

Search and Determine Integrated Environment (SADIE) for Space Situational Awareness

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ABSTRACT

A new high performance computing software applications package called the Search and Determine Integrated Environment (SADIE) is being jointly developed and refined by the Air Force and Naval Research Laboratories (AFRL and NRL) to automatically resolve uncorrelated tracks (UCTs) and build a more complete space object catalog for improved Space Situational Awareness (SSA). The motivation for SADIE is to respond to very challenging needs identified by and guidance received from Air Force Space Command (AFSPC) and other senior leaders to develop this technology to support the evolving Joint Space Operations Center (JSpOC) and Alternate Space Control Center (ASC2)-Dahlgren. The SADIE suite includes modification and integration of legacy applications and software components that include Search And Determine (SAD), Satellite Identification (SID), and Parallel Catalog (ParCat), as well as other utilities and scripts to enable end-to-end catalog building and maintenance in a parallel processing environment. SADIE is being developed to handle large catalog building challenges in all orbit regimes and includes the automatic processing of radar, fence, and optical data. Real data results are provided for the processing of low Earth radar and Air Force Space Surveillance System fence observations and for the processing of Space Surveillance Telescope optical data.

1. INTRODUCTION

Correlating tracks of resident space objects that do not correlate with an object in the space object catalog is a very difficult problem for the space surveillance system [4]. Such tracks are called Uncorrelated Tracks (UCT). Currently 11 nations maintain 22 launch sites and 60 countries and consortia operate satellites on orbit. The Department of Defense (DOD) tracks 22,000+ satellites and pieces of space debris on orbit [2], and those numbers are anticipated to increase greatly in the years ahead, which will also result in a substantial increase in the number of UCTs that must be resolved. As the future catalog, that will contain many new small objects due to improved sensor capabilities, is built, this correlation task becomes even more daunting, since every object begins as a UCT. The SADIE project was initiated in October 2011 to automatically build and maintain orbits using radar, Air Force Space Surveillance System (AFSSS) fence, and optical data. SADIE is addressing JSpOC mission requirements and threads that flow down from the United States Strategic Command (USSTRATCOM) [1].

SADIE is an evolution of work that has been performed with the Navy automated Search and Determine (SAD) legacy parallel program high performance computing application to address uncorrelated tracks (UCT) and encapsulates three development efforts: Auto-SAD, uncertainty-based track association, and SAD optical processing. This is aimed provide a more complete UCT resolution and catalog maintenance capability utilizing a combined, layered approach. SADIE is a joint Air Force Research Laboratory (AFRL) and Naval Research Laboratory (NRL) effort under the High Performance Computing Software Applications Institute for Space Situational Awareness (HSIAI-SSA).

SAD was originally developed for AFSSS fence processing and requires position observations [3]. The SAD legacy software executes in a parallel computing environment and deduces orbital elements from a set of unknown objects using a static algorithm with fixed gates for correlation. It generates candidate orbits through all possible pairs of UCT positions and reduces the number of candidate orbits through quality metrics. The result is a list of candidate orbits of varying quality that still requires further analysis. SAD is currently processing real UCT data from the

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AFSSS at the DSC2-Dahlgren and is used, manually, in conjunction with a suite of other tools to generate maintainable orbits.

Auto-SAD was initiated by the HSAI-SSA and developed by NRL to link those legacy tools together to automatically construct and maintain catalog-accurate orbits from UCT observations. Auto-SAD includes the legacy SAD software, the Navy's Satellite Identification (SID) correlation software, the NRL's Parallel Catalog (ParCat) software, and a host of processing and automation component scripts. Three noticeable advances were made with Auto-SAD: 1) the use of observation rate filters to help reduce the number of false candidate orbits, 2) modernization of the legacy SAD software to run on modern computing platforms, and 3) the automated scripting to allow the end-to-end functionality. Initial Auto-SAD results are provided in this paper.

The SADIE team is also utilizing its core competencies in astrodynamics to incorporate improved multi-hypotheses management and uncertainty-based data association methods for improved association performance with short-track radar data and sparse observing periods. While Auto-SAD still uses position-only UCT pairings and fixed gate associations, which is a sound approach for AFSSS data, uncertainty-based methods utilize additional information in track data to produce full orbit states and error distribution functions, which can be used to statistically associate tracks together. The first HSAI-SSA venture into this approach is Covariance Based Track Association (CBTA) [6]. CBTA employs a dynamic algorithm with variable gates that are based on the uncertainty (covariance) of each track. If the covariance represents actual error distributions, then this algorithm is optimal in that it maximizes the probability of correlation. Covariance matrices can be used to associate the UCTs in a more statistically valid and automated manner. CBTA has been tested in special-perturbations (SP)-based simulations with fragmentation events and catalog builds of up to 100k objects. Simulation results have shown CBTA to reduce missed associations by two orders of magnitude when compared to a fixed gate approach [6]. The combination of Auto-SAD and uncertainty-based data association methods will provide significant capability for UCT resolution for Low Earth Orbits using AFSSS and Space Surveillance Network (SSN) radar data.

Methods to process optical data from the Space-Based Space Surveillance (SBSS) satellite, Space Surveillance Telescope (SST), and all other line-of-sight (LOS) angles-only space surveillance sensors are being developed and built into SADIE. SBSS and SST provide the ability to detect an unprecedented number of objects with accuracies and sensitivities beyond that of older legacy sensors. Large scale, high fidelity simulations and real data demonstrations are being used to evaluate SADIE's optical processing capability with some initial results presented in this paper.

As elements of SAD, uncertainty-based track association, and the optical processing are merged into the SADIE architecture, a layered, multi-sensor, multi-orbit regime capability results. Considerable effort was put forth to develop the SADIE architecture that will allow for future improvements as new techniques are developed from within or external to the HSAI-SSA team. The remaining parts of this paper describe the SADIE functional architecture and development strategy, advances made with a Special Perturbations (SP) capability within SID, Auto-SAD approach and current results, SADIE version 1 (SADIEv1) candidate generation approach and optical processing results, and then an alternate candidate generation approach to be considered for SADIE version 2 (SADIEv2) along with optical processing results.

2. SADIE ARCHITECTURE AND DEVELOPMENT STRATEGY

The SADIE architecture separates the catalog maintenance and building processes into four major stages: 1) observation correlation against the catalog and catalog update, 2) uncorrelated observation correlation against the previously generated select candidates and candidate catalog update, 3) the generation of new candidates or hypotheses from the remaining uncorrelated observations, and 4) observation correlation against the newly created select candidates. This processing flow is shown in Fig. 1. While critical to the process, the first processing stage, correlation against the catalog, is not considered part of the SADIE tool. From a functional and software perspective, stages 1, 2, and 4 are very similar but can operate on different data sets with different correlation gates. The architecture was developed to allow alternate approaches to correlation and observation or track associations to be implemented and enable continued evolution and improvement of capabilities.

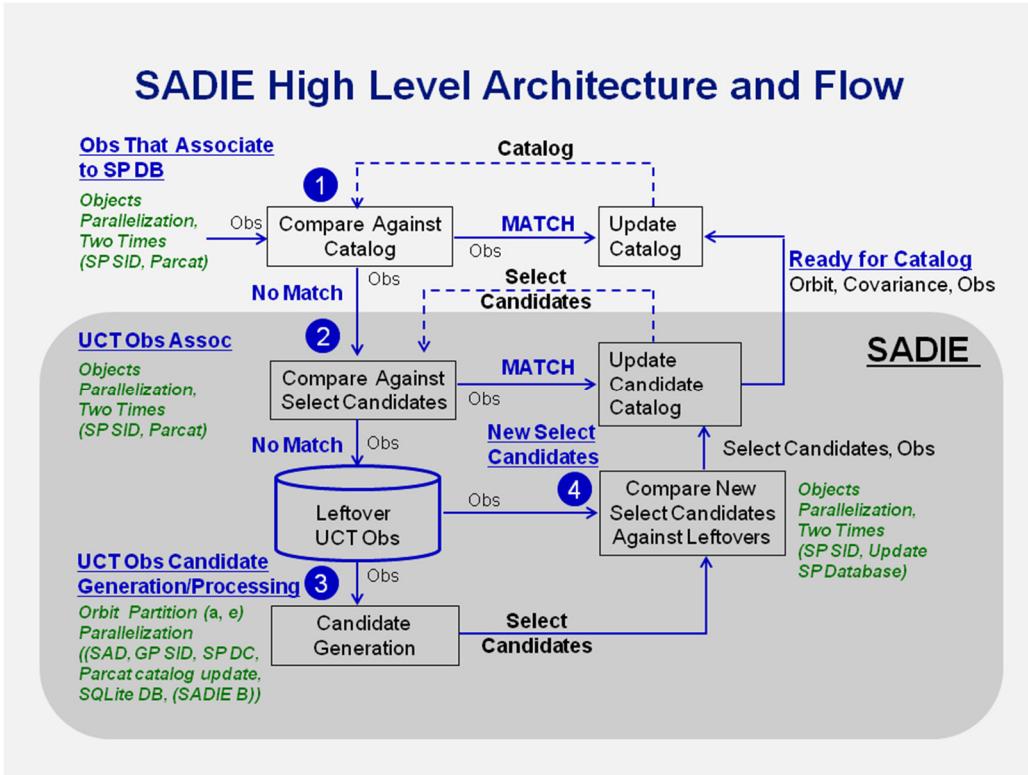


Fig. 1. SADIE High Level Architecture and Flow

SADIEv1 builds upon the integration of legacy Search and Determine (SAD), Satellite Identification (SID), Parallel Catalog (ParCat). SID is used for observation association. ParCat is used for orbit determination and propagation. SAD is used for candidate generation. The initial focus for SADIEv1 was on the processing of optical observations and the implementation is different from Auto-SAD. As of the writing of this paper, the AFSSS fence and radar processing capability of Auto-SAD has not been fully incorporated into SADIEv1; however, initial Auto-SAD results are provided in this paper. SADIEv2 will look to incorporate uncertainty-based track association methods and potentially other improvements for candidate generation; one such example is provided in this paper.

Various utilities and other software has been integrated and developed to enable SADIE execution. This includes a routine, which was needed in Stage 1 for use by SID and SAD components, to take Right Ascension and Declination data, along with station position information, and convert it to Azimuth and Elevation data. This was necessary because Azimuth and Elevation coordinates are used by the legacy RF data UCT processing applications in SADIE. The observatory station position is the geodetic latitude, longitude, and height for ground-based observations.

Our team has been steadily building the SADIE application and code base. Efforts at the project outset developed the project goals and requirements, data flow, performed initial architectural engineering, and initially ascertained the needed components and execution sequence. Preliminary code parallelization, integration, and message passing needs were also identified. Tasks were delineated and resources assigned to tasks, and a schedule with milestones was established. A Streamlined Software Development Plan (SSDP) was developed for the project, with the usual SDP format streamlined by using only those sections deemed necessary to coordinate the experienced, but small, software project team to perform agile software development.

SADIE is designed to utilize shell, Perl, and Python scripts for building and for runtime execution. MPI is utilized for the code stages that employ parallel programming. SADIE is being designed to provide orbital analysts with user interface methods and tools for batch processing operations and analyses. The plan is to include future controls for various items such as association tolerances, step sizes and others. Feedback means will also be provided for visibility into key items after running the SADIE code such as metrics, statistics, and histograms to aid analyst use.

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Like SAD and ParCat before it, the new SADIEv1 integrated application package will also utilize parallel processing, performing objects parallelization in six places in three of the four stages of the SADIE software processing flow. Parallelization by orbit partitioning using semimajor axis and eccentricity, is also used in the candidate generation stage. Parallel programming has been previously developed, tested, and employed on the SAD software component in the high performance computing environment to significantly reduce run times. This allows more data to be processed and distributes the processing across multiple processors, resulting in a greater number of orbits being discovered than previously possible. With the advent of new sensors being added to the SSN, the number of space objects detected, observed, and processed is expected to increase dramatically, and may well have to deal with over 100,000 objects -- presenting an enormous processing problem [7]. More recent improvements to SAD over the past few years to address this increased load have resulted in days and hours of processing time being further reduced to only minutes. SAD is a major component of SADIE and comprises a significant amount of SADIE processing time.

All codes were mounted on the *Mana* HPC platform at Maui High Performance Computing Center DOD Supercomputing Resource Center (MHPCC DSRC) with successful initial processing runs and benchmarking completed. The team also coordinated software needs for future use of HPC clusters located at other facilities.

3. OBSERVATION CORRELATION WITH SP SID

SID is a fixed gate observation correlation tool developed for use at Naval Space Command, now the ASC2-Dahlgren [8]. It uses fixed correlation gates (scaled by semimajor axis) projected into the orbit radial, transverse, and orbit normal directions. As part of the SADIE project, the ability to use SP vectors and ephemeris tables was added to SID as well as the ability to specify fixed gates independent of semimajor axis. For deep space satellites, it was expected that the SP processing would allow for correlation gates an order of magnitude smaller than gates used for GP processing, strictly due to the lack of solar radiation pressure and tesseral resonance modeling in the PPT3 GP theory used in SID. A similar reduction may be observed in low Earth orbit due to better drag and gravity modeling. The utilization of smaller correlation gates decreases the chances of false-positive correlations (falsely identifying object B as object A).

The new SP SID component was proof-of-concept tested using a strenuous simulated test case where 35 near-geosynchronous objects were placed within a one degree longitude band. Optical observations with 1" of noise were simulated over 30 nights with four observations being produced each night. The first 20 nights of data were used to generate an SP catalog that could be used as the correlation basis for the remaining 10 nights. Correlation was performed using legacy GP and new, tighter, SP gates. The results are provided in Table 1 and expectedly showed the large GP correlation gates resulting in a huge number of false associations. The SP implementation, however, did quite well, producing two orders of magnitude fewer false associations than the GP version.

Table 1. SADIE SP SID Tolerance and Association Testing

	Original GP Tolerances (hard coded)	Tested SP Tolerances
du (radial)	0.1 a'	0.0001 a
dv (transverse)	5.625 a'	0.000225 a
dw (orbit normal)	min(0.0145 Re , 0.005 a)	min(0.0145 Re , 0.00075 a)
False Associations	1,168	12

Further testing was performed using simulated SST data. 1118 deep space objects were chosen from the predicted NASA Debris Catalog and propagated for 10 days using an SP six degree of freedom (6DOF) propagator. 6DOF was chosen to model more realistic radiation pressure effects in the truth than the spherical satellite model used in the catalog maintenance. Initial SP and GP catalogs were created by performing differential corrections to the first five days of data. These results were then fed into SID for correlating the second five days worth of data. An orbit update was not performed during the second five days. SP SID was run on the using 3x22x35 km gates while two

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sets of GP gates were used: 1) default Dahlgren GP SID gates ($0.1a \times 5.625a \times 0.005a$), and 2) smaller GP SID gates ($0.0008a \times 0.0072a \times 0.0026a$) tailored towards deep space observations. A comparison of SP and GP SID performance with the SST and SBSS data is contained in Table 2 and shows SP SID provides considerably better results than the GP implementation.

Table 2. Comparison of GP and SP SID

Metric	GP SID Default	GP SID Tailored	SP SID
Tracklets correctly correlated by tool	83%	65%*	95%
Tracklets incorrectly correlated by tool (False Positives)	542%	17%	1%

* (Note: 149 objects had no correlations)

An SP ephemerides interpolator was also added as an upgrade to SID in place of calls to the ephemerides generator routines.

4. AUTO-SAD INITIAL RESULTS

SAD forms all-on-all pair-wise combinations of observed position vectors to generate candidate orbit using a modified solution to Lambert's problem to create candidate orbits from uncorrelated data [7]. SAD uses a bootstrapping method to go from a starter-pair to a PPT3 (GP) theory candidate orbit with multiple data points associated to it. Similar to SADIEv1, Auto-SAD adds SID and SP ParCat elements to further refine the SAD output candidate orbits, correlate additional data against the candidates, and grow and maintain a database of catalog-ready orbits. The primary component of Auto-SAD that has not yet migrated to SADIEv1 is the inclusion of observation rate criteria, which can be used to prune false candidates.

Auto-SAD demonstrated the automatic generation of SP catalog-ready orbits from real Iridium-Cosmos collision (which occurred on February 10, 2009) data, primarily from the AFSSS, for up to 50 days after the collision. Fig 2 plots the resulting SAD catalog population size for a varying number of updates required for catalog addition within a five day window. As the number of updates required increases, the number of orbits maintained decreases. Given this same data, analysts from the Joint Space Operations Center (JSPOC) and DSC2-Dahlgren were able to add 824 objects to the catalog using manual processes. This is represented by the upper horizontal red line on the plot. One can see that Auto-SAD is able to automatically recover approximately the same number of objects using a single update criterion.

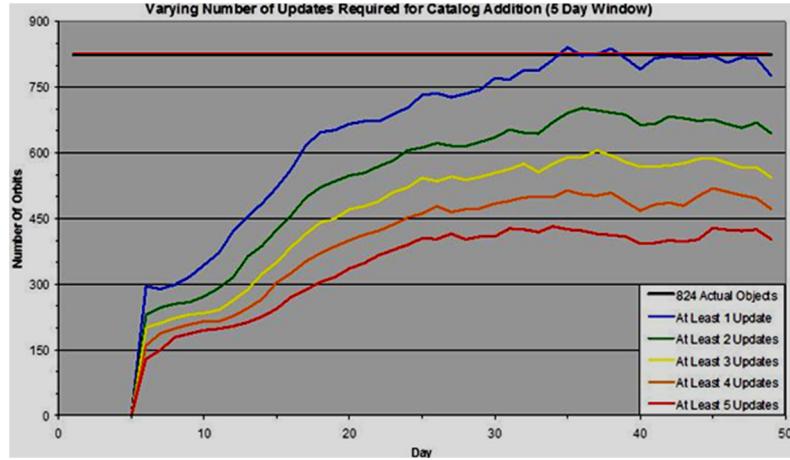
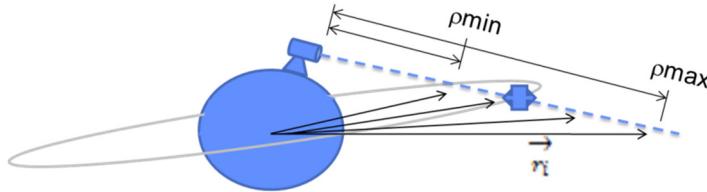


Fig. 2. Auto-SAD Results and Automatic SP Catalog-Ready Orbits from Real Iridium-Cosmos Data

5. SADIEv1 CANDIDATE GENERATION FROM OPTICAL DATA

Under the SADIE v1 approach, which builds on the Navy legacy program SAD multi-hypothesis tracking algorithm, position vectors must be formed from the uncorrelated observation data to feed the Lambert solution based candidate generation approach. Analysis showed that meaningful range information could not be estimated from short angles-only tracks so an alternate approach was needed. A range hypothesis approach is used where a single angles pair is matched with a series of range observations at uniform steps; this results in a potentially large group of UCT data being fed into SAD for each optical observation as shown in Fig 3. Typically, a 10-100km range step size is chosen and centered around the range to GEO for optical processing. Maximum and minimum ranges are based on semimajor axis and eccentricity criteria; future implementations may use the derived rate information from optical tracks to limit the admissible ranges. Candidate orbits are output from SAD and then fed to GP SID for initial correlation against the UCT observations and then further refined to an SP orbit. The hypothesized ranges are not used in the candidate orbit refinement.

There were many things to consider in the practical deployment of SADIEv1, some of which are still being explored. Correlation gates can be set internal to SAD, at the GP SID processing of SAD candidates, and at the SP SID processing components. ParCat differential correction tolerances are also adjustable. Generally, if looser tolerances are set, the likelihood of poor candidates emerging from Stage 3 increases; if tighter tolerances are used, the likelihood of missing correct candidates increases. Tuning these settings is an area of continuing development.



$$\begin{aligned} \rho_i &\leq -(\mathbf{R}_i \cdot \mathbf{u}_i) + \sqrt{(\mathbf{R}_i \cdot \mathbf{u}_i)^2 + [a_{\text{MAX}}^2(1 + e_{\text{MAX}})^2 - \mathbf{R}_i \cdot \mathbf{R}_i]} , \quad i = 1, 2 \\ \rho_i &\geq -(\mathbf{R}_i \cdot \mathbf{u}_i) + \sqrt{(\mathbf{R}_i \cdot \mathbf{u}_i)^2 + [a_{\text{MIN}}^2(1 - e_{\text{MAX}})^2 - \mathbf{R}_i \cdot \mathbf{R}_i]} , \quad i = 1, 2 \end{aligned}$$

Fig. 3. SADIEv1 Range Hypotheses Approach for Candidate Generation

Initial proof-of-concept simulation results showed that SADIEv1 candidate generation worked well for small groups of objects with ground-based observations, associating 12 of 12 near GEO objects within 1 degree of longitude. These simulations assumed four observations per object per night and used spherical solar radiation pressure modeling that was not accounted for in the candidate generation.

SADIEv1 candidate generation was then tested on a larger, more realistic simulated data set. 675 deep space objects from the NASA debris catalog were propagated using 6DOF dynamics and SST observations were simulated for one day. 331 of those objects had 4+ tracks, which is the minimum requirement for SADIEv1 to generate a candidate orbit. A +/- 20 min from GEO period and eccentricity < 0.01 limits were used in the range-hypotheses generation. This reduced the number of potential SADIE candidates to 174. With the one day of simulated data, SADIEv1 produced 112 correct candidates and 16 incorrect candidates. It is expected that the incorrect candidates would be pruned out of the Stage 2 processing and not make it to catalog-ready status. Increasing the candidate criteria to 6+ tracks allowed SADIE to recover 98 correct candidates with only 3 incorrect candidates out of a possible 207 objects with 6+ tracks. While not ideal, the simulation results show SADIEv1 candidate generation is recovering most of the objects it has a chance to recover with relatively few false candidates.

Next, ten nights of real SST was processed. Observations were gathered on six of those ten nights. 102 known objects were chosen from the data set that had 4+ tracks and were thought to have a lower probability of mistags by

the Lincoln Laboratory SST team; however, analysis by the SADIE team and the AFRL/RV ASTRIA team indicated that mistags were still possible within this data, which is consistent with the GP SID simulation results described earlier. Of these 102 objects, 80 were within the range-hypotheses and processing limits utilized by the SADIEv1 candidate generation software. SADIEv1 recovered 67 of the objects. Increasing the track requirements for candidate generation to 6+ resulted in SADIEv1 recovering 52 out of 70 potential objects. Note, the number of potential objects assumes all SST data tags are correct.

Comparing the real and simulated data results provides the unexpected impression that SADIEv1 candidate generation works better with real data than with simulated data. The primary reason for this is that the simulated data set had over six times the number of objects and over an order of magnitude more observation data on a per night basis. Denser satellite populations and data sets provide challenges for the candidate generation since, internal to SADIEv1, the likelihood of being able to generate a false candidate increases with more data in a confined time and sky space and these internal false candidates can claim observations within SAD that prevent the generation of correct candidates. These challenges increase dramatically as the range hypotheses bounds are increased. Future work for SADIEv1 candidate generation includes the use of techniques to reduce range hypothesis bounds such as constrained admissible regions [9], the use of techniques to reduce the number of initial candidate orbits and altering the processing architecture to more effectively deal with the number of candidates.

6. ALTERNATE CANDIDATE GENERATION APPROACH

Six pieces of information are needed to describe a simple orbit, be it orbital elements, position and velocity, or some other form. SAD uses two position vectors to generate initial candidates with positions typically derived from range, azimuth, and elevation data. SADIEv1 optical processing uses hypothesized ranges to supplement the information provided by optical line of sight observations. Rather than forming initial orbit candidates from two positions, an alternate approach for line of sight data would be to form the initial candidate from three observations, provided the data was sufficiently separated in time in order to estimate the orbit shape. Furthermore, if four temporally separated optical observations are combined into a hypothesis, a simple orbit determination can test whether that hypothesis is a viable orbit.

This angles hypothesis approach is depicted in Fig. 4. Consider an SST-like sensor that surveys a region of space four times. A hypothesis is generated for every combination of detections from each of those four surveillance sweeps. For example, in Fig 4, Hypothesis 1111 takes the first detection from each data set and Hypothesis 1292 takes detection 1 from the first set, 2 from the second, 9 from the third, and 2 from the fourth. Orbit determination can be performed for each hypothesis and if all observations are not utilized or fit residuals are inconsistent with the sensor performance, that hypothesis can be pruned. If the fit to the data is good, however, the hypothesis is released as a candidate orbit. This approach "connects the dots" in angles space and initially utilizes a very large number of hypotheses; however the hypotheses can be quickly pruned with fairly small chance of false candidate generation.

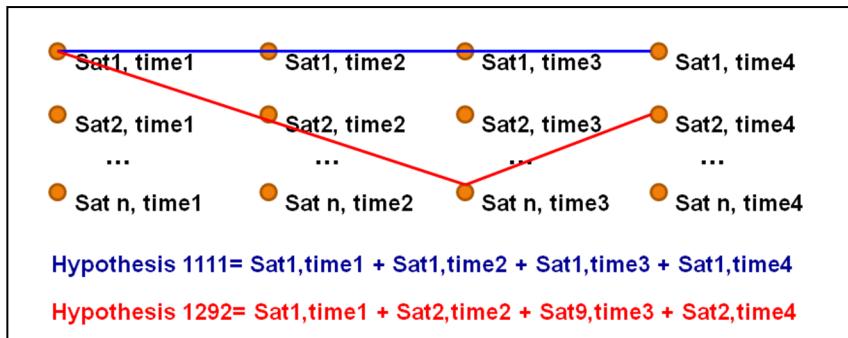


Fig. 4. Alternate Candidate Generation Approach for Optical Processing

As a proof of concept, the approach was tested with an SST-like simulation with nine (9) satellites in a 0.25 degrees longitude band. The simulation also included large, unmodeled radiation pressure effects using spherical satellite

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models. The results showed that the correct hypotheses have a solution Root Mean Square (RMS) of at least one order of magnitude smaller than incorrect hypotheses. These results are plotted in Fig. 5.

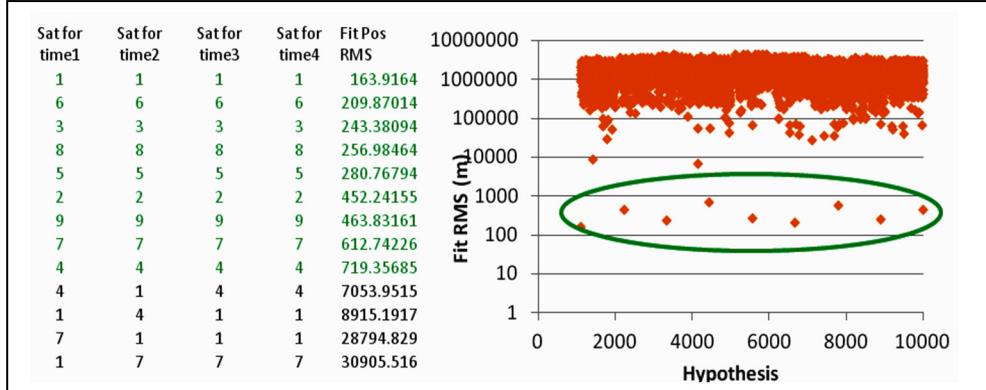


Fig. 5. Proof of Concept Results for Four-Angles Hypothesis Candidate Generation

Clearly, the approach was effective; however, n^4 scaling with observations is not computationally attractive even with DOD supercomputing resources available. There are ways to partially this but it is still a computationally challenging approach.

The angles-only hypothesis approach was tested with a single night of real SST data obtained during engineering testing of the system. Observations obtained from SST sweeps of the GEO belt and tagged to cataloged objects by the Lincoln Laboratory SST engineering team were utilized. Data counts showed 70 objects contained 4+ tracklets and 61 of those objects remained within the 5 deg hour angles bins used in the hypothesis generation. 46 candidate orbits were generated, 41 of which had consistent observation tagging. Five false candidates were generated, three of which had all of the azimuth observations of a single tracklet edited out of the differential correction process; the hypothesis pruning criteria was subsequently changed to check for this behavior and remove the false hypothesis. Two of the other false candidates had three tracklets from a commonly tagged object and one from another; however, correct candidates were also generated for the objects that owned the three tracklets so the SID multi-tag reconciliation process would effectively remove these false candidates from consideration. Manual inspection took place for the remaining 20 cases where the observation tags predicted a viable candidate but the approach did not recover one. Of those 20 cases, 19 had evidence of a mistag or a maneuver. The remaining case was a viable orbit but the initial orbit determination scripting failed during processing; this has since been fixed. In summary, the angles-only hypothesis approach could recover every object within its hour angle bin limitations.

The angles-only hypothesis approach was also tested against the same single day of SST simulated observations of 675 objects as SADIEv1, described in the previous section. Of the 675 objects, 331 had 4+ tracks and approximately 244 fell within the 10 deg hour angle bins utilized in the hypotheses generation. The approach recovered 208 objects with zero false candidates. Extending the approach to require 6 tracks to form a candidate resulted in 145 recovered orbits out of 172 objects in the bins, again with zero false candidates. It should be noted that not all hypotheses were considered in the candidate generation process, which could account for the method not recovering more of the possible objects.

This approach will be further considered and developed pending further tuning and performance testing of SADIEv1. Its possible that both approaches can be combined such that the angle-only approach is used to recover near-GEO objects and reduce the observation density prior to utilizing the range-hypothesis based approach of SADIEv1.

5. CONCLUSIONS AND FUTURE WORK

While highly complex, SADIE design, development, integration, evaluation, and early simulation testing of optical data processing have realized a good degree of success thus far. SADIE optical data processing components and modifications have been successfully tested and evaluated and will augment the pre-existing AFSSS fence processing of Auto-SAD and promise of uncertainty-based track association techniques.. SP correlation with ephemerides interpolation has proven to be a computationally easy means of associating observations to established orbits and SP SID dramatically outperformed GP SID for processing of simulated optical data. Auto-SAD has been shown to build and maintain an SP catalog-ready database of objects from real AFSSS fence data with the Iridium-Cosmos collision providing a challenging test case. SADIEv1 candidate generation using optical data has been shown to be effective with real and simulated SST data. Lastly, an alternate candidate generation approach has been shown to provide improved accuracy for SST-like instruments but may not be applicable to non-search and survey concepts of operations due to computational limitations.

SADIE is being jointly developed and refined by the Air Force and Naval Research Laboratories (AFRL and NRL) to automatically resolve uncorrelated tracks (UCTs) and build a more complete space object catalog for improved Space Situational Awareness (SSA). The SADIE project plans call for continued tuning work to increase the technical performance results and accuracy, and to further integrate all four SADIE stages for easier use and end-to-end processing, and optimize the software and speed up the runtime execution. Completion of SADIEv1 integration wrappers is proceeding. Additional SADIE improvements and UCT correlation and association runs are planned that will continue using simulated and real space sensor data. Uncertainty-based track association for processing radar track data is expected in SADIEv2 in 2013.

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