravity Errors. Paper AAS-94-3722 presented at the AIAA/AAS Astrodynamics Conference, Scottsdale, AZ.