Synthetic-Aperture Silhouette Imaging (SASI)

Richard G. Paxman

MDA Information Systems, P.O. Box 990, Ypsilanti, MI 48197, USA

ABSTRACT

The problem of ground-based fine-resolution imaging of geosynchronous satellites continues to be an important unsolved space-surveillance problem. We are investigating a passive-illumination approach that is radically different from amplitude, intensity, or heterodyne interferometry approaches. The approach, called Synthetic-Aperture Silhouette Imaging (SASI), produces a fine-resolution image of the satellite silhouette. When plane-wave radiation emanating from a bright star is occluded by a GEO satellite, then the light is diffracted and a moving diffraction pattern (shadow) is cast on the surface of the earth. With prior knowledge of the satellite orbit and star location, the track of the moving shadow can be predicted with high precision. A linear array of inexpensive hobby telescopes can be deployed roughly perpendicular to the shadow track to collect a time history of the star intensity as the shadow passes by. A phase-retrieval algorithm, using the strong constraint that the occlusion of the satellite is a binary-valued silhouette, allows us to retrieve the missing phase and reconstruct a fine-resolution image of the silhouette. Silhouettes are highly informative, providing diagnostic information about deployment of antennas and solar panels, enabling satellite pose estimation, and revealing the presence and orientation of neighboring satellites in rendezvous and proximity operations.

1. SASI CONCEPT

The problem of ground-based fine-resolution imaging of geosynchronous satellites continues to be an important unsolved space-surveillance problem. If one wants to achieve 10cm resolution at a range of 36,000km (range to geosynchronous satellite) at a wavelength of 0.5μm via conventional means, then a 180m diameter telescope with adaptive optics is needed. Clearly such a system is prohibitively expensive. This has lead researchers to investigate interferometric-imaging approaches that have sufficiently large baselines (e.g. 180m) to collect the spatial-frequency information needed to achieve the desired resolution on target. We are investigating a passive-illumination approach that is radically different from amplitude, intensity, or heterodyne interferometry approaches. This approach, called SASI, produces a fine-resolution image of the satellite silhouette.

When plane-wave radiation emanating from a bright star is occluded by a GEO satellite, then the light is diffracted and a moving diffraction pattern (shadow) is cast on the surface of the earth, as illustrated in Fig. 1.

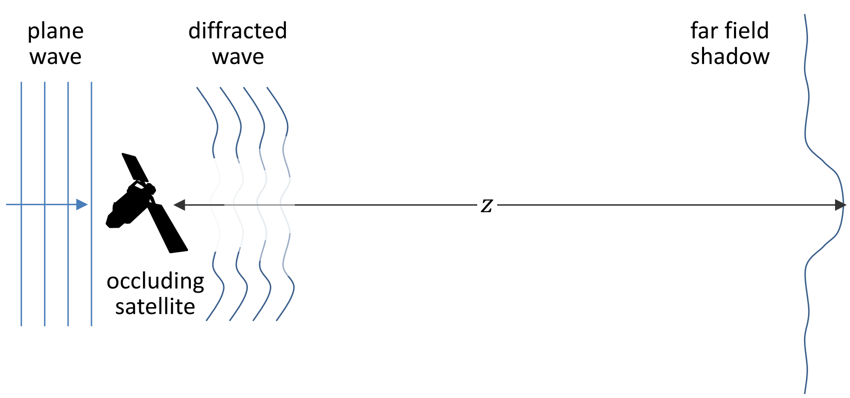

Fig. 1. Light from a bright star is diffracted by an occluding satellite to cast a shadow on the earth's surface.

With prior knowledge of the satellite orbit and star location, the track of the moving shadow can be predicted with high precision. A linear array of inexpensive hobby telescopes can be deployed roughly perpendicular to the shadow track in order to collect a time history of the star intensity as the shadow passes by. This synthetic aperture allows us to capture the entire 2D diffraction pattern cast by the occluding satellite, as illustrated in Fig. 2.

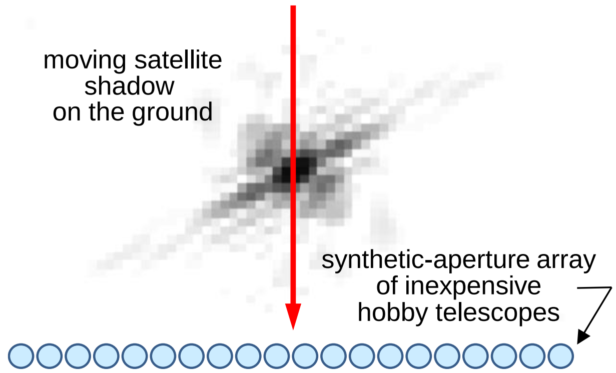

Fig. 2. A linear array of inexpensive hobby telescopes captures the entire 2D diffraction pattern

If the satellite is small, then the Fraunhofer approximation is valid and the collected data can be converted to the silhouette's Fourier magnitude. The method also accommodates Fresnel diffraction in the case of larger satellites. A phase-retrieval algorithm, using the strong constraint that the occlusion of the satellite is a binary-valued silhouette, allows us to retrieve the missing phase and reconstruct a fine-resolution image of the silhouette.

SASI will deliver fine-resolution silhouettes of GEO satellites. Fig. 3 illustrates that silhouettes are highly informative, providing diagnostic information about deployment of antennas and solar panels, enabling satellite pose estimation, and revealing the presence and orientation of neighboring satellites in rendezvous and proximity operations (e.g. GSSAP or DARPA Phoenix satellites). Multiple silhouettes collected from different aspects can be used to construct a 3D visual hull of the satellite. Silhouettes also complement gray-level images, providing information about regions not illuminated.

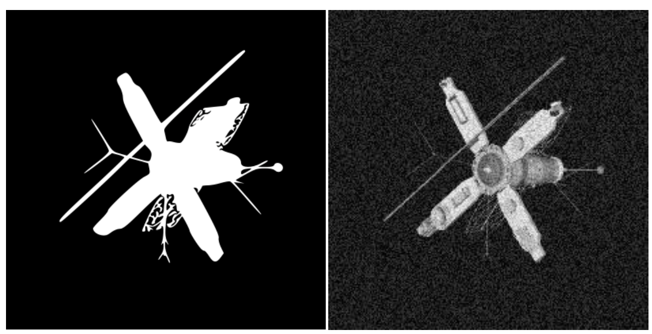

Fig. 3. A fine-resolution image of a satellite silhouette (left) is highly informative and complements a gray-level image (right)

3. SIMULATION

We performed a simple proof-of-concept simulation to investigate the use of an opacity (binary-object) constraint in Phase Retrieval (PR). We investigated a related and simplified problem that served as an initial surrogate for the full SASI scenario. According to Babinet's principle, diffraction by occlusion is closely related to diffraction by the binary aperture that is the complement of the occluding silhouette. Accordingly, the complement of a representative satellite silhouette was discretized to serve as the truth image. This image was then Fourier transformed, yielding a complex-valued image. We saved only the amplitude portion of this image and treated this as the preprocessed noiseless data (derived from the detected intensity). The Fourier amplitude was then used to enforce a Fourier-domain constraint in a simple-iterative PR algorithm, as illustrated in Fig. 4. The object-domain constraint was enforced on an object estimate by setting the gray-level value to unity or zero, based on adaptive thresholds. Iterations consist of transforming between object and Fourier domains and enforcing the respective constraints.

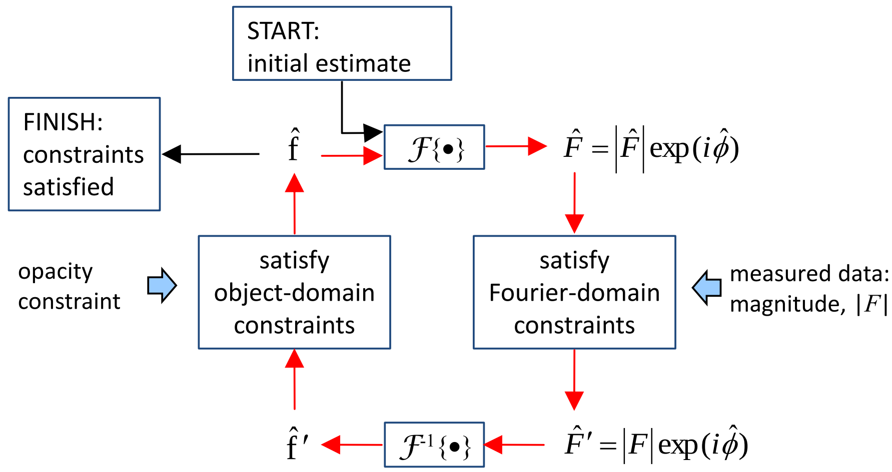

Fig. 4. Elementary iterative phase-retrieval algorithm used to investigate the use of an opacity constraint in phase retrieval.

The results, shown in Fig. 5, indicate that the binary silhouette was retrieved perfectly.

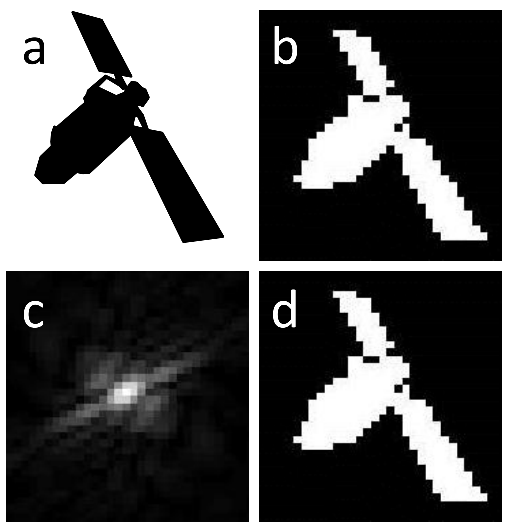

Fig. 5. The opacity constraint works well with phase retrieval for the surrogate problem of diffraction from an aperture. (a) Continuous silhouette of an occluding satellite; (b) discretized complementary aperture (used as a surrogate problem); (c) noiseless Fourier amplitude of (b); (d) perfectly estimated aperture using only (c) and an opacity constraint.

This is an encouraging result, although the noise sensitivity of this kind of PR has yet to be quantified. We believe that the opacity constraint is potent and will be noise tolerant. This is partly because a silhouette image is extremely sparse relative to its gray-level counterpart. As an example, the fine-resolution silhouette shown in Fig. 3 is efficiently characterized with spline parameters as opposed to pixel values. Even though this silhouette is complex and highly articulated, the spline rendering represents a compression factor of 22.5 relative to its counterpart gray-level image. Clearly, it is easier to estimate fewer parameters in the presence of noise.

Modern PR algorithms use nonlinear optimization in contrast to the iterative algorithm shown in Fig. 4 [1]. New PR algorithms that use nonlinear optimization need to be developed to estimate silhouette parameters (e.g. spline parameters) from noisy Fourier- or Fresnel-amplitude data. MDA researchers have had success estimating silhouettes from extremely noisy data [2]. In addition, the opacity constraint, has been shown in other applications to be extremely powerful [3-5], providing further evidence that there will be a degree of noise tolerance in silhouette estimation using PR.

4. ACCESS

An important consideration for the SASI concept is access. We performed a preliminary analysis regarding access to shadows cast by a given GEO satellite. This is a complicated problem that involves the satellite orbit, the earth's rotation, the time of year, and selecting from a list of bright stars. We have learned how to map a star/satellite-shadow track on the earth's surface using AGI's STK software. An example shadow track cast by the star Zeta Ophiuchi (magnitude 2.57) and a representative satellite is shown in Fig. 6.

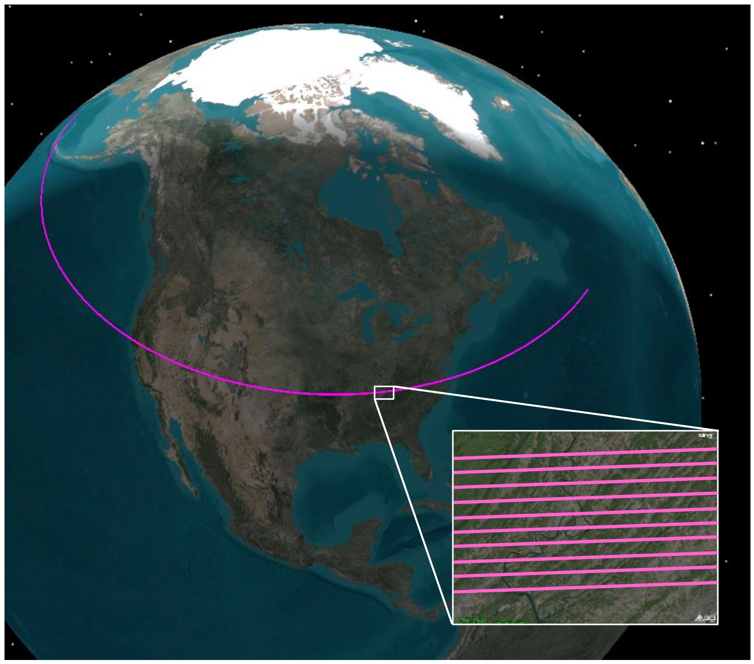

Fig. 6. A representative star/GEO satellite shadow ground track, shown for 10 consecutive days.

The moving shadow traverses this track (the magenta semi-circle) in about 47 minutes. The track cuts through the center of the CONUS, as well as portions of the Pacific and Atlantic oceans, all during the night. Note that the track will change from day to day. The detail in Fig. 6 shows the track for 10 consecutive days, which migrates roughly 1 mile in latitude daily. These plots suggest a wide variety of geographic and temporal choices for site selection, including the option for daily monitoring of a high-interest satellite with only modest relocation.

Fortunately, shadow tracks are precisely predictable for known satellites so that a relocatable observing system can be accurately prepositioned to capture the shadow signature. A collection plan for a specific satellite can be formulated by evaluating candidate shadow tracks from differing stars on different days to find a region suitable for deployment. Relocation could be achieved with rail cars (using a roughly north/south abandoned rail system), with a convoy of trucks having telescopes mounted in the beds, or with a repurposed cargo ship for ocean access. Note that the SASI signal will be relatively insensitive to ship motion.

5. ADVANTAGES OF SASI

A compelling reason to pursue the SASI concept is that it will be extremely cost effective relative to other ground-based approaches. The hardware required is embarrassingly inexpensive. SASI only requires an array of tracking hobby-class telescopes, each with a low-cost APD detector. The telescopes can be deployed in a linear array that spans the desired effective diameter, say 180m. The linear array provides a 2D data set via temporal synthesis. The telescope/sensor modules can be identical, enabling economies of scale. Each telescope tracks the designated star and collects its time history with the aid of a field stop and a single APD detector. Signals must be detected at kHz bandwidths and must be synchronized to millisecond accuracy, which is easy to achieve. The expense for operations, including relocation of the array, is manageable.

Another advantage of the SASI concept is that the signal depends on the star magnitude, not the magnitude of the satellite. Because we are collecting an indirect signal provided by satellite occlusion, there is no limit to how faint the satellite can be under direct observation. In fact, SASI works well for unilluminated satellites (in the earth's shadow) or satellites with low optical signature. It is difficult to countermeasure occlusion.

Unlike many ground-based observational methods, SASI is insensitive to atmospheric-turbulence effects. SASI indirectly measures Fourier (or Fresnel) amplitude, which is insensitive to turbulence-induced aberrations, so long as the turbulence is near the pupil. This obviates the need for complicated phase-tracking and wavefront-sensing instrumentation.

Finally, SASI acquisition is extremely rapid. Whereas other methods may need extended observation of a target to build sufficient signal, the SASI acquisition is extremely quick. For one representative geometry, the satellite shadow travels on the ground at a speed of 2.6 km/sec. This means that the entire acquisition takes place in about 1/10th of a second.

6. NEXT STEPS

An important next step is to develop a phase-retrieval algorithm that is tuned to the problem of utilizing an opacity constraint. This will require an efficient parameterization for silhouettes (e.g. some sort of spline parameterization) and the use of modern nonlinear optimization. Having developed such an algorithm, we will be able to exercise it to determine the noise sensitivity of phase-retrieval with an opacity constraint. Although we believe that phase-retrieval with an opacity constraint will be noise tolerant, there are a variety of ways to increase the SNR in the acquired data if needed. These include using brighter stars, utilizing multiple stars, collecting multiple spectral bands, increasing the telescope diameter, and using of more telescopes (e.g. multiple linear arrays).

7. CONCLUSIONS

Synthetic-Aperture Silhouette Imaging (SASI) is a concept for ground-based imaging of the silhouette of a satellite. SASI appears to be a highly cost-effective way to achieve fine-resolution images of GEO satellites, relative to other ground-based satellite-imaging approaches. Phase Retrieval with an opacity constraint is a key component of SASI image formation. A proof-of-concept simulation was presented that shows that PR with an opacity constraint works well in the absence of noise. The noise sensitivity of such algorithms remains an important open question that needs to be answered to determine the viability of the SASI concept.

8. REFERENCES

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