Realistic Sensor Tasking Strategies

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Abstract

Efficient sensor tasking is a crucial step in building up and maintaining a catalog of space objects at the highest possible orbit quality. Sensor resources are limited; sensor location and setup (hardware and processing software) influence the quality of observations for initial orbit determination or orbit improvement that can be obtained. Furthermore, improved sensing capabilities are expected to lead to an increase of objects that are sought to be maintained in a catalog, easily reaching over 100'000 objects.

Sensor tasking methods hence need to be computationally efficient in order to be successfully applied to operational systems, and need to take realistic constraints, such as limited visibility of objects, time-varying probability of detection and the specific capabilities in software and hardware for the specific sensors into account.

This paper shows a method to formulate sensor tasking as an optimization problem and introduces a new method to provide fast and computationally efficient real time, near optimal sensor tasking solutions. Simulations are preformed using the USSTRATCOM TLE catalog of all geosynchronous objects. The results are compared to state of the art observation strategies.

1. INTRODUCTION

Observations are the only independent source of information on Earth orbiting space objects. Traditionally, surveys and follow-up observations are discriminated [5, 3, 4]. In surveys, parts of the sky are scanned fort he detection of new objects, for which no a priori information is available. Follow-up observations are carefully planned observations of objects for which orbital information is available; the telescope is pointed to the predicted astrometric position of the object.

The Deutsches Zentrum für Luft- und Raumfahrt (DLR, German Aerospace Center) is currently in the process of building a network of small robotic wide field telescopes, the Small Aperture Robotic Telescope network (SMARTnet), with several locations around the globe. The aim is to build and maintain a complete and redundant coverage of the geosynchronous region and to build and maintaing a catalog of the full probability density function of all detectable space objects. The development of adequate survey and follow-up strategies are an integral part in the development and operation of SMARTnet. In the current investigation, focus is laid on the first of the operational stations of SMARTnet, located in Zimmerwald, Switzerland.

In this paper a new way of planning and conducting surveys is presented, in treating the sensor tasking and object coverage as an optimization problem via a weighted sky area approach. The paper is organized as the following: In the first section, classical survey strategies are illustrated. In the second section, the new approach in viewing surveys and follow-up as a holistic optimization problem. In the third section, the near-optimal solution computationally fast solution to the optimization problem is presented. In section four, simulation results are shown. The paper concludes with with a summary and conclusions. This paper is kept short a more extensive treatment of the problem can be found in the journal paper.

2. CLASSICAL SURVEYS

In classical surveys for geosynchronous objects, so-called declination stripes are scanned [5, 1, 2, 6]. These stripes are formed, in keeping a fixed right ascension and visiting several declinations. A number of l exposures are made for the h different declinations.

2.1. One-Stripe strategy

An initial right ascension and declination is chosen. The right ascension is kept fixed and the center of the pointing direction is placed at the declination, which is one field of view width higher than the previous declination. Often a small overlap is used to in order not to miss objects, which are just at the edge of the field of view, computing the new declination as the width of the field of view minus this overlap compared to the previous declination. After h number of changes of the declination, and $n \times l$ number of exposures, the first declination is chosen again. An important factor herewith is the cycle time, that is the time which it takes, till the first declination is used again. The cycle time is given by:

$$t_{\text{cycle,one}} = l \cdot t_{\text{exp}} + (l-1)t_{\text{readout}} + h \cdot t_{\text{repos1}} + t_{\text{repos2}}, \tag{1}$$

where t_{exp} is the exposure time, t_{readout} is the readout time of the image, t_{repos1} is the time to reposition the telescope within the stripe, and t_{repos2} is the reposition time of the telescope to the initial declination position. Depending on the telescope setup both times can be identical, as repositioning is dominated by the vibration settle time of the telescope mount rather than slewing time. The readout of the last frame can be done in parallel to the repositioning.

In order to not miss objects and to be so-called leak proof on average, the cycle time needs to shorter than the time it takes one of the target objects to pass through the field of view. The passing time for GEO is:

$$T_{\text{pass}} = \frac{v_{\text{GEO}}}{FOV} \qquad v_{\text{GEO}} = \frac{2\pi}{24\text{h}}. \tag{2}$$

This way a maximum amount of the sky is scanned as the geosynchronous objects are passing through the field of view.

2.2. Two-Stripe Strategy

For a successful first orbit determination, at least two observations spaced significantly in anomaly are needed. This is aimed for with the two stripe strategy. A first stripe is scanned upon rise of the stripe. Upon finishing the last declination direction of the first stripe the telescope is repositioned to start to observe a second declination stripe at a different right ascension. Only after the last declination of this second stripe is scanned, the telescope is repositioned to the first declination of the first stripe. This increases the cycle to:

$$t_{\text{cycle,two}} = \sum_{j=1,2} l_j \cdot t_{\text{exp},j} + (l_j - 1)t_{\text{readout}}) + h_j \cdot t_{\text{repos1,j}} + \tilde{t}_{\text{repos2,j}}, \tag{3}$$

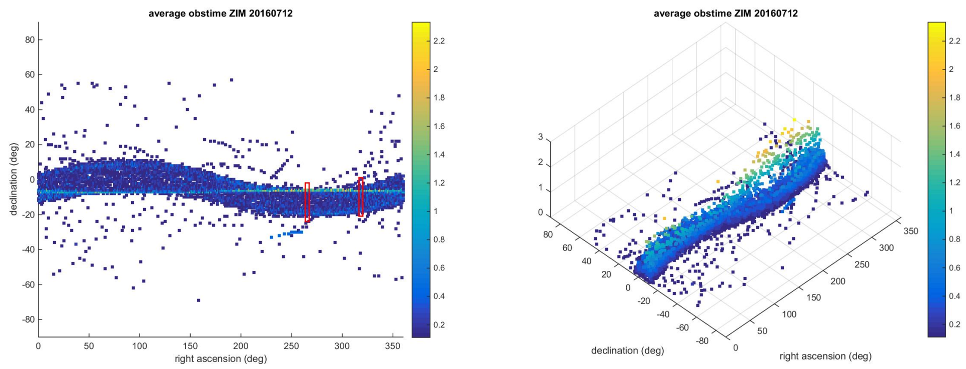
most often the number of exposures, the exposure times and declination directions and declination repositioning times are the same for both stripes. $\tilde{t}_{\text{repos2,j}}$ is the repositioning time from the final declination of one stripe to the first declination of the other stripe. It is possible to the repositioning time from stripe one to stripe two is differs from the time to perform the reverse.

Several objectives can be leveraged in selecting the position of the two stripes, two are dominating. One is a spacing of the two stripes by one hour in right ascension, with the second stripe being started to be observed one hour after the first one, and observing both in parallel, till one hour of the end of the night. This way, in general two observations, spaced by 15 degrees in anomaly. The scenario can be thwarted by the Earth shadow. It also does not provide an optimal spacing in anomaly, and does not take illumination conditions into account. In the ideal case all newly detected objects with the geosynchronous mean motion are detected twice, when the cycle time is sufficiently low.

A second objective is to detect the objects in best possible illumination close to the Earth shadow. The first stripe is observed until the second stripe rises, and two stripes are observed in parallel, until the first one sets. It has to be noted that optimal phase angle provides optimal illumination and visibility only for either uniform spherical objects or box-wing satellite configurations which are actively stabilized with the panels towards the sun. This allows a bit larger anomaly spacing, however, not all objects that are detected are guaranteed to be observed twice.

2.3. Selection of the Stripe(s)

The size and location of the declination stripes are oriented not independently, using first principle, but are rather oriented at the objects currently listed in the US Strategic Command two line element catalog (short: TLE catalog). Fig.1 binned the location of the TLE catalog objects of July 12, 2016 and shows operationally chosen declination stripes for SMANRTNET,



(a) Averaged binned catalog with stripes

(b) Averaged binned catalog overview.

Figure 1: Binned TLE catalog object positions over the night relative to the Zimmerwald topocentric location and chosen declination stripes.

the Earth shadow is between the two stripes. It is already obvious that there is a trade-off between covering all possible and interesting inclinations, that is the number of single declinations that are touched upon, which have a high potential to bear objects, and to be leak proof. With this strategy, one observation tracklet, that is a maximum number of l single very closely spaced observations, which in an astrodynamic sense accounts for one observation of astrometric position and velocity, per object passing the field of view with the average expected velocity is targeted. In the two stripe strategy, the problem of the sufficient cycle time is because of the repositioning to two different stripes exacerbated. Furthermore, a trade-off is made between choosing an optimal revisit time of each object and the optimal illumination ensured by the best phase, which is in immediate vicinity of the earth shadow.

3. SURVEYS AS OPTIMIZATION PROBLEM

It has been shown that the surveys are despite the fact that they are designed to efficiently scan the sky are oriented at the TLE catalog, in order to determine which fields are likely to bear new objects. It has also been shown that trade-offs have to be made, balancing the two stripes, the cycle time and illumination conditions at a minimum.

Another way of looking at the problem is to formulate it as an optimization problem. The maximum amount of the sky is sought to be observed. This can be obtained by not allowing observed and newly to observe sky field of views to overlap. However, also *good* field of views shall be observed. In the classical strategies, the good field of views are judged based on the TLE catalog and

3.0.1. Formulation for the Maximum Observed Weighted Areas

Formulating the problem in the standard form of the optimization problem to fit the exact form of the constrained optimization problem:

$$\min D(\alpha_g, \delta_g) = -\sum_{g=1}^{l}\sum_{f=1}^{m_g}\sum_{i=1}^{n} \mu(\alpha_{\text{past}}, \delta_{\text{past}}) p(\alpha_i, \delta_i, \mathbf{o}) d(\alpha_{f,g}, \delta_{f,g}) \tag{4}$$

$$\begin{aligned}
\alpha_{f,g} - \frac{1}{2}\text{FOV} - \alpha_i &\leq 0 & (5)\\
-\alpha_{f,g} - \frac{1}{2}\text{FOV} + \alpha_i &\leq 0 & (6)\\
\delta_{f,g} - \frac{1}{2}\text{FOV} - \delta_i &\leq 0 & (7)\\
-\delta_{f,g} - \frac{1}{2}\text{FOV} + \delta_i &\leq 0 & (8)\\
\mathbf{U} - \sigma(\alpha_i, \dot{\alpha}_i, \delta_i, \dot{\delta}_i, \rho_i, \dot{\rho}_i, \nu) &\leq 0 & (9)
\end{aligned}$$

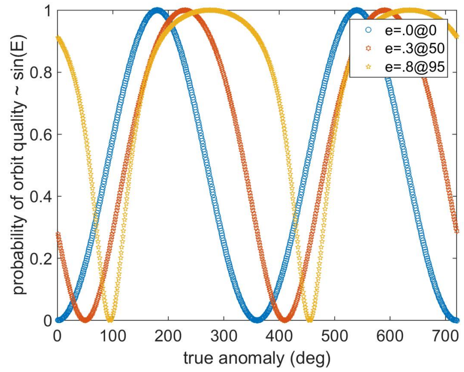


Figure 2: Probability of orbit quality for three different orbits with first observation at true anomalies of zero, 50, and 95 degrees and eccentricities of zero, 0.3, and 0.8.

$D : \mathbb{R}^{k+4} \to \mathbb{R}$ being the cardinality of the weighted viewing direction areas, $p(\alpha_i, \delta_i, \boldsymbol{o}) \in [0,1]$ is the probability of detection of the single object of interest located at right ascension $\alpha_{i,\mathrm{f}}$ and declination $\delta_{i,\mathrm{f}}$. The probability of detection is not only dependent on the astrometric position of the objects, but also on other parameters, conflated under $\boldsymbol{o} \in \mathbb{R}^k$ including distance to the observer and the sun, location of the sun and object dependent parameters, such as the object's size, shape, attitude, and surface reflection properties. Most of the object dependent parameters are not exactly known in general and unknown for most of the objects. In the chosen representation, the function $d(\alpha_{f,g}, \delta_{f,g}, \alpha_i, \delta_i) : \mathbb{R}^4 \to \mathbb{R}$ has been defined for the sensor to object association, for sensor g and object i. Theoretically one could merge functions p and d into one function, defining that the probability of detection is zero when the object is not in the field of view (FOV) of the sensor, however for cleanness of representation and ease of understanding the more extensive definition has been selected. The sensor g has a specific viewing direction, that allows it to detect objects, denoted by right ascension and declination, $\alpha_{f,g}, \delta_{f,g}$, respectively.

Per observation run (e.g. one night), l sensors can be employed, those can take on a maximum of m_g viewing directions within the night. m_g is determined by the time that is allocated and how much time $t_{\mathrm{frames},g}$ it takes the specific sensor to make a fixed number of frames j_g with exposure time t_{exp}, readout time t_{read} and repositioning time t_{repos}, for the last frame in a series, repositioning and readout can be done simultaneously $m_g = \mathrm{int}(t_{\mathrm{obs},g}/t_{\mathrm{frame},g})$, with $t_{\mathrm{frame}} = t_{\mathrm{repos}} + j \cdot t_{\mathrm{exp}} + (j-1) \cdot t_{\mathrm{read}}$. In total n objects are in the scene that can be surveyed, or are of interest.

The constraint embeds a twofold, for one, the objects can only be observed if they are in the field of view (FOV), in which case the step function d just takes on value one, secondly, the more demanding constraint is that diversity in the objects that are sought to be observed is demanded. If the object is outside the FOV, it cannot be observed and does not count towards the weight of the viewing direction area D; however, it has to be prevented that always the same objects are observed. In order to prevent the trivial solution that the sensors stay on the most highly populated area of the sky and then just reobserving the same objects over an over again, making the most possible observations, and a high D count, however, not leading to diverse observations. In SSA the objective is to observe the objects that are either new, and when the catalog is growing to observe the objects as frequently such they do not get lost, but regularly updated. This is represented by the re-observation function $\sigma(\alpha_i, \dot{\alpha}_i, \delta_i, \dot{\delta}_i, \rho_i, \dot{\rho}_i, \nu) : \mathbb{R}^q \to \mathbb{R}^r$. It is a function of the full state of the object at minimum and potentially other parameters represented in ν. One interpretation of σ could the orbital covariance. Is it over a threshold $\mathbf{U}$ the object contributes again the to maximization of D; that is when e.g. the covariance is large enough to be updated, or other parameters in σ trigger that it is opportune to re-observe the object. In addition, the function $\mu(\alpha_{i,\mathrm{past}}, \delta_{i,\mathrm{past}})$ has been introduced. It is the probability of orbit quality, a function ensuring that anomaly diversification is present in the observations. It amounts to one when only one observation per object is sought and no information from previous nights is used. It can be formulated via the mean anomaly, an illustration can be found in Fig.2.

The problem can be solved if it fulfills the convexity criteria both, in time, that is at every time step, and over time as the objects are not static. Although, the problem is solvable (at least for static objects), e.g. via branching methods, it is NP-hard, with object numbers of around $n \approx 1300$ would take a long time to provide an exact solution. The pick of the viewing direction of the first frame even for a single sensor influences the viewing direction of **all** subsequent viewing directions. Solutions for the problem are along the lines of branch and bound algorithms, and sequential methods.

Furthermore, the scenario is not flexible to include a priori concepts of hypothesis objects.

4. NEAR-OPTIMAL SOLUTION OF THE OPTIMIZATION PROBLEM

A simpler formulation is to making a significant restriction. Not all viewing directions are allowed, but only fixed grid points in the right ascension, declination space can be visited. The maximum area problem with fixed visitation grid points is easily solvable and has the optimal solution that the maximum number of different fields are visited. This leads to a fixed number of grid points which can be visited for a given night per sensor. The advantage besides the computation time is that areas with object populations that have not been detected and no precise information is available are easily incorporated. In the previous approach, hypothetical orbits would have needed to be inserted. The downside is that the proposed strategy is only optimal for the given grid and not in general. The hope is to show that it is still near-optimal for the object scenario. The formulation would lead to the following:

$$\min A(\alpha_g, \delta_g) = -\sum_{g=1}^{l} \sum_{f=1}^{m_g} \left[\left(\sum_{i=1}^{n} \mu(\alpha_{\text{past}}, \delta_{\text{past}}) p(\alpha_i, \delta_i, \mathbf{o}) d(\alpha_{f,g}, \delta_{f,g}) \right) + k(\alpha_{f,g}, \delta_{f,g}) \right] \tag{10}$$

$$\alpha_{f,g} = \{\alpha_1, \alpha_2, ..., \alpha_m\}, m \in \mathbb{N} \tag{11}$$

$$\delta_{f,g} = \{\delta_1, \delta_2, ..., \delta_m\}, m \in \mathbb{N} \tag{12}$$

$$d(\alpha_{f,g}, \delta_{f,g}) = \begin{cases} 1 \quad \text{for} & \alpha_{f,g} - \frac{1}{2}\text{FOV} < \alpha_i < \alpha_{f,g} + \frac{1}{2}\text{FOV} \\ & \wedge\ \delta_{f,g} - \frac{1}{2}\text{FOV} < \delta_i < \delta_{f,g} + \frac{1}{2}\text{FOV} \\ 0 \quad \text{for} & \text{else} \\ & \vee\ \sigma(\alpha_i, \dot{\alpha}_i, \delta_i, \dot{\delta}_i, \rho_i, \dot{\rho}_i, \nu) + \tilde{\sigma}(\alpha_{f,g}, \delta_{f,g}) < \mathbf{U} \end{cases} \tag{13}$$

The formulation only changed in a few places. In Eq.10 both or either one of the terms can be present. Either the probabilities of the objects present in the field of view is added up, as before, and/or an additional term, which defines a quantity only dependent on the viewing direction, can be used, that does not bear object specifics, but denotes priorities just associated with the area covered in the specific viewing direction. This can be suspected object populations. They may be represented with a distribution just over the area of specific viewing directions, rather than individual orbital elements of the objects. Compared to the object specific optimization from before, additional limitations imposed by Eq.11 and Eq.12; those make the problem actually less complex. They imply that right ascension and declination of the pointing directions are restricted and can be written as a set of finite entries. A binning of the visible part of the sky of the size of the FOV suggests itself. A finer binning does not offer any advantages, same as a significantly broader one. Furthermore, an additional term can be used for viewing directed suspected population and their need to be (re-)observed, which can be represented by the area-reobservation function $\tilde{\sigma}$, that again is just viewing direction dependent.

Again this problem can be solved via integer math formulations of the association problem, optimality of the full problem cannot be guaranteed any more because of the fixed viewing directions.

4.1. Global and Local Optimum

A local optimum of the problem can easily be found in selecting the area with the highest weight at each time step. However, compared to the global optimality, two problems arise. One, areas with the identical weight can occur and it is to a certain extend arbitrary which one to pick for the local optimal at this time, or in other words the local optimum at this time instant is not unique, called an same-time conflict. The second problem is the more severe problem, of over time conflicts, that is the weight of the area can change and can become higher at a later point in time; overal my solution would be more optimal to visit this area later; this is called an all-time conflict. A full solution of the optimization problem, e.g. via branch and bound would of course find a global optimization and those conflicts would be meaningless. However, in the complete absence of these conflicts, same-time and all-time, the local optimal, that is the highest weight at each time step, and the global one would coincide. As the physics of the problem is known a diversification of the weighting of the area can be obtained. For one, an urgency probability can be defined. This takes into account that different fields containing objects that are setting and are hence at a later point in time not visible any more. A further step that has not been implemented is to take the time evolution of the probability of detection into account. A simple linear definition of the probability of urgency has been implemented, see Fig.3.

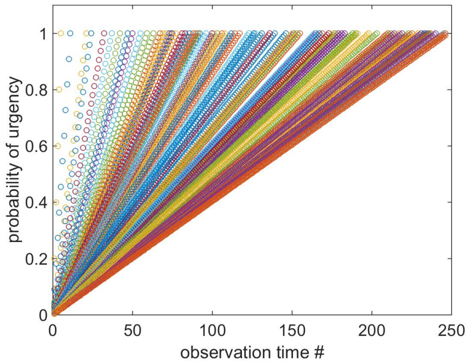
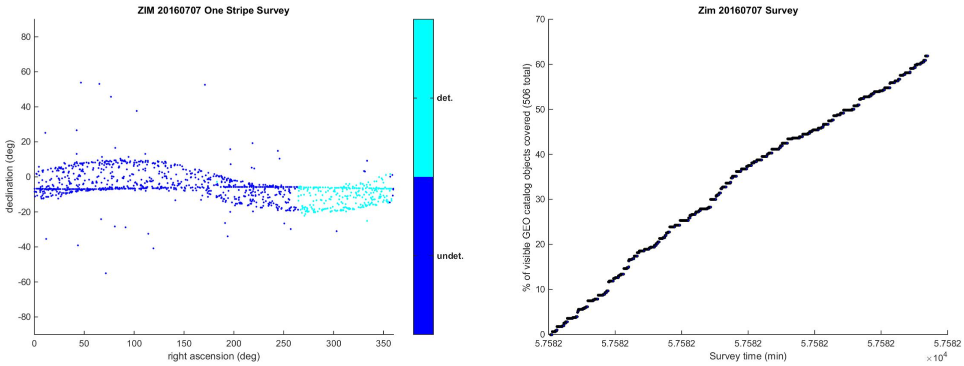


Figure 3: Diversification in time and over time for local optimization via the urgency probability function.



(a) Detected versus undetected objects

(b) Rate of the Detected Objects.

Figure 4: Simulation of the TLE objects from a Zimmerwald observer on July 12, 2016 with a single stripe strategy.

5. SIMULATION RESULTS

Simulations have been made for according to one SMARTnet sensors, holding a 3.77 x 3.77 degrees field of view, exposure time of eight seconds, readout time of seven seconds, repositioning within the stripe nine seconds and a repositioning to the beginning or the next stripe 30 seconds. Seven exposures per declination point are taken. Eight declination positions are chose to cover the dispersion of the known objects in inclination, cause by gravitational perturbations of the non-sherical Earth, the sun and moon in combination with the obliquity of the ecliptic. For the near optimal scenario, only the repositioning between the different fields have been modeled using the 30 seconds. Two different scenarios have been modeled. A one stripe scenario has been compared to an area weighting near optimal solution of touching upon all objects in the area fields once, secondly, two observations for all objects are aimed for. This is achieved with a two stripe scenario, placing the two stripes at the two sides of the Earth shadow, and with a two observations weighted area formulating utilizing the orbit quality probability function.

5.1. One Observation per Geosynchronous Mean Motion Object

The classical one stripe scenario is leak proof with the field of view that has been used under the constraints of the repositioning, readout and exposure times. Of the 1285 objects in the catalog at this day, 506 are visible from the Zimmerwald location during the time of the observation night. Around 63 percent of the TLE objects were detected in consistently scanning one stripe, see Fig.4.

The near optimal strategy is scanning the same net area of the sky during the night. As a solution the local optimization under the use of the urgency function has been used. Fig.5 shows the chosen areas, which the telescope visited. It has

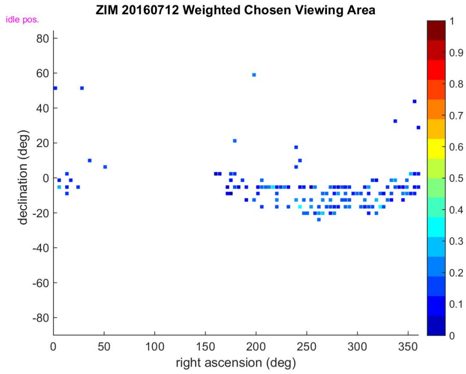
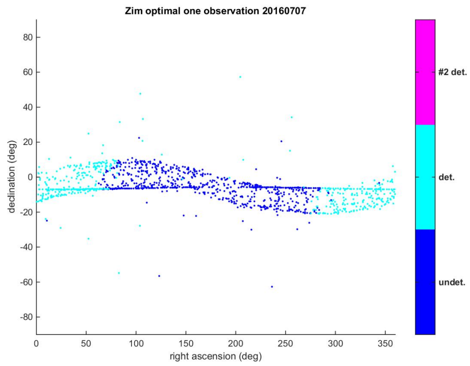
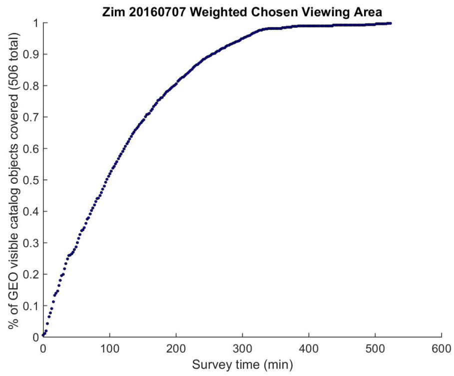


Figure 5: Chosen grid point viewing directions for a Zimmerwald observer on July 12, 2016 with near optimal solution utilizing urgency function.

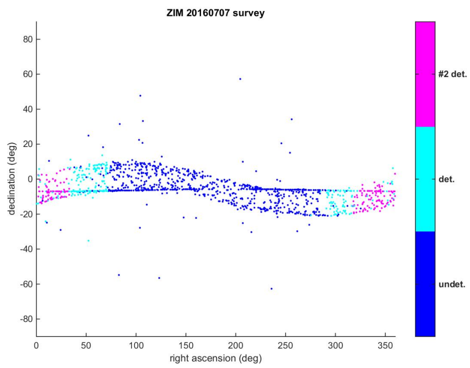


(a) Detected versus undetected objects

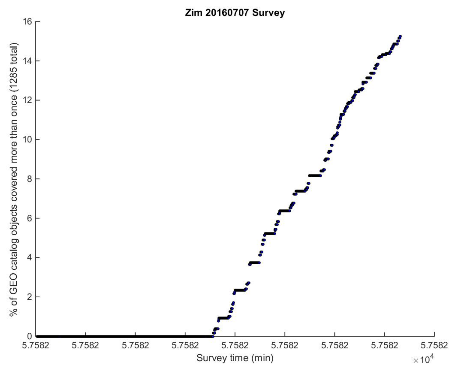


(b) Rate of the Detected Objects.

Figure 6: Simulation of the TLE objects from a Zimmerwald observer on July 12, 2016 with near optimal solution utilizing urgency function.



(a) Detected versus undetected objects



(b) Rate of the Detected Objects.

Figure 7: Simulation of the TLE objects from a Zimmerwald observer on July 12, 2016 with a two stripe strategy.

to be noted that the telescope had idle time as it had covered all visible objects. This time can be used to scan addition areas, via populating the function k in Eq.10. The rate of the detected objects is 100 percent of the visible ones, see Fig.6.

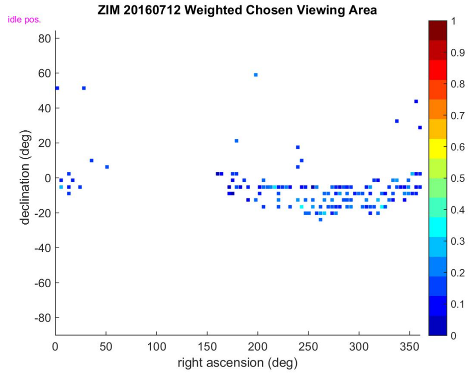
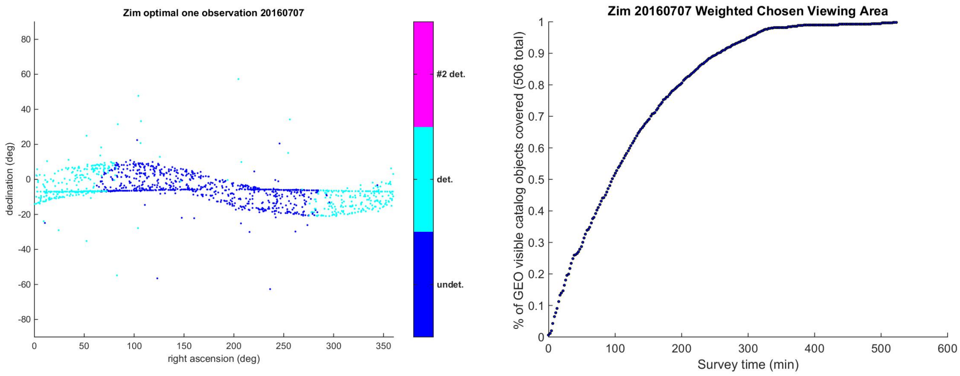


Figure 8: Chosen grid point viewing directions for a Zimmerwald observer on July 12, 2016 with near optimal solution utilizing urgency function.



(a) Detected versus undetected objects

(b) Rate of the Detected Objects.

Figure 9: Simulation of the TLE objects from a Zimmerwald observer on July 12, 2016 with near optimal solution utilizing urgency function.

5.2. Two Observations per Geosynchronous Mean Motion Object

A more realistic scenario is that two observations per newly detected object are sought within the same night, in order to allow for an initial orbit determination. In the classical scenario this corresponds to a two stripe scenario. For SMARTnet, two stripes in the vicinity of the Earth shadow were planned, see Fig.1. When two stripes are observed in parallel with the given constraints on repositioning, the scenario is not leak proof any more. That is objects with a geosynchronous mean motion are passing by without being detected. This is clearly visible in Fig.7. This leads to a rate of just under 16 percent of objects that have been observed twice, which corresponds to only 40 percent of all visible objects.

As a solution the local optimization under the use of the urgency function and the probability of orbit quality has been used. Fig.8 shows the chosen grid point areas, which the telescope visited. In this scenario no idle time is present. Fig.9 shows that a hundred percent of the visible objects have been observed once, a rate of just below 40 percent of all the catalog objects have been observed twice, which is a rate of 95 percent of all visible objects. That not all objects are observed twice is due to the fact that for some objects not a good enough anomaly difference can be reached, so they are discarded over detecting all objects once. Fig.10 shows the anomaly spacing, most objects have anomaly difference of around 50 degrees or more.

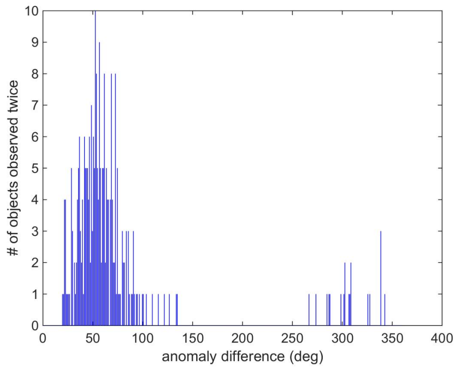


Figure 10: Anomaly difference between two observations.

6. CONCLUSIONS

Classical declination stripe observation strategies have been illustrated.

The problem has been reformulated as an optimization problem. In order to reduce the computational complexity, a grid based viewing direction formulation has been introduced. The portion of the sky that is viewed is optimized in weighting the different viewing directions by how many objects, that are either in the TLE catalog or via definition of regions with high probabilities for new objects. Detection conditions are conflated in the probability of detection. The user can define the sought number of detections of new objects within the night, such as to observe each object only once or for example twice within one night.

A near optimal solution is shown in further diversifying the weights both at the observation times and over the whole night, via the urgency and the anomaly probability formulations.

When taking the TLE catalog as a basis, the new strategy outperforms the traditional ones. For a field of view of 2.3 by 2.3 degrees and realistic exposure, readout and repositioning times, all areas containing visible objects are visited once in a July summer night on the western hemisphere. For the same field of view, the fields are visited in a manner that two observation tracklets are provided for over 80 percent of the visible objects.

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