Serendipitous Acquisition of Space Situational Awareness From Astronomical Surveys (SASSAFrAS)

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ABSTRACT

As the rate of new objects in Earth orbit continues to accelerate due to new launches and debris creation, the data volume required to keep pace rapidly increases utilizing traditional algorithms. Penn State is developing a novel concept to fuse cutting edge star catalogs, radiometry and astrometry to increase the value of the data already available by utilizing every pixel, not just the pixels with detections meeting threshold requirements. This paper will discuss the methodologies of the two major efforts that will utilize probabilistic approaches to improve catalog accuracy: Something From Nothing (SFN) and Streak Harvest (SH). SFN is developing algorithms to utilize pixels that have NOT detected an object. SH is developing algorithms to utilize pixels that have detected streaks that have not met the n out of m criterion or only partially streak through the field of view resulting in missing endpoints. This paper will also discuss the dangers of utilizing these dataset types. This effort is inspired by the work done by the Air Force Research Laboratory (AFRL) with the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) astronomical telescope, un-cued detection efforts such as the Space Surveillance Telescope (SST) and Un-cued detection of Low Inclined LEO Object (LILO), and the large volume of wide field astronomical sensors collecting unutilized SSA data everyday around the world.

INTRODUCTION

Since the 1950’s, humanity has been launching satellites into Earth orbit for a multitude of applications. Most of these objects eventually decay and burn up in Earth’s atmosphere, however this process can occur over centuries, and a small subset never decay. The vast majority of the satellites currently in the United States’ Space Surveillance Network catalog are defunct satellites.[i] These satellites threaten other capabilities with possibilities of collisions since they have no ability to maneuver. While the Keplerian force acting on these objects is well quantified, there are multiple non-conservative forces, which perturb the satellites’ orbits requiring regular tracking to avoid possible conjunctions. (It is important to note, that if the attitude, shape, mass, non-conservative forces were known and modeled in the orbit propagation processes, the required revisit times would be significantly longer, however, for many debris and active payloads it is unlikely to obtain this information in the current SSA culture.)

The Defense Advanced Research Projects Agency (DARPA) is beginning to develop more sensors such as the Space Surveillance Telescope[ii] and LILO (Un-cued detection of Low Inclined LEO Objects)[iii], which employ survey, vs. traditional task-track concepts of operations. In addition, DARPA is also investing in the ability to utilize non-traditional sources such as civil or university astronomical telescopes[iv]. This introduces the possibility of generating SSA from astronomical capabilities, many of which perform survey missions with large fields of view. There is a common linkage between all of these data sources: they will spend a lot of time detecting nothing. In addition, most of their detections will be single streaks, which may or may not contain two endpoints within the field of view. For faster moving objects, such as Highly Elliptical Orbit (HEO) and Low Earth Orbit (LEO) objects, and longer exposures the serendipitous detections may streak fully across the focal plane.

Assuming all of this data was made available, two basic research questions arise: “How do you exploit knowing that an object was NOT detected,” and “How do you exploit data sets with large ambiguities?” These will each be addressed as part of the SASSAFRAS “Something From Nothing” and “Streak Harvest” efforts.

Based upon the open literature available, it does not appear that an effort to utilize serendipitous streaks or non-detections to improve catalog accuracy has ever been attempted. According to the University of Hawaii/Institute for Astronomy, in the early phases of the Pan-STARRS telescope program, there was a software package, known as Magic, which detected and removed all serendipitous partial detections[v]. Additional literature searches do not uncover any efforts to utilize the information in those partial detections.

However, in 2011 the Air Force Research Laboratory did publish details on the concept of operations (CONOPS) they developed to utilize the astronomical telescope Pan-STARRS to survey the Geosynchronous belt to detect satellites and debris[vi]. The paper describes how the telescope was specifically tasked to optimize sensitivity and false alarm rates for GEO detections. SASSAFrAS is implementing techniques to take the next step to utilize serendipitous detections and non-detections. There are significant additional challenges to utilize these datasets.

Before tackling these technical challenges it was prudent to perform an analysis of the value added assuming successful development and information access. DARPA published a paper[vii] that offered an equation for establishing the relative value of information and the information required for Space Situational Awareness (SSA). While the cost per relevant byte metric can be debated, it does establish a defined standard that can be utilized for the purposes of this “back of the envelop” sanity check.

In the analysis DARPA proposes 30 gigabytes of “relevant” SSA data is required to track over 100,000 objects by the year 2050. Utilizing the information in the paper, we have recreated the analysis, but restricted the equation to only account for tracking information and not satellite imagery as well resulting in a 27.6 gigabytes required per year for satellite tracking.

After performing a literature search of the available astronomy sensors, a reference was found for the America Association of Variable Star Observers (AAVSO), which plotted the number of observations received as a function of time. Extrapolating this curve provided an estimate for the number observers in 2050. Assuming 1% of the AAVSO observations provided enough information to establish a serendipitous track on an object resulted in providing <<1% of the data volume needed.

We made the assumption that if one were able to determine that there was NOT an object present and propagate and reconstruct that volume of space for future exploitation, it was equivalent to producing 200 tracks per observation. This is a drastic oversimplification of the various parameters such as, field of view, instantaneous field of view, relative value of a negative detection, sensitivity limitations, etc. however this analysis is only for the purpose of justifying a more in depth investigation. The results with these assumptions can be seen below in figure 1.

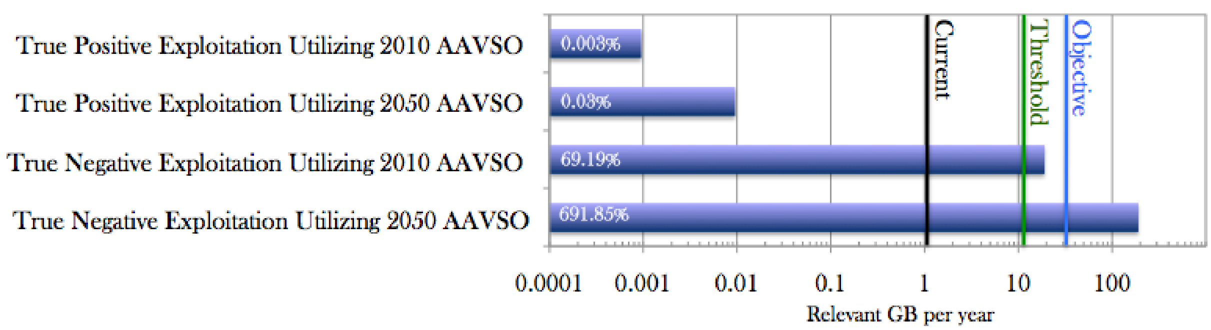

Fig. 1. Percent of required relevant SSA information available from serendipitous AAVSO observations

While a superficial analysis, this clearly demonstrates that attempting to exploit negative detections could prove to be a very valuable data source for Space Situational Awareness however the technical challenges to exploit this information requires a new methodology for detection and catalog maintenance.

STREAK HARVEST (SH)

The SH effort is developing algorithms to update the probability distributions of space objects in a specified regime utilizing the knowledge that an object was possibly partially detected. For the purposes of this proposal partial detections are defined as detections with less than 2 streaks with 2 endpoints. Most SSA detection algorithms require a minimum of two full streaks for optical systems. This requirement exists to resolve ambiguities from optical point spread functions, discerning between prograde and retrograde orbits, and rejecting false positives caused by detector and environmental effects. Based on this definition, the categories of partial detections are:

1. [1 streak, 2 endpoints]
2. [1 streak, 1 endpoint]
3. [1 streak, 0 endpoints]
4. [1 streak, 2 endpoints] + Infinite permutations of [1 streak, 1 endpoint] & [1 streak, 0 endpoints]

SH will fuse a high accuracy satellite catalog, historical radiometics, and radiometric/astrometric star catalog, to determine probabilities of detection within the field of view of the optical image.

The SH effort has three fundamental technical challenges to solve:

1. Assigning probabilities of True Positive vs. False Positive
2. Utilizing True Positives to update regime probability distribution
3. Utilizing False Positives to update regime probability distribution

If solved, this technique is not only applicable to astronomical data sources, but also any optical system, which may produce partial detections.

Determining True Positive vs. False Positive

The optical astronomy and SSA communities have spent a great deal of time attempting to solve this challenge and have developed methods for detecting false positives. These methods range from PSF cosmic ray/hot pixel rejection[viii] to multi-detection thresholding.[ix] Utilizing these methodologies partial detections will not be utilized. To assign probabilities we need to think about how a telescope operator or researcher decides that they are tracking the right object real time. The SH effort automates this manual process by fusing all available information through a probabilistic approach. Instead of assuming truth above a threshold, each possibility (hot pixel, cosmic ray, saturation effect, valid detection etc.) will be assigned a probability by computing the Weighted Mahalanobis distance in multiple dimensions:

1. Angles (Right Ascension / Declination)
2. Angle rate (Minimum & Maximum)
3. Historical radiometry as a function of phase angle
    a. Note: Phase angle is most effective for a stable GEO however the standard deviation can be constrained by making simple shape assumptions.[x]
4. Point spread function as a function of magnitude
5. Alignment with pixel readout
6. Proximity to saturated pixels
7. Previous detector statistics (e.g. previous false detections as a function of pixel)
8. Miscellaneous (additional literature searches and community engagement will add to/refine this list)

By weighting each parameter for each solution, we can analytically produce a metric of probability that the detection is a True or False positive.

Utilizing True Positives to update regime probability distribution

True positives will provide high accuracy angles information for each pixel, however the angle rate uncertainties will be large compared to detections from multiple streaks. While the uncertainties are high, these can be utilized to update the probability distributions available in the regime probability distribution. Each of the four categories of partial detections provides additional knowledge on the regime probability distribution.

<u>[1 streak, 2 endpoints] Exploitation</u>

A true positive of 1 streak with 2 endpoints can be utilized to determine optical cross section, potentially periodicity, angles, and angle rate. While traditional approaches utilize the midpoint of the streak and infer angle rate by utilizing other streaks, the angle rate can also be determined if the PSF is well characterized and the sign of the direction of motion is known or assumed. Since the detection has been assigned a probability of association to a known object in the catalog, that probability can be leveraged as the probability that the detection sign of the direction of motion is consistent with the expected object distribution. Based on the PSF determined from the stars, the streak can then be utilized to determine an angle rate and the associated uncertainty based on the PSF knowledge uncertainties. The derived angles and angle rate can then be utilized to update the regime probability distribution with a given confidence. The pixels can be utilized to generate a light curve for periodicity analysis and summed to provide an average optical cross section. The uncertainty for the periodicity is quantifiable but may be high due to a nonlinear mapping of average angle rate to time per pixel. (i.e. the ratio of effective integration time per pixel may be inconsistent). This uncertainty however can be constrained utilizing the updated object state vector.

<u>[1 streak, 1 endpoints] Exploitation</u>

A true positive of 1 streak with 1 endpoint can be utilized to determine the minimum optical cross section, periodicity, angles of one endpoint, and a minimum and/or maximum angle rate. This can be performed utilizing the same process as described previously, and constraining the missing endpoint by the upper and lower bound of the pixel mask. Important to note that if the missing endpoint is a result of the streak leaving or entering the FOV during the exposure, only a minimum angular rate can be determined. A minimum optical cross section and periodicity can also be determined from the pixels with associated uncertainties.

<u>[1 streak, 0 endpoints] Exploitation</u>

A true positive of 1 streak with 0 endpoints can be utilized to determine the minimum optical cross section, periodicity, and minimum/maximum angle rate. This is determined utilizing the same approach as previously presented and constraining the missing endpoints by the upper and lower bounds of the pixel mask. Important to note that if the missing endpoints are a result of the streak leaving or entering the FOV during the exposure, only a minimum angular rate can be determined.

<u>[1 streak, 2 endpoints] + Infinite permutations of [1 streak, 1 endpoint] & [1 streak, 0 endpoints] Exploitation</u>

The possible permutations of the previous cases are infinite in theory and only bounded in practice by the ability to associate partial detections from frame to frame. This is primarily possible if two capabilities sample the same volume with similar sensitivity limitations in overlapping/similar time frames. Since most astronomical systems tend to seek out dark skies with good astronomical seeing (Chile, Hawaii, Tucson, New Mexico, etc.), it seems quite possible that this could be a frequent occurrence, and a category worthy of further investigation.

Utilizing False Positives to update regime probability distribution

False positives, as defined by the SASSAFRAS effort, will be assigned a probability for each of the following top-level categories:

1. False detections due to detector or environmental factors (hot pixel, camera artifact, cosmic ray, etc.)
2. Non-correlated detections (not in catalog, large uncertainties in correlations, etc.)

<u>False Detections</u>

False detection probabilities will not provide direct value to the regime probability distribution; however will be recorded to determine the frequency with which a particular sensor or environmental factors generates this class of object. An example would be saturated stars causing false detections due to charge trails in the read-out. This historical information will then be utilized to assign probabilities for future detections of being a false positive or false negative. Overtime these statistics should accumulate since there is a fundamental assumption of consistent large data volumes available for each sensor. Trust in a given sensor will be analytically quantified and built over time.

<u>Non-Correlated Detections</u>

While some detections will not correlate with a known object, they may still be valid detections of objects not in the high accuracy catalog or a result of a large maneuver. These solutions will be weighted lower when updating the regime probability distribution, because there is a higher probability they are false since there is no other corroborating source. This highlights the need for more than just serendipitous observations for catalog maintenance, since this technique is biased against new objects. However, overtime an object's probability of existence increases as it is seen by more sensors, and will thus gradually be incorporated into the distribution.

SOMETHING FROM NOTHING (SFN)

The SFN effort will develop algorithms to improve the regime probability distribution utilizing the knowledge that no object was detected. SFN has two fundamental technical challenges to solve:

1) Assigning probabilities of True Negative vs. False Negative
2) Utilizing True Negatives to improve regime probability distribution

If solved, this technique is not only applicable to astronomical data sources, but any data source with knowledge of its detection threshold and the volume of space sampled. The SFN algorithms will update the regime probability distribution based on the sensitivity limitations and probability of no detection.

Determining True Negative vs. False Negative

In order to solve this challenge both the detection threshold and the expected object signal must be known. The proposed solution will develop a new technique to fuse radiometric and astrometric data. Determining the detection threshold for an a wide field astronomy sensor is fairly low hanging fruit due to the accuracy and sensitivity of cutting edge star catalogs. By evaluating the star detections, a probability of detection as a function of magnitude can be determined. The uncertainty in the probability of detection will be a function of the available correlated stars per image.

Determining the expected signal from a satellite is a significantly more difficult challenge. While there are many efforts, such as TASAT or DIRSIG, which attempt to model the radiometry of satellites, they are very rarely able to model all of the possible variables (crinkled MLI, unknown structures, inaccurate BRDFs, space aging, etc.) to accurately predict the radiometry of an object. In most cases an accurate satellite model is not even available. Rather than rely on unavailable high fidelity satellite models SASSAFRAS will fuse the historical observables for an object. In this case, our method will utilize the historical radiometry as a function of phase angle for the object.

Using this type of method is not possible to do deterministically, thus it must be done probabilistically. For example, if the historical data for an object has a mean visual magnitude of 6^{th} magnitude with a low variance over a statistically significant sampling, and it is not detected by a capability sensitive to 17^{th} magnitude for that orbit regime, there is a high probability the object is not within the field of view. However it may be that the satellite configuration has changed, or that it has never been sampled in these geometric conditions. While some of these variables can be assessed, for example, phase angle, without precise attitude truth the body angle could have changed.[xi]

Utilizing True Negatives to update regime probability distribution

The lack of detection is best utilized by updating the regime probability distribution for the sampled object set. In the previous example given, probabilities would be assigned for each solution (inadequate historical radiometry, object not within sampled volume, object configuration change affecting radiometry, object no longer exists [break-up event], etc.). AFRL has begun investigating these types of techniques for classifying space-craft[xii] however SASSAFRAS will leverage this approach for decision analysis to classify detections as true or false positives or negatives. As a function of the various probabilities the true negative will be weighted before updating the regime probability distribution.

Computing the Weighted Mahalanobis distance or "out of family analysis" in multiple dimensions can potentially provide probabilities for each scenario possibility. While still a work in progress, the candidate dimensions that could potentially be combined produce the probabilities for scenarios are:

1) Anticipated Angle rate vs. maximum number of masked pixels per cluster / number of clusters
2) Historical radiometry as a function of phase angle
3) Minimum Delta V required to maneuver out of FOV since last confirmed detection vs. radiometrically inferred size (ideally mass would be known for the object)
4) Atmospheric drag required to perturb out of FOV since last confirmed detection vs. radiometrically inferred size (ideally area to mass ratio would be available for the object)
5) Solar radiation pressure required to perturb out of FOV since last confirmed detection vs. radiometrically inferred size (ideally area to mass ratio would be available for the object)
6) Miscellaneous (additional literature searches and community engagement will add to/refine this list)

PROBABILIY DISTRIBUITION FUNCTIN ORBIT PROPAGATION (PDFOP)

The end product of SH and SFN are detection probabilities over a volume of sampled space as a function of visual magnitude. One technique to utilize these metrics is to threshold the probabilities and apply traditional covariance constraints to state vectors. SASSAFRAS will explore a non-traditional approach to catalog maintenance: probability distribution function propagation. In this approach, data association will not be performed utilizing a single detection. Instead the observation will be utilized to update a probability distribution in multiple dimensions.

This multi-dimensional matrix will contain the probability of an object's existence in space-time as a function of optical cross section, confidence, range normalized magnitude, phase angle, wavelength, age of information source, and trust level of the source. Similar to propagating a fluid or quantum particles, there always exists a probability of collision with other particles, which will also be captured in the propagation process along with potential new objects as a result of the possible collision. To be clear, no data association has yet been performed in this process. This distribution function propagator will have rule functions built into it that propagate all parameters forward and backward in time.

Utilizing this methodology it is possible to real time update your situational awareness without having to re-run the entire data association algorithm with each new information collect. State Daemons will monitor the distribution for probability divergences, which represent potential collisions. Another will monitoring the distribution for volumes that have low confidence due to high uncertainty or stale information. This provides a means to perform intelligent sensor tasking without ever correlating an information collect to the catalog.

The big challenge with this type of approach is that space is big, and the resolution required is comparatively small. As a result this 10 dimensional matrix will be quite large throughout the space-time projection. However, the universe has thrown us a proverbial bone, space is incredibly sparse. Even with 30,000 objects sub-GEO graveyard, the domain is extremely sparse compared to other domains. As a result there are a multitude of options to perform matrix compression.

SASSAFRAS will explore these compression methodologies and develop a propagator for this probability distribution function. While there are a multitude of potential benefits to this approach, it is important to leverage other information sets, such as SP catalogs or space-track.org. As a result, SASSAFRAS will develop methodologies to convert these information sources into a probability distribution function, and the ability to convert the updated / propagated distribution function back to Two Line Element (TLE) sets.

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