Weather Considerations for Ground-Based Optical Space Situational Awareness Site Selection

Mark R. Ackermann, Sandia National Laboratories
Colonel Rex R. Kiziah, USAF Academy
Peter C. Zimmer and John T. McGraw, J.T. McGraw & Associates

Abstract

Continuous surveillance of the night sky with ground-based optical sensors requires a number of sites distributed around the globe. Due to variable cloud cover, the number of sites required to guarantee nightly observation of all Geosynchronous Earth Orbit slots is greater than that simply required to provide partial coverage. Combining this consideration with the requirements for dark sky sites and adequate supporting infrastructure presents additional limitations on where ground-based telescopes can be located. The authors examine this problem and present results of an optimization approach that can both recommend sites and networks of sites, as well as provide insight into the utility of any individual geographic location.

1. INTRODUCTION

For most countries, ground-based optical telescopes provide the majority of useful observations necessary for effective space situational awareness (SSA) of high-altitude satellites. While the United States (US) uses a combination of ground-based and space-based sensors for detection and tracking of satellites in highly-elliptical earth orbit (HEO) and geosynchronous earth orbit (GEO), ground-based optical telescopes still provide the best combination of sensitivity and search rate [1].

The two great limitations for ground-based optical telescopes are weather and the inability of most telescopes to observe satellites during hours of daylight. This paper examines the impact of weather on the overall performance of ground-based telescope networks.

2. BACKGROUND

When selecting locations for ground-based telescopes, the typical considerations are for sky coverage, infrastructure, local weather and how the telescope will fit into an overall observing architecture. On first examination, these considerations seem to be correct, but weather statistics for individual stations can be very misleading.

For routine SSA—more commonly known as catalog maintenance—weather outages are not seen as a significant limitation. If one site is unable to make observations for several days, there is no cause for concern. Once skies clear, observations will resume and satellite positions and orbits will be updated. The slight changes in the catalog that occur day to day are not significant.

Unlike routine catalog maintenance, potential orbital conjunctions are of significant concern and require relatively short-notice observations to obtain more precise observations of satellite position and orbit to determine whether a potential conjunction is of concern. Weather outages that prevent or hinder observations of satellites headed for a potential collision are of significant concern. Normally there are work around solutions for weather outages, such as obtaining observations with a high-resolution ground-based radar, tasking a non-traditional ground-based optical telescope, or obtaining data from a space-based sensor. However, for reasons of redundancy and resiliency, it is desirable to have a ground-based network capable of uninterrupted nightly observations of every position along the GEO belt without weather limitations.

Ideal observing sites are normally found at high elevations, such as on or near the tops of mountains. They frequently have very dry air and cloud-free skies, such as arid or desert locations. They require dark skies implying they are some distance from large population centers, yet they require infrastructure in the form of utilities, communications and transportation, implying that they cannot be too far from developed areas. Finally, to minimize seasonal variations in observing hours, locations on or near the equator are desirable. The problem with this list of requirements is that some of them are often mutually exclusive, or are only available with significant site development.

While placing observing sites along the equator works well from a modeling and simulation point of view, in practice the equator proves to be less than an ideal location. When considering the locations of most major astronomical observatories around the world, one finds they are not located anywhere near the equator, as shown in Figure 1.

Figure 1. Location of Major Astronomical Observatories around the World [2]

Other than a small observatory located near Quito, Ecuador (not shown in Figure 1), one does not find observatories located near the equator. Why is this true? Most of the world's equatorial region is covered with water. Those parts not covered by water usually have tropical climates, complete with copious cloud cover. Finally, most of the near-equatorial locations not covered by clouds are controlled by entities not always interested in international relations and cooperative ventures.

Geographic issues are easy to identify by looking at a traditional map, but other issues such as cloud cover, elevation and sky brightness require consulting different maps. To examine the problems of site selection, telescope network optimization and weather limitations, the authors developed a simple tool to evaluate and optimally select location sites to provide guaranteed nightly observing of each orbital position along the GEO belt. The tool was used to evaluate current, proposed and notional networks of ground-based optical telescopes for nightly coverage.

3. APPROACH

3.1. Data Collection

To automate the analysis of potential satellite observing sites, it is necessary to collect data relevant to the problem. The first—and arguably most important—information was a list of potential observing locations. These were collected in the form of lists of known observatories, islands around the world, cities, government facilities, military facilities and sites already known to support SSA. The initial list included 1,863 such locations, specified by longitude and latitude. Elevation information were not always available. Figure 2 shows a graphic presentation of the potential observing sites included in the first version of the site selection and evaluation tool.

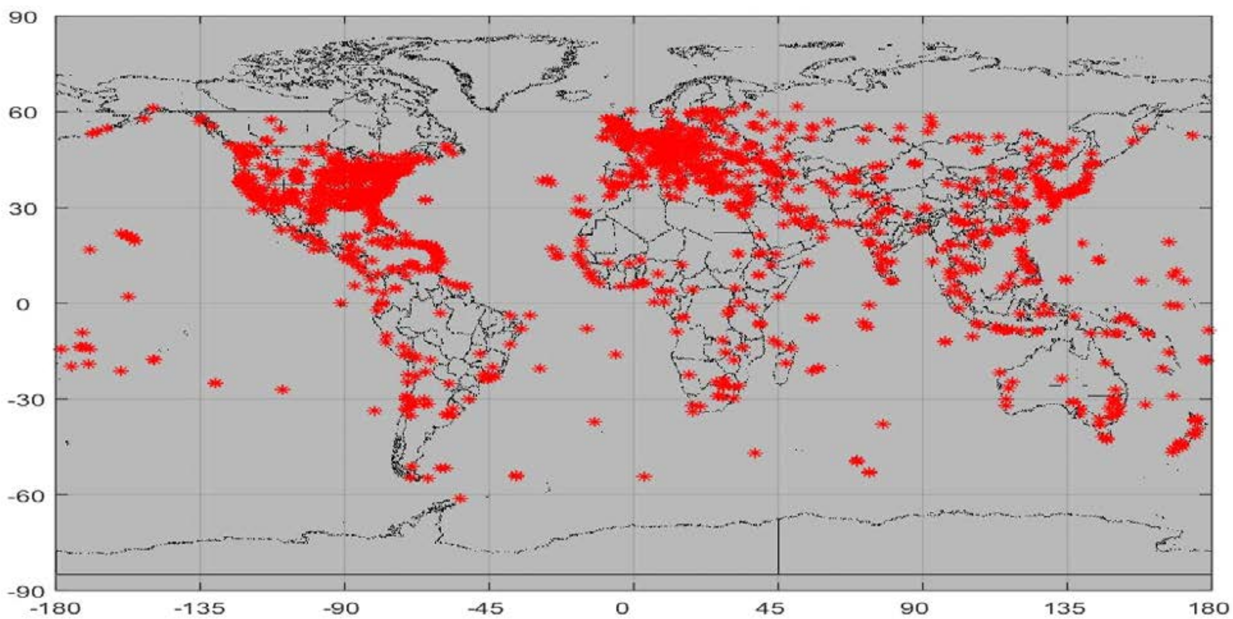

Figure 2. Database of 1,863 Global Potential Observing Sites

To find the elevation for all potential observing sites quickly, a global digital elevation map available from NASA was employed. An image of such a map is shown in Figure 3.

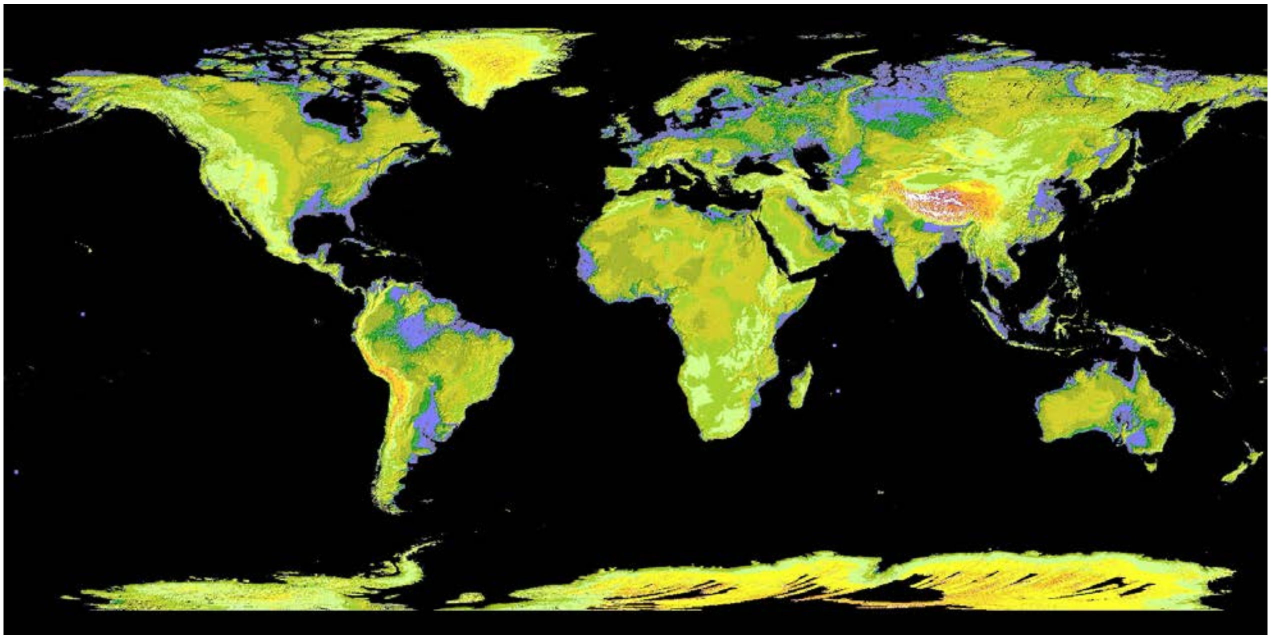

Figure 3. NASA Global Digital Elevation Map [3]

Night time sky brightness data were derived from the model developed and supported by the International Dark Sky Association [4]. A rendering of night sky brightness around the globe is seen in Figure 4. The colors in Figure 4 correspond to specific brightness levels measured in visual magnitudes per square arc second of sky.

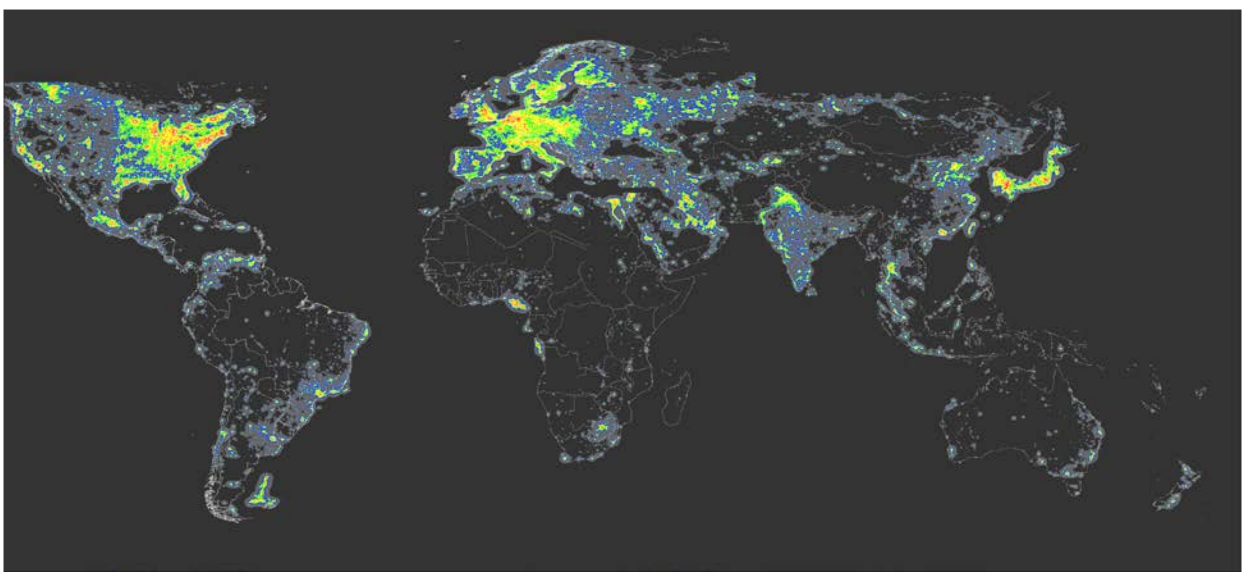

Figure 4. Night Sky Brightness [5]

The original plan for the site evaluation tool was to include models and measurements of daily and nightly atmospheric transparency. This feature will be included in future versions of the tool, but was not functional for the research presented in this report. Nonetheless, atmospheric transparency data based on a NASA measurement of atmospheric aerosols were collected. A typical depiction of such data is shown in Figure 5. The darker areas in this figure indicate regions of increased aerosol concentration, and therefore, decreased atmospheric transparency.

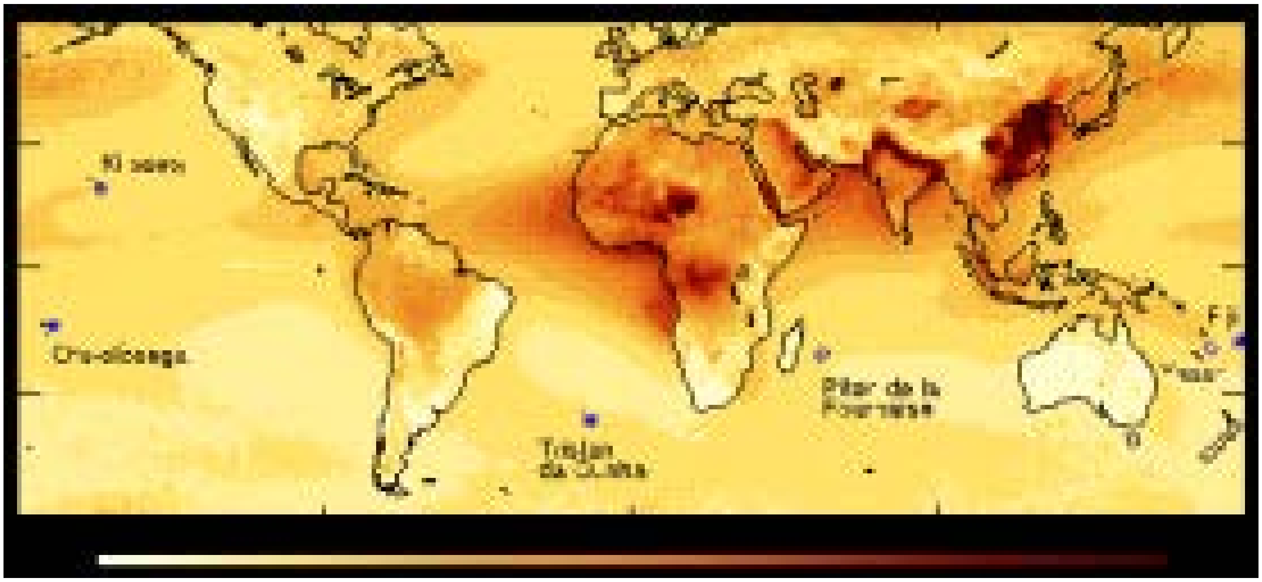

Figure 5. Example of Daily Measured Atmospheric Transparency [6]

The final data required were measured daily and nightly cloud cover around the globe. These data are collected by NASA satellites and made available to support various research and environmental monitoring projects across the government and within academia. An example of cloud cover data for a single day is shown in Figure 6.

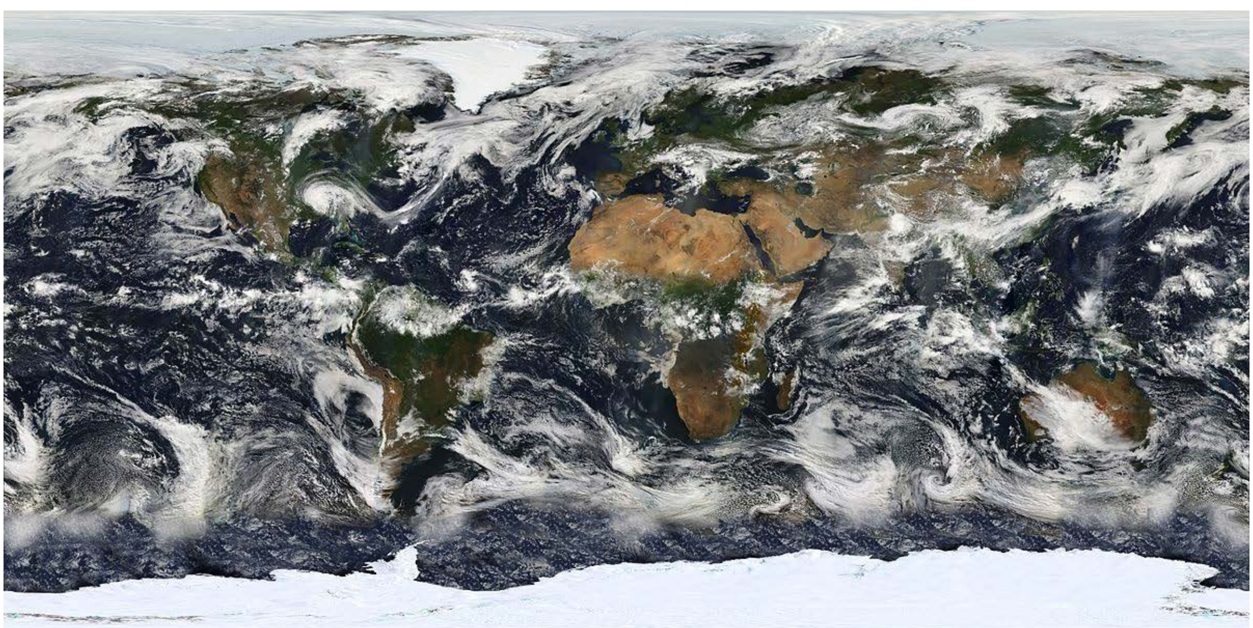

Figure 6. An Example of NASA Generated Global Cloud Cover Data [7]

3.2. Analysis Tool Development

With the necessary input data collected and ready for processing, the site evaluation tool was developed as a MatLab script. The process flow is conceptually simple, but as with any code there are many details that make it work.

The code first loads the list of observing site candidates with the critical information being the latitude and longitude. These coordinates are converted into X and Y coordinates in a Mercator projection of the earth. The global data sets are then individually loaded and processed as images. For each observing site, the X and Y coordinates are used to extract the relevant datum from the image with physical values then calculated from the relevant data scale. First, the elevation for all sites is extracted from the global digital elevation map. Next, night sky brightness values are extracted and finally, cloud cover statistics for 1,095 consecutive nights (three years) are loaded, processed and extracted. As the extraction of physical values from the image data is a time consuming process, it is accomplished only once. All extracted values are stored in a large table and written to a file for rapid retrieval.

Once data are available in tabular format, they can be used to generate annual statistics for each observing site. The range of GEO slots that can be observed from any individual site are calculated from the site coordinates and observing elevation angle limits. Locations at higher latitudes (north or south) view smaller arcs of the GEO belt as compared to lower latitude sites, making them somewhat less useful. Combinations of multiple sites can be simultaneously evaluated to see how frequently (or infrequently) they are able to view an individual GEO slot. Such assessments are useful when two or more *eyes on target* are desired for either redundancy or to derive range from measurements of parallax.

As an example, consider the annual cloud cover statistics for the four US sites for ground-based optical SSA collection (Ground-Based Electro-Optical Deep Space Surveillance [GEODSS] plus Space Surveillance Telescope [SST] in western Australia). Figure 7 shows the expected number of observing nights each year for all GEO slots, based on a user requested maximum nightly cloud cover of 30%. Users who are willing to make observations with higher maximum nightly cloud cover would be able to observe more nights per year, while those requiring lower nightly cloud cover would see a reduction in the number of observing nights.

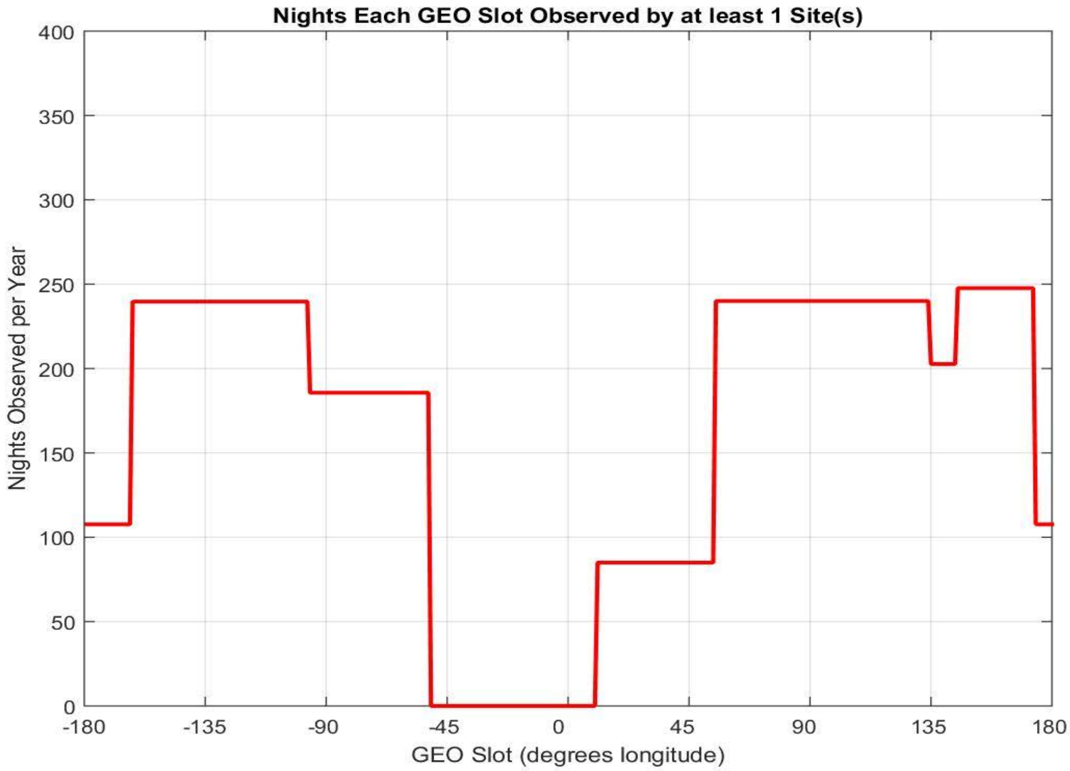

Figure 7. Observing Statistics for GEODSS + SST with <30% Nightly Cloud cover

Ground-based telescope networks with a larger number of observing sites are able to achieve higher coverage statistics. The International Scientific Optical Network (ISON), managed by a group of Russian academics and businessmen, currently operates approximately 100 telescopes from 30 sites scattered around the world [8]. With this greater number of sites, the ability of ISON to observe each GEO slot is quite good, as shown in Figure 8. ISON, with observing sites as shown in Figure 9, is able to observe most GEO positions more than 300 nights per year, provided they can operate with cloud cover of 30% or less.

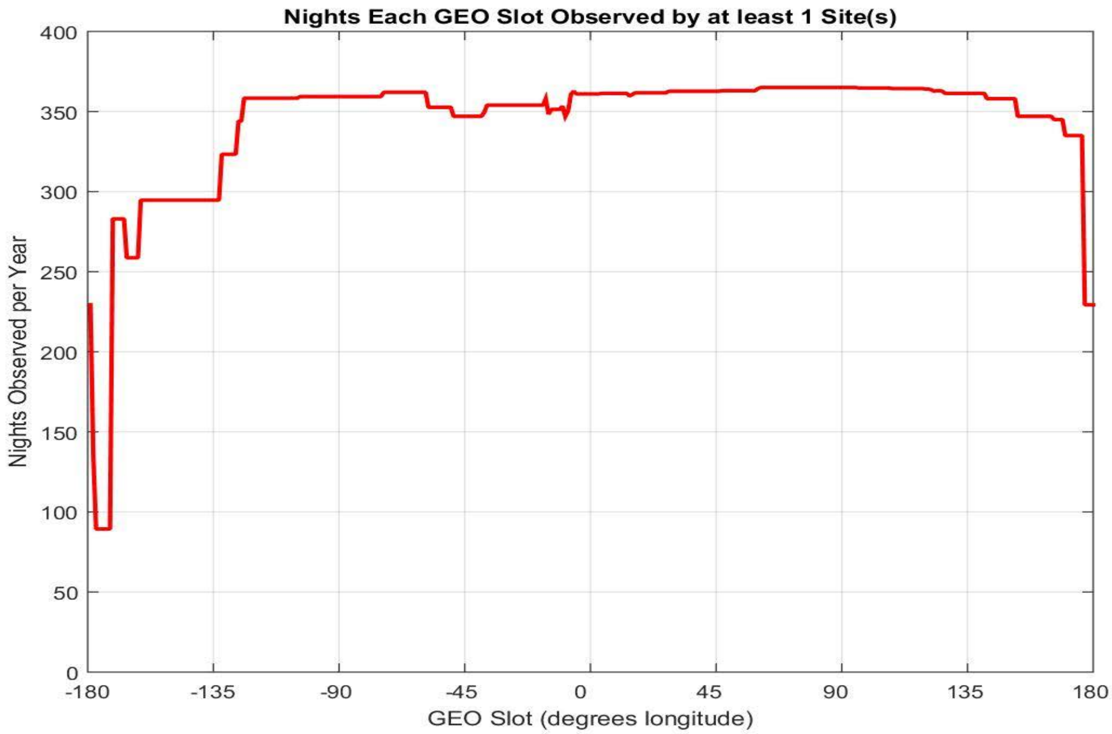

Figure 8. Observing Statistics for ISON with <30% Nightly Cloud cover

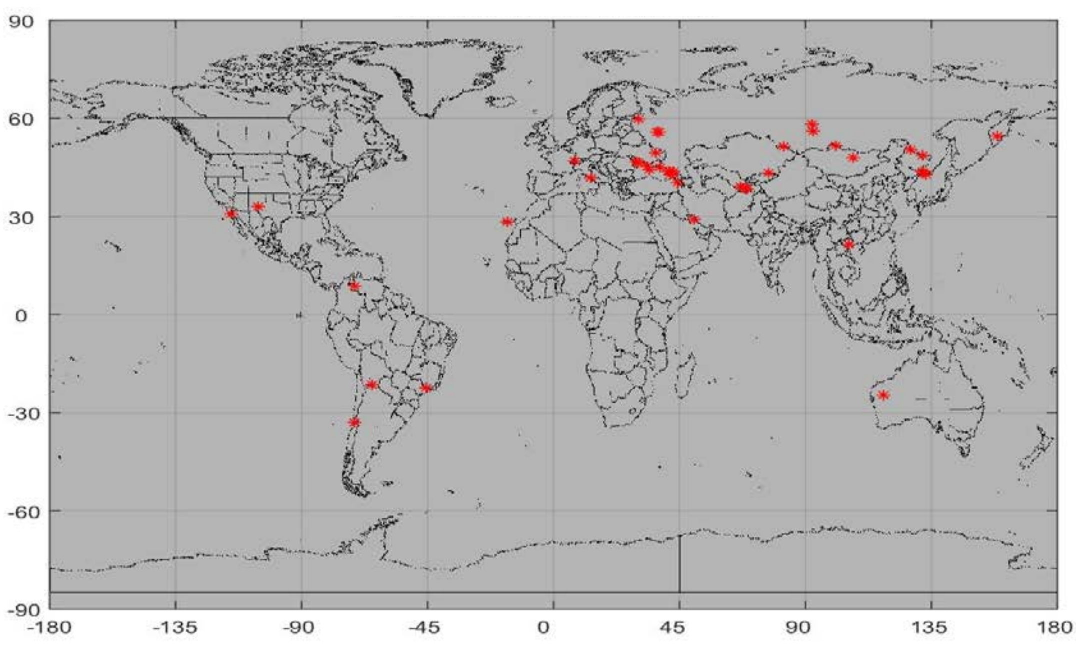

Figure 9. ISON Locations

3.3. Optimization

The basic capabilities of the site evaluation tool are useful for developing optimized lists of observing sites. While 1,863 sites provide much observing redundancy, not all are ideal locations for SSA and the expense of operating and maintaining such a large number of sites would become excessive. From an optimization point of view, the question to answer is—*What do 1,863 sites provide that cannot be achieved with 30 or 50 or 100?* Also, if one can achieve guaranteed complete observational coverage of the GEO belt each night with some notional 50 sites, do these sites represent the optimal combination, or are there better combinations of sites to consider?

To answer such *what if* questions, a simple optimization routine was written into the MatLab script. The optimization routine allows the user to weight different characteristics of a site, such as elevation, sky brightness, cloud cover and latitude. The tool can then produce a reduced list of sites by culling out lower performing sites—eliminating sites that are not necessary to achieve guaranteed nightly observation of each and every GEO slot, either individually or with some desired level of redundancy.

Finally, the user also has the ability to restrict the starting condition to consider some subset of the original 1,863 locations. As each location is identified by its type (island, city, existing observatory, government facility, etc.), the user can restrict an optimization run to only consider existing observatories around the world. For example, one subset of potential observing sites would consist only of existing observatories (as shown in Figure 10), while another subset would consider only the location of US government facilities (as shown in Figure 11). Possible island locations are shown in Figure 12, with former SSA sites operated by the US shown in Figure 13.

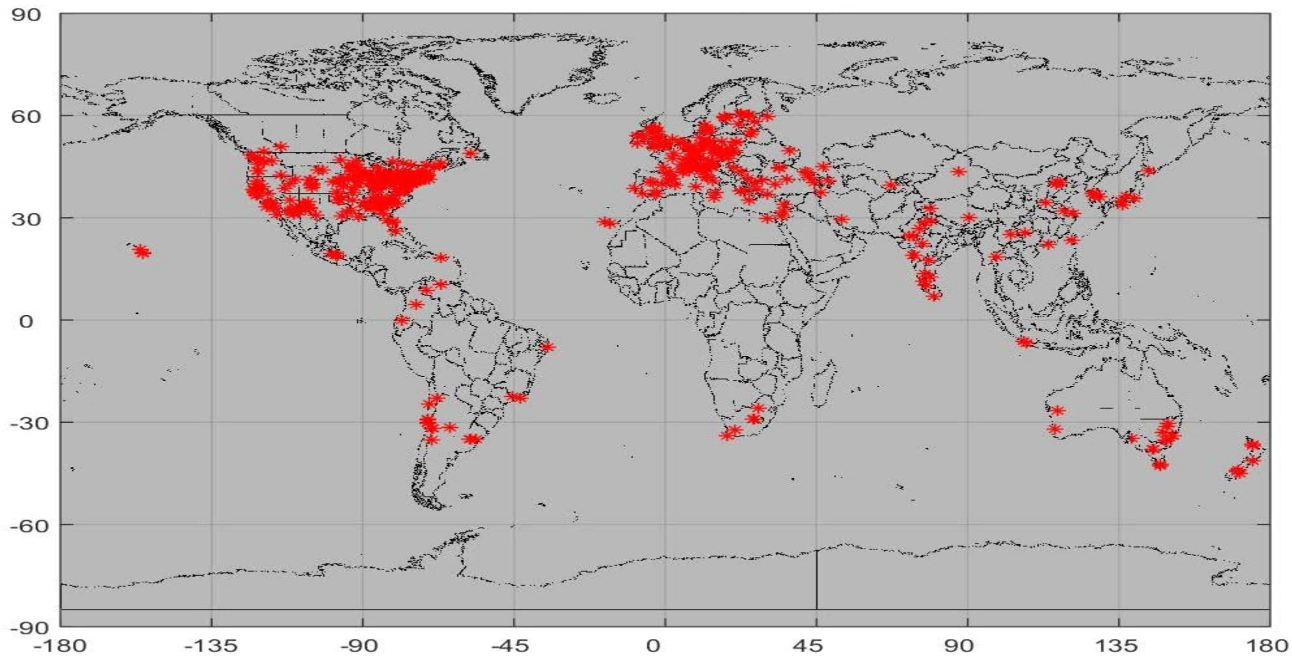

Figure 10. Location of Known Astronomical Observatories

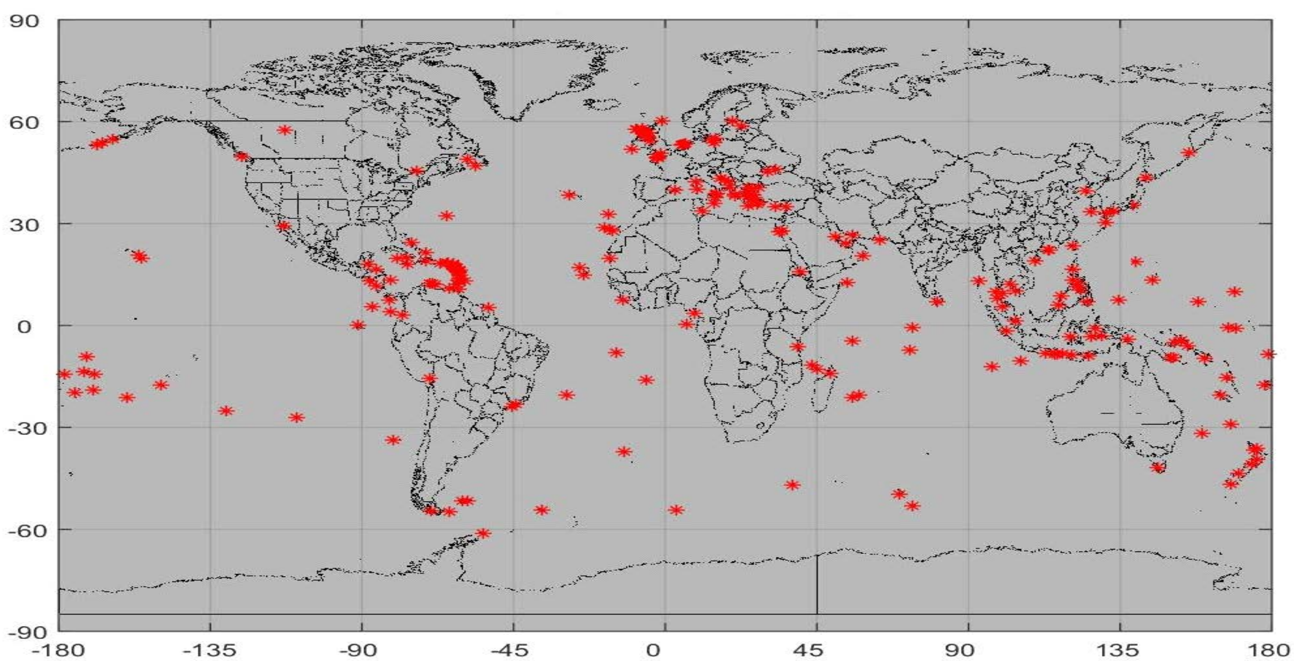

Figure 11. Possible Observing Sites on Larger Islands

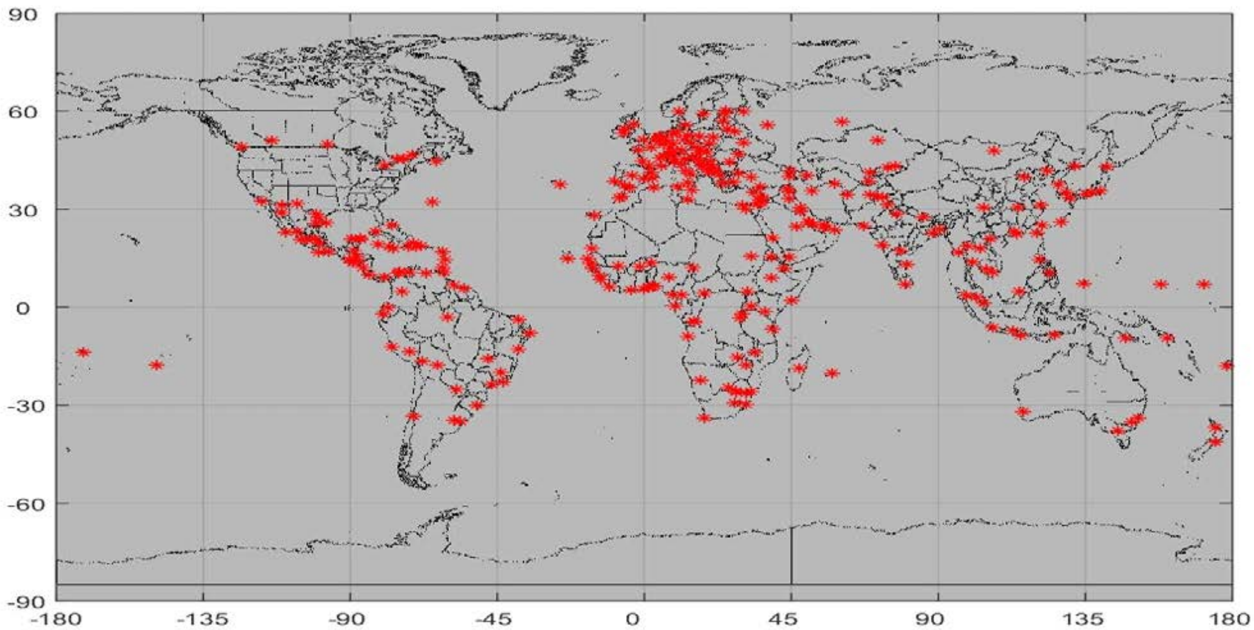

Figure 12. Location of US Government Facilities

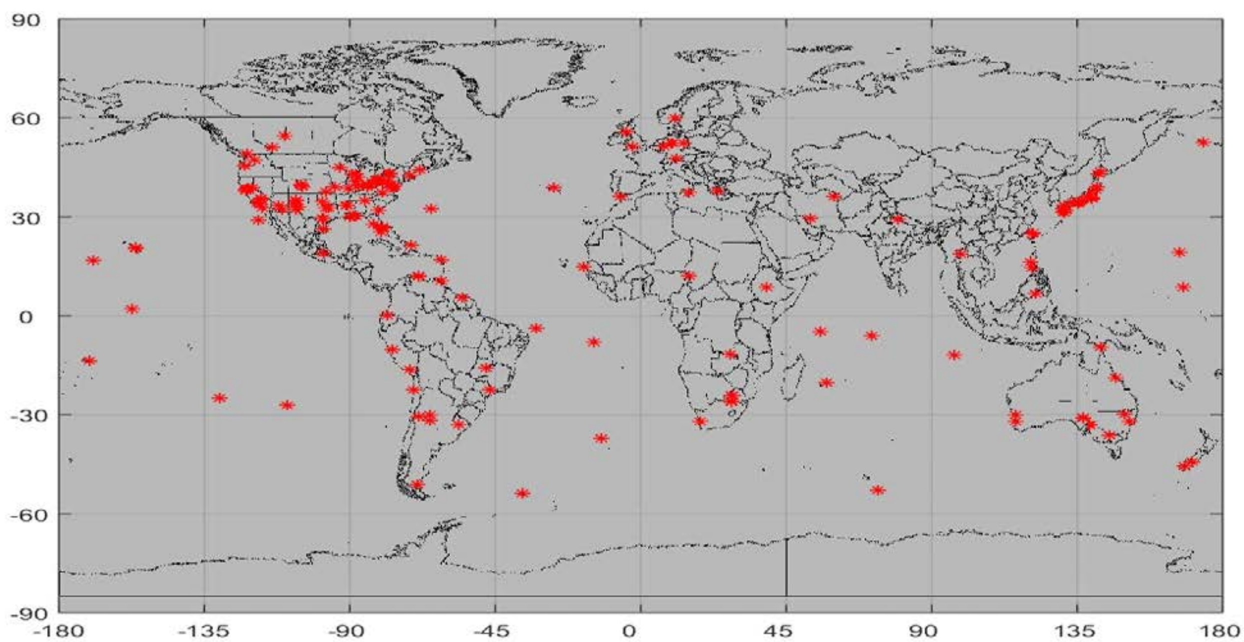

Figure 13. Location of Former US Sites Used for SSA Observations

4. RESULTS

A 2015 SSA architecture study [1] proposed 13 observing sites located at lower latitudes and somewhat uniformly around the globe. These sites were selected simply based on their location and global distribution, without consideration of weather effects. The 13 sites are shown in Figure 14. Using the site evaluation tool, it is a simple task to show that while these sites do provide somewhat uniform coverage of all GEO slots—and when weather data are consulted— it is clear that these 13 sites are not sufficient to guarantee nightly observation. The observing statistics for this 13-site network, assuming a single observer and cloud cover of 30% or less, are shown in Figure 15. With only 13 sites, this network does provide for over 300 nights per year observation of most GEO slots. If instead, the user wanted either redundancy or the ability to collect parallax observations, then at a minimum, each GEO slot would need to be observed by two sites on any given night. When this requirement is included, the notional 13-site network results in lower nightly coverage, as shown in Figure 16.

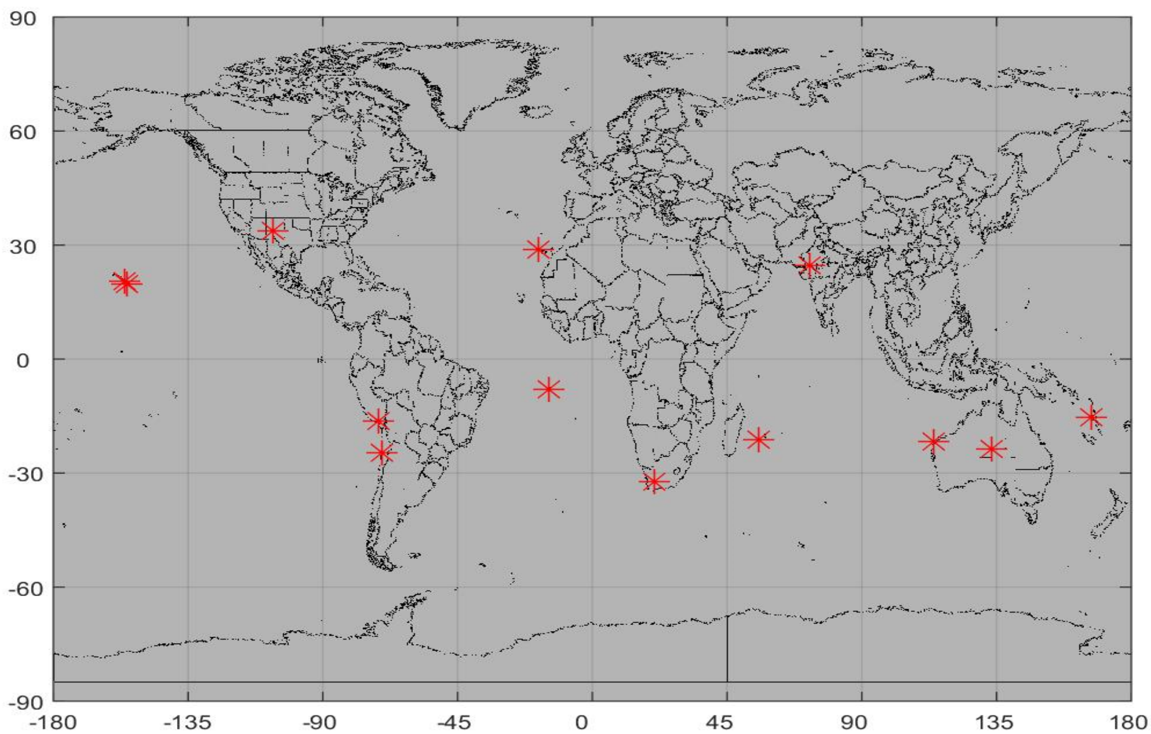

Figure 14. Notional Location of 13 Observing Sites from Previous SSA Study [1]

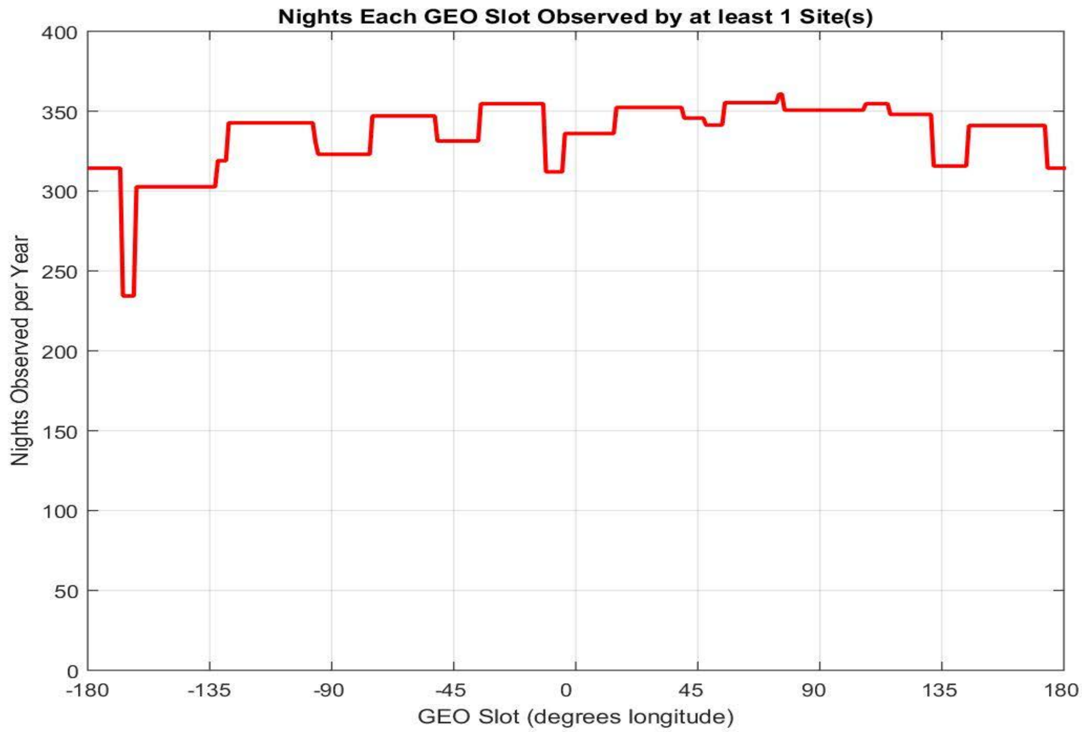

Figure 15. Observing Statistics for 13-site Network, Single Observer, <30% Cloud cover

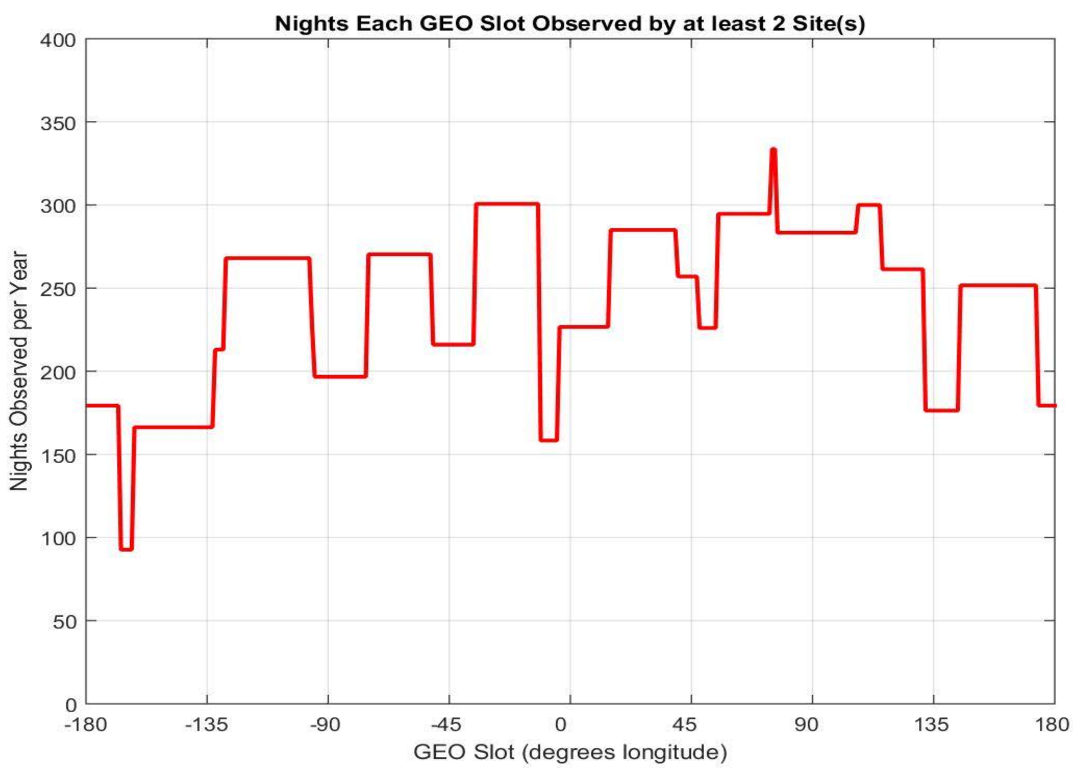

Figure 16. Observing Statistics for 13-site Network, Double Observer, <30% Cloud cover

As the notional 13-site observing network is clearly insufficient for guaranteed single observations, the site evaluation tool can be used to identify the minimum number of observing sites and provide their location. To find an optimal set, the list of potential sites was allowed to include cities, known observatories, islands, existing SSA sites, government and military facilities. Sky brightness was required to be darker than 19th visual magnitude per square arc second. Latitude was required to be within 40 degrees of the equator. Higher elevations were favored over lower ones, but no minimum elevation was specified.

Initially, the optimization was accomplished requiring at least one observing site able to view each and every GEO slot on any given night, 365 nights per year with cloud cover of 30% or less. The results of this simulation are shown in Figures 17 and 18. Figure 17 shows the location of the selected observing sites, while Figure 18 shows that each GEO slot can be observed 365 nights per year. In Figure 17, one finds multiple examples of observing sites being located in relatively close proximity to one another. An examination of the data reveals that these combinations of sites have slightly different weather patterns and there are times during the year when one or the other is required to close an observation gap.

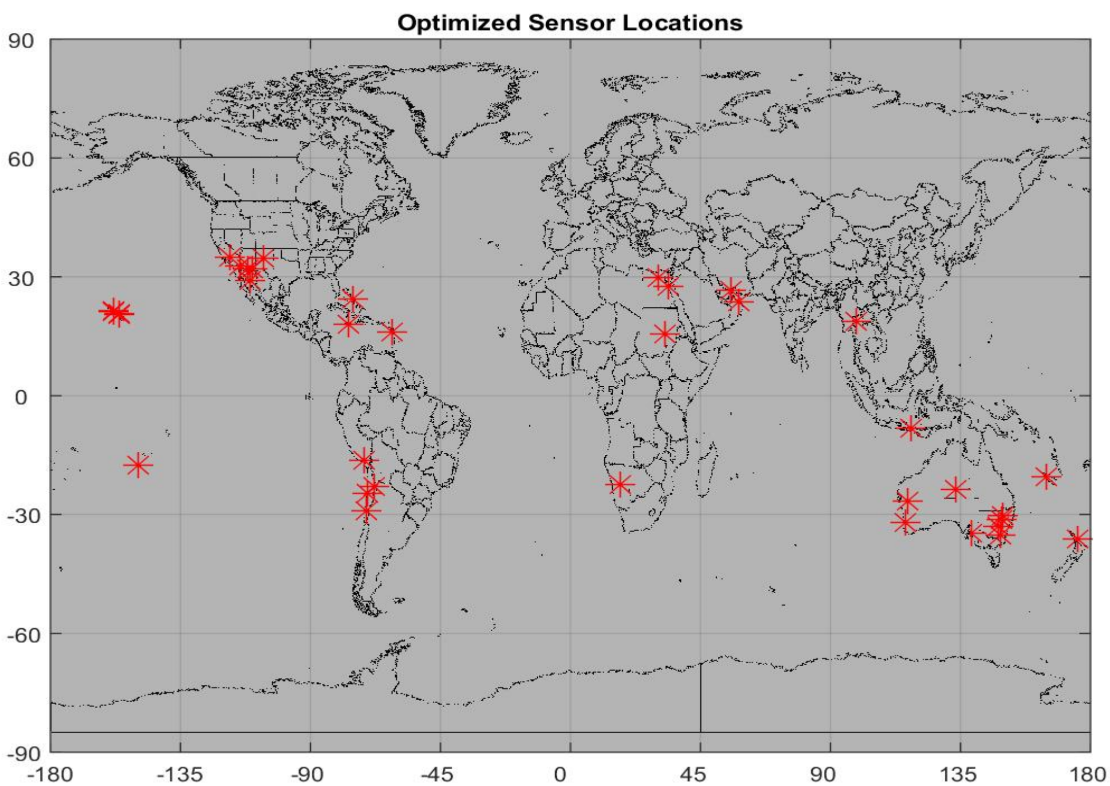

Figure 17. Optimized 36-site Observing Network

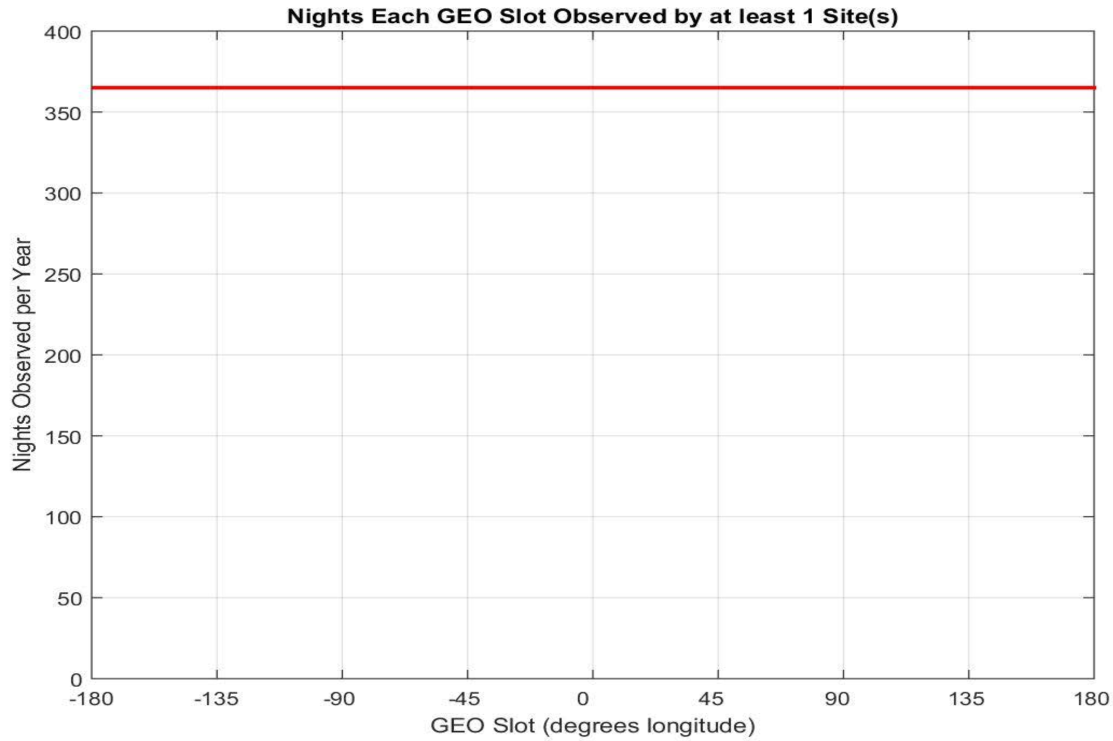

Figure 18. Single-observer Performance of Optimized 36-site Network

The ground-based telescope network required to observe each GEO slot with two or more observers each night is much larger, requiring a total of 56 sites. The problem with designing a network for double or triple redundancy is that of diminishing returns. The number of unique observations contributed by some sites ends up being very small, but without the site the network cannot achieve redundant coverage of each GEO slot for 365 nights per year. To help illustrate this, consider the 36-site network shown in Figure 17. This network achieves 100% single observer coverage of the GEO belt for 365 nights per year, but this same network can observe GEO slots with multiple observers on most nights as shown in Figure 19. For this simulation, the same network was required to have two or more observers for each GEO slot. The 36 sites result in more than 350 nights of double coverage for all GEO slots. This suggests that the additional 20 sites required to achieve double coverage 365 nights per year are of limited value on most nights.

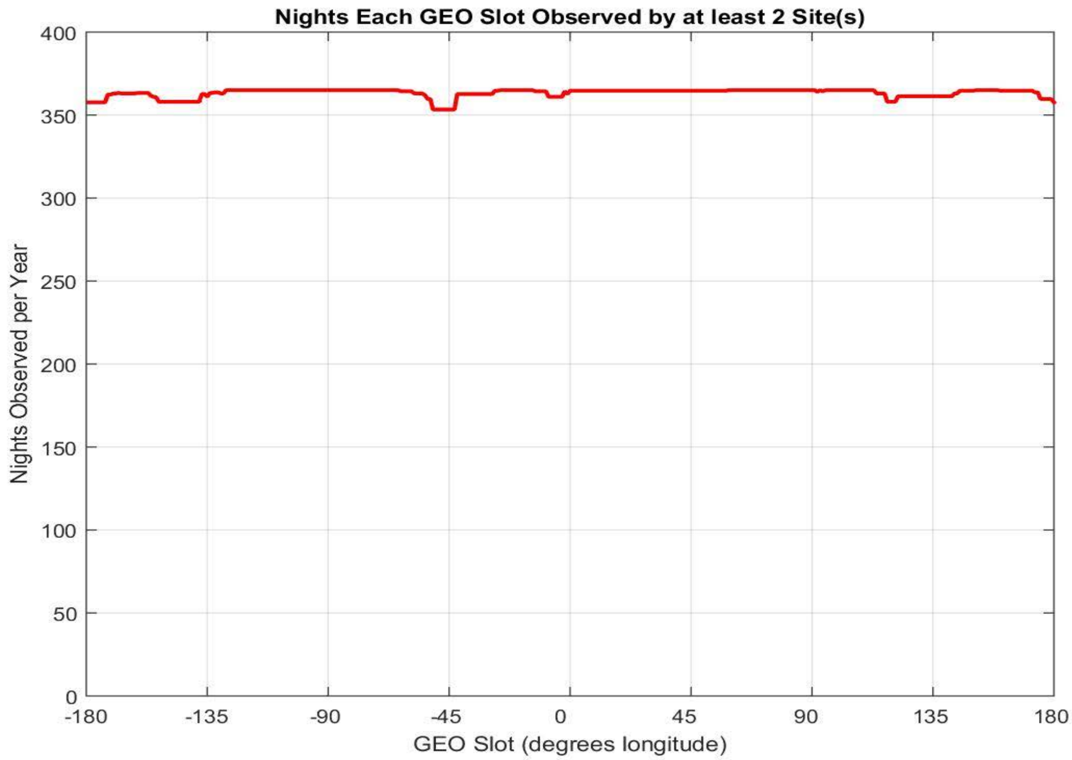

Figure 19. Double-observer Performance of Optimized 36-site Network

Figure 20 provides some insight on the number of observing sites required for various conditions. The graph clearly shows the difference between requiring single vs. double observer coverage of each GEO slot and also shows the impact of cloud cover on the number of observing sites. The data in Figure 20 suggest that most of the results presented previously would change only slightly if one changed from a maximum of 30% cloud cover, to a maximum of 20%. However, if requiring skies with less than 20% cloud cover, the number of observing sites begins to increase dramatically.

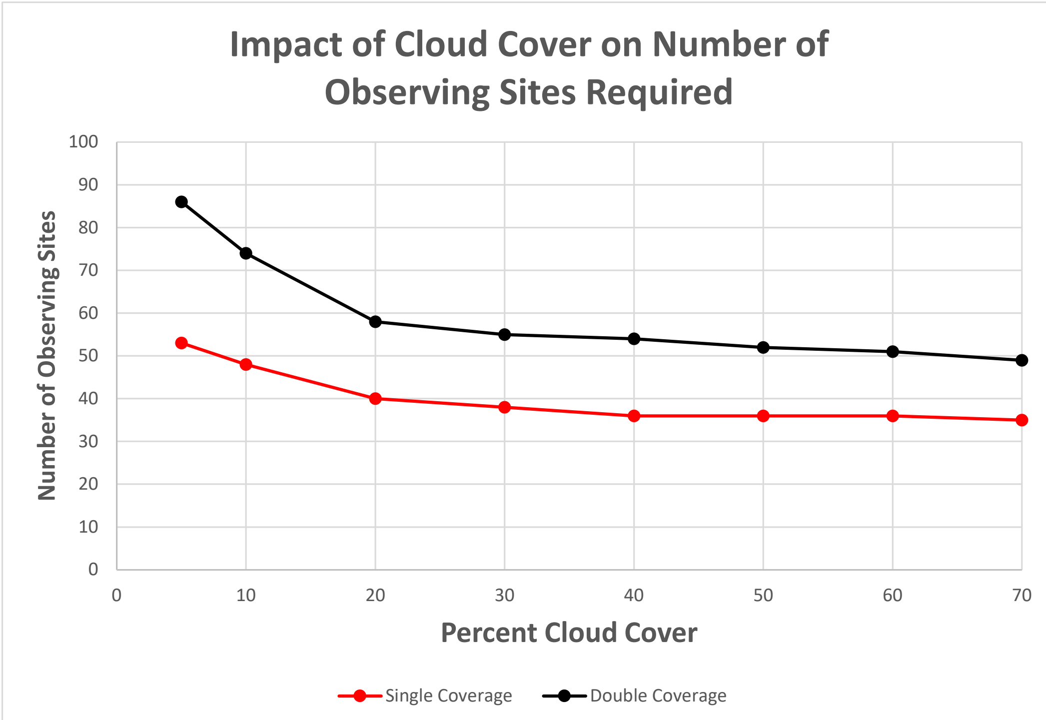

Figure 20. Impact of Cloud Cover on Required Number of Observing Sites

5. SUMMARY

Cloud cover is an important consideration when selecting sites for ground-based optical telescopes used to collect data for space situational awareness. Using nightly cloud cover data for three consecutive years, it is easy to evaluate existing or notional networks of observing sites, and equally easy to develop a list of observing sites optimized to meet specific observer requirements.

Simulations suggest that an optimal network of ground-based optical telescopes requires 36 sites dispersed world-wide. Similar simulations demonstrate that smaller networks, while useful, end up with outages where certain GEO slots are not observed on given nights. More observing sites help to close these gaps, but only a properly optimized network can close all gaps and provide guaranteed nightly coverage with the minimum number of telescopes. Even for networks that include tens to hundreds of telescopes, the number of observing sites and their locations determine whether or not the network is robust to weather induced observing outages.

REFERENCES

[1] Ackermann, M.R., Kiziah, R.R., McGraw, J.T., Zimmer, P.C., Cox, D.D., *A Systematic Examination of Ground-Based and Space-Based Approaches to Optical Detection and Tracking of Satellites*, 31st Space Symposium, Technical Track, Colorado Springs, Colorado, United States of America Presented on April 14, 2015, SAND2015-3276C.

[2] https://www.quora.com/Where-is-the-best-location-on-earth-to-build-an-observatory-so-as-to-observe-most-of-the-celestial-sphere, accessed July 2018.

[3] https://www.nasa.gov/multimedia/imagegallery/image_feature_1545.html, accessed July 2018.

[4] Darksky.org, accessed August 2018.

[5] http://www.inquinamentoluminoso.it/worldatlas/pages/fig1.htm, accessed July 2018.

[6] http://comet.nerc.ac.uk/about/volcanic-aerosols-affect-cloud-properties/, accessed July 2018.

[7] https://en.wikipedia.org/wiki/File:MODIS_Map.jpg, accessed July 2018.

[8] http://astronomer.ru/forum/index.php?topic=5970.0, accessed July 2018.