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# Small glints as an aid for imaging geosats using an optical Michelson interferometer

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**Abstract.** A Michelson optical interferometer, such as an upgraded version of the Navy Precision Optical Interferometer, could image geosynchronous satellites (geosats) with resolution of roughly 1 m. Baselines that sample features as small as 0.2 m can be built, however, the fringes would be swamped by the resolved component. Recent observations have shown that small glints known as “glintchen,” aside from being a nuisance, serve to isolate and highlight the signal from these structures. Imaging of geosats during glintchen events can determine the dimensions of these structures and can also play a critical role in determining if these glintchen are due to a previously undetected companion satellite. An approach for performing this glint-aided imaging of geosats and the wealth of detail it would yield, is discussed. © *The Authors*. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.7.073549](https://doi.org/10.1117/1.JRS.7.073549)]

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## 1 Introduction

The first steps toward imaging a geosat using a Michelson interferometer have been taken and a fringe has been successfully tracked on one baseline (a baseline is a vector between a pair of telescopes) using the Navy Precision Optical Interferometer (NPOI).<sup>1</sup> By adding more imaging elements and baselines, we will be able to generate an image. There are still some shortcomings with NPOI geosat observations. Most notably, the observation can only be made when the geosat is glinting, i.e., specularly reflecting during two periods in early October and February to March. This restriction is due to the low sensitivity of the NPOI which uses 0.12 m apertures. The NPOI cannot fringe track on an object fainter than about  $R \sim 6.5$  magnitude. During the two roughly week-long glint seasons, geosats can increase in brightness by a factor of  $10^4$  (10 mag) for a period of a few minutes each night and many become naked-eye objects.<sup>2</sup> Interference fringes have been detected on one geosat to date using the NPOI, DirecTV-9S.

Although the possibility of imaging geosats during the glinting season may seem to solve the brightness limit issue, Jorgensen et al. pointed out a less obvious drawback of imaging during glints.<sup>3</sup> While the glint greatly enhances the signal-to-noise ratio (SNR) for fringe tracking, it degrades the SNR of the image itself. Simply put, the immense amount of light coming from the glinting structures swamps the amount of light from the smaller structures. The glinting structures are on the order of 1 m or more in size. Smaller structures, even if they are also glinting, produce fringes that are lost in the noise from the bright glint. In essence, the image shows only the glinting structures, which must be large to glint so brightly, at the expense of the smaller structures.

Clearly, both of these issues, being able to image only during the short glint seasons and being able to image only the large glinting structures, could be obviated if larger apertures are used. This would allow observing when the geosat is not glinting, however, it introduces the need for adaptive optics.

Nevertheless, there is a fundamental issue due to the nature of the objects themselves. There is little power in the fringes produced by structures much smaller than the largest structures (e.g., solar panels or the main bus). Long baselines are sensitive to the high spatial frequencies but the largest structures, with dimensions of the order of a few meters or larger, are resolved on these baselines, i.e., they do not produce interference fringes. Due to their large dimensions, these structures are bright, even though reflecting diffusely, and swamp the signal from the small structures (10 s of cm). The fringes due to small structures could be brought out with long-enough integration times, however, the inescapable fact is that they are weak against the background due to the larger components and this renders it difficult to obtain geosat images with resolutions much smaller than 1 m.

We propose an alternative technique that allows the imaging of these small structures. Because many of these structures are oriented differently than the large structures, they glint at different times. Furthermore, because these structures are physically small, they produce fainter glints, which we have dubbed “glintchen,” using the German diminutive ending “-chen.” These glintchen would seem to increase the difficulty in obtaining long integration times as the surface brightness of these small structures would suddenly increase by factors of roughly 100 and put a halt to any exposure. However, it turns out that these glintchen can be exploited not only to obtain images that display small structures, but spectra obtained during the glintchen can be compared to spectra before or after to provide some information on the composition of the glinting structure. This paper is organized in the following way. Examples of glintchen are presented in Sec. 2 and the physics behind them in Sec. 3. Characteristics of a Michelson optical interferometer, specialized for glint-aided imaging, are described in Sec. 4. Section 5 explains how additional data from auxiliary telescopes can be exploited as well and how the combination of imaging with other data would prove useful. Section 6 discusses the abilities and limitations of the concept, and a concept of operations is described in Sec. 7, as an efficient way of performing the observations is not obvious. Conclusions are presented in Sec. 8.

## 2 Glintchen Examples

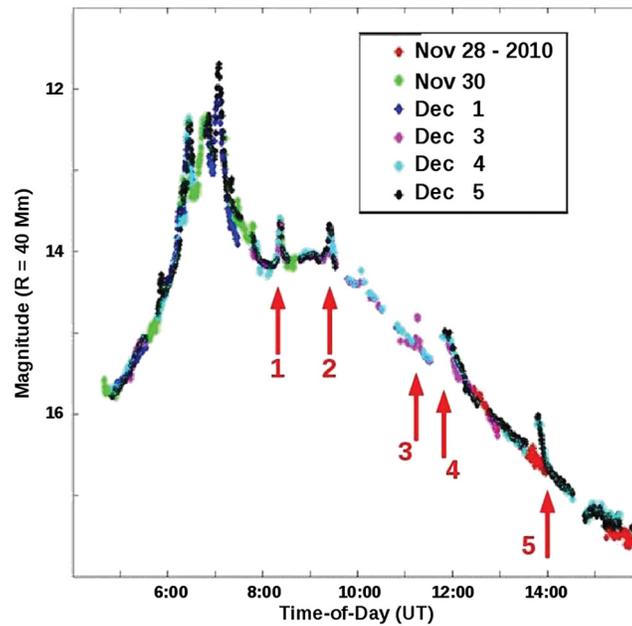
It has been known for decades, that geosats glint when major structures on the geosat reflect specularly and cause the geosat to brighten by factors of  $\sim 10^4$  (10 mag) or more. We will refer to these extreme events as “major glints.”

Hall presented photometry of several satellites as part of a study of the “zombie” satellite Galaxy 15.<sup>4</sup> Of particular interest is the *I*-band photometry of Galaxy 12. Figure 5, from Hall,<sup>4</sup> is presented here as Fig. 1. In these data, five events, that we will categorize as glintchen, are indicated by arrows and are clearly visible. Several common characteristics should be noted:

1. All except #3 are seen on multiple nights, and this exception is not significant, as the amplitude was small and that time span was not observed on many nights.
2. All seem to last at least 20 min, except for #3 which is markedly shorter.
3. These glintchen brighten the photometry by about ½ to 1 mag (roughly 50% to 100% increase in flux).

The physics behind these characteristics will be explained in Sec. 3.

A second example of observed glintchen is taken from Vrba et al.<sup>2</sup> Figure 1 from that paper, is presented here as Fig. 2. While these data were obtained on a single night, they are multicolor data obtained in the broadband standard system filters *BVR<sub>I</sub>*.<sup>5</sup> This complicates the comparison with the glintchen from Fig. 2 as nothing can be said about the repeatability from night to night. More obvious, and of great importance, is the difference in the glintchen as observed in the different filters. The increase in brightness is ½ to 1 mag in the *B* filter, only 0.1 to 0.2 in the *V* filter, and barely detectable in the *R* and *I* filters. This means that the additional light during the glintchen doubles the flux in the *B* filter while adding almost nothing in the redder filters. Such spectral characteristics can be used to identify the material responsible for the glintchen.



**Fig. 1** Here, we reproduce Fig. 5 of Hall with arrows and corresponding numbers added to indicate glintchen.<sup>4</sup> Observations performed on multiple nights and overlaid according to time-of-day (universal time). Measurements were acquired in the I band using a 0.4 m telescope at the AMOS remote Maui experiment (RME) site.

### 3 Physics of Glintchen

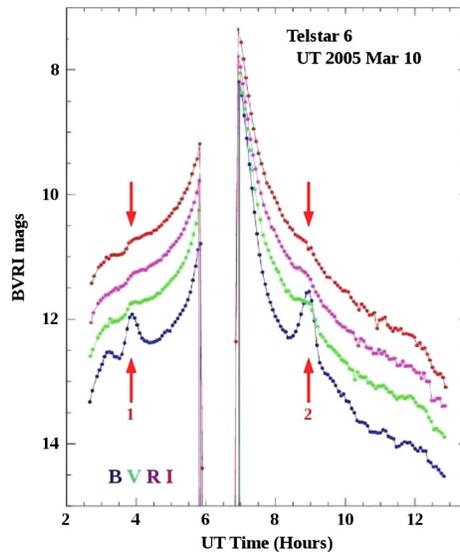
The obvious cause of glintchen is that these events are specular reflections off small surfaces. “Small” in this context, should be taken to mean significantly smaller than the overall size of the geosat which is generally on the order of a few meters to 10’s of meters. Because the glinting surface is small, the amount of light added to the geosat’s image is also small.

The phenomenon of glinting is well-described by Schaefer et al. in connection with the “Perseus Flasher.”<sup>6</sup> To estimate the brightness of a glinting surface, Eq. 2 of Schaefer (dropping the term including the integration time) is used

$$m - m_S = -2.5 \log \left( A \frac{L_G^2}{\pi H^2 \theta_S^2} \right),$$

where  $A$  = albedo,  $L_G^2$  is the area of the glinting surface,  $H$  is distance to the detector (approximately 36,000 km for a geosat),  $\theta_S$  is the solar angular radius = 15.95 arcmin = 4.64 mrad,  $m$  is the apparent magnitude of the glint and  $m_S$  is the apparent magnitude of the Sun,  $-26.75$  in the  $V$  filter, or  $-27.44$  in the  $I$  filter.<sup>7,8</sup>

What is the effective size of the structure that produces glints like those seen in Figs. 1 or 2? For a structure with  $A = 1$  and area  $0.04 \text{ m}^2$  (0.2 m on a side, roughly the resolution of longest current NPOI baseline), the formula above predicts an  $I$  magnitude equal to 3.41. This is almost 10 mag brighter than these glintchen. The primary cause of this unexpected faintness is most likely that the structure is not flat and the specular reflection is spread over an angle larger than the angular size of the Sun, an idea that is supported by the glint durations. If a glintchen were just a reflection of the Sun off a perfectly flat surface, it would last only 2 min. In Figs. 1 and 2, most of the glintchen last at least 30 min. An increase of a factor of 15 in the width of the angular reflection pattern in both dimensions would decrease the observed  $I$  magnitude to 9.29, still much brighter than observed. An  $A$  of 0.16, as is typical of satellite materials, would reduce the brightness by two magnitudes more, but even  $I = 11.3$  is still too bright. The observed glints are fainter by about two magnitudes, or a factor of 6.3. The structure must be only 0.08 m on a side to be this faint or, more likely, it is not sufficiently flat to glint as a unit and, thus, represents only the effective area of a larger physical structure.



**Fig. 2** Here, we reproduce Fig. 1 of Vrba et al. with arrows and corresponding numbers added to indicate glintchen.<sup>2</sup> Measurements were acquired using a 1.0 m telescope at the Flagstaff Station of the U.S. Naval Observatory. These are observations taken at B, V, R and I band (blue, green magenta, and red, respectively).

For discussion purposes, we limit the term glintchen to events that, by themselves, would be fainter than magnitude 10. The particular filter in which the brightness is measured will vary. The glintchen in Fig. 2 occur only in the *B* filter and possibly *V*, there are no glintchen in the other, redder filters.

As noted above, the glintchen in Fig. 1 are seen to repeat over several nights when observed on more than one night. There is only one glintchen that does not occur on multiple nights, glintchen #3, which occurs only on December 3. An inspection of this glintchen indicates that it has relatively small amplitude, thus, suggesting that the fact that it does not repeat on December 4 may be due to a change in the solar inclination. A similar behavior is observed in glintchen #5, which shows similar peaks on December 4 and 5, but no corresponding glintchen on November 28. During the interval from November 28 to December 4, the declination of the Sun changes from  $-21.3$  to  $-22.3$ . The major glints near equinox typically occur over an interval only a few days long with the rate of change in solar declination defining the length of the major glint season near equinox. A change in solar declination, equivalent to that seen from November 28 to December 4, occurs in only about three days near equinox. It is possible that the change in declination between November 28 and December 4 is sufficient to change the Sun-geosat-observer configuration so that the glintchen is no longer seen by the observer.

Is it legitimate to compare the Fig. 1 glintchen, measured in the *R* filter, to the Fig. 2 glintchen that do not even appear in the *R* filter? In both cases, a surface is reflecting specularly and both surfaces are small compared to the size of the satellite. The difference in Fig. 2 is that the glintchen are measured in the different filters, thus, giving us an indication of the composition of the glinting structure. Cowardin et al. describe how photometric data can be used for material identification.<sup>9</sup> The use of such data is explored further in Sec. 5.

#### 4 Observing Geosats with a Michelson Interferometer

The NPOI is the only Michelson interferometer to date to detect interferometric fringes from a geosat. Here, we describe the NPOI along with some of the associated challenges in geosat imaging. A full description of the NPOI can be found in Armstrong et al.<sup>10</sup> We also describe some of the characteristics of an interferometer designed to image geosats. Given the existing infrastructure at the NPOI and the ability to upgrade it with larger aperture telescopes and different beam combiners, it would be an excellent potential site for a dedicated geosat imaging instrument.

#### 4.1 Navy Precision Optical Interferometer

The NPOI is a collaborative effort of the U.S. Naval Observatory, the Naval Research Laboratory, and Lowell Observatory. It is located about 19 km southeast of Flagstaff, Arizona on Anderson Mesa. The array has three arms, 120 deg apart, with arms running north, southeast, and southwest. Siderostats, at fixed stations, direct light into the system. Although the siderostat flats are 0.5 m in diameter, the aperture is set at 0.12 m by the fast-steering mirrors that guide the light into the vacuum system. Some of the siderostats can be shifted from station to station and the stations which are populated by siderostats determines the baselines. While eventually the NPOI will have baselines as long as 437 m, currently, the longest baseline is 79 m and, in the case of the 2009 geosat observations, we used only a 15.9 m baseline oriented close to the east to west direction.<sup>1</sup> Currently, the NPOI observes in 16 channels spanning 550 to 850 nm in wavelength. Data taken at the longer wavelengths samples source structure at lower resolution, while data taken at shorter wavelength samples source structure at higher resolution.

The NPOI maintains a zero delay difference among paths by employing a delay line for each siderostat. When the path lengths are equal, the NPOI sees the central fringe of the interferogram. To ensure that the fringe is, in fact, the central fringe, the delay lines dither around the expected position of the central fringe, thus, producing an estimate of the fringe position (and delay mismatch) every 2 ms. This time frame is imposed by the atmospheric coherence time.

The ability to track fringes is limited by a combination of two factors, target brightness and size, which, so far, have limited the use of the NPOI to observations of major geosat glints. Having enough photons to make a reliable estimate of the central fringe position every 2 ms sets the faint magnitude limit for NPOI observations, which is about  $R = 6.5$  mag in the Johnson system on the best seeing nights. Fringes are unacceptably noisy for fainter stars. However, this magnitude limit is only applicable to slightly resolved stars. Targets that are significantly resolved by a given baseline have low fringe amplitudes and require a higher number of photons in order to be detected on a 2 ms time frame, thus, limiting the interferometer to observe even brighter targets.

When the central fringe is found, it is tracked by the NPOI control system. For stellar observations, computer memory constraints limit how long an attempt at obtaining fringes can be attempted. For geosats, the observations may be limited, instead, by the time interval during which the geosat is sufficiently bright.

#### 4.2 Designing the Ideal Geosat Imager

Although the NPOI did succeed in obtaining fringes from a geosat, it is not the optimal instrument for observing geosats. The NPOI was built for imaging stars, which are smaller in angular extent than any geosat and have greater surface brightness. An interferometer, optimized for geosat observations, would use shorter baselines to avoid resolving the object combined with some baselines, as long as 100 m, to achieve resolution of 1 milli-arcsec, or about 0.2 m for a target at a distance of 36,000 km. The baselines needed to observe geosats are available at the NPOI, however, geosat observations would require other upgrades to the system. A discussion about other interferometer designs, the u-v coverage (modulation transfer function) and image quality they achieve, and their application to the imaging of geosats can be found in Refs. 10–16.

Observing in the near infrared, such as  $K$  band at  $2.2 \mu\text{m}$ , has certain advantages. Geosats are brighter in the near infrared and the atmosphere is better behaved at these wavelengths, thus, resulting in longer coherence lengths ( $r_o$ s) and coherence times ( $t_o$ s). This would allow the use of larger apertures and longer integration times. However, because resolution is a function of wavelength as well as baseline length, switching from the optical to  $K$  band would require baselines longer by about a factor of 3, or up to 300 m.

Larger siderostats, or telescopes, would be needed to make an instrument sensitive enough to observe geosats year round. This, in turn, requires adaptive optics as the apertures now extend over multiple  $r_o$ s. Simulations suggest that apertures of 1.5 m are sufficient. Again, this is somewhat alleviated by switching to the infrared.

The NPOI feed system can accept light from only six siderostats at a time which corresponds to 15 baselines. An operational instrument would require more than this as simulations show that 9 to 12 siderostats (36 to 66 baselines) are the minimum required.<sup>11,14</sup> The NPOI could switch siderostats during an observation in order to recover some of the missing baselines, however, this has never been implemented or attempted and would not generate the  $u$ - $v$  coverage that would be obtained with 12 siderostats simultaneously.

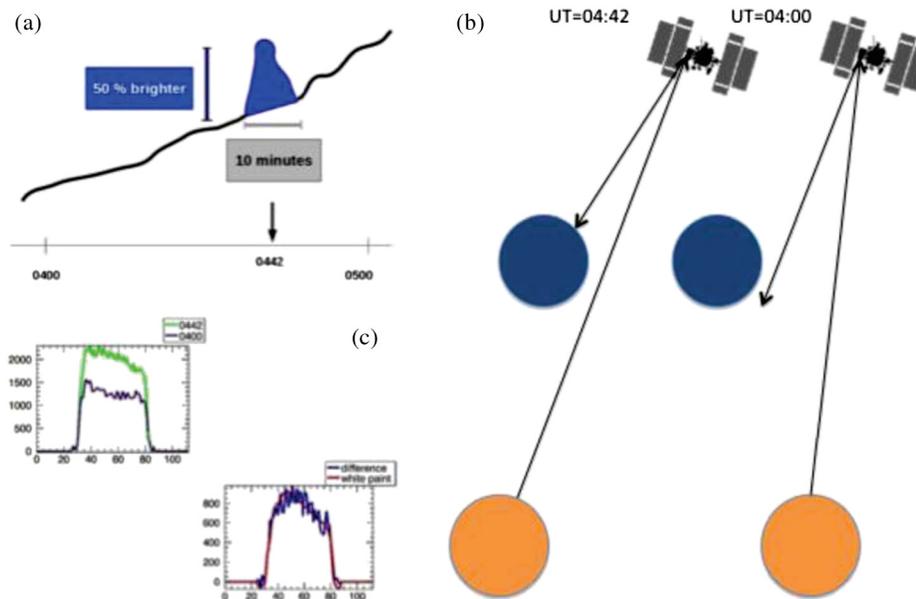
## 5 Combining the Interferometric Data with Other Data

The information obtained with optical interferometric observations of glintchen can be augmented with information from other kinds of observations. For example, Cowardin et al., among others, have used photometry to characterize the surfaces of geosats.<sup>9</sup> In Sec. 3, it was demonstrated how the size of a glinting surface can be found based on the photometry, albeit, with rather large uncertainty in the results. In Fig. 3, a schematic of a glint is used to demonstrate other characteristics of the satellite that can be measured:

**Orientation:** The solar phase angle at which a particular glintchen occurs indicates the orientation of the surface with respect to the line between the observer and the geosat, as shown in Fig. 3(b).

**Composition:** The spectrum during the glintchen should combine the spectrum as seen outside glintchen plus the spectrum of the glinting structure. Figure 3(c) shows two simulated spectra, one taken inside and one taken outside of glintchen. This difference spectrum, also shown in Fig. 3(c), is due to the glinting structure and can yield the composition of the structure. It may be the case that the spectrum is a composite of two or more different materials.

**Flatness:** The duration of the glintchen indicates the flatness or smoothness of the structure. A perfectly smooth and flat structure would glint for only 2 min (determined by the angular size of the Sun). Broadening of the reflected pattern is due to irregularities in or lack of flatness of the glinting surface.



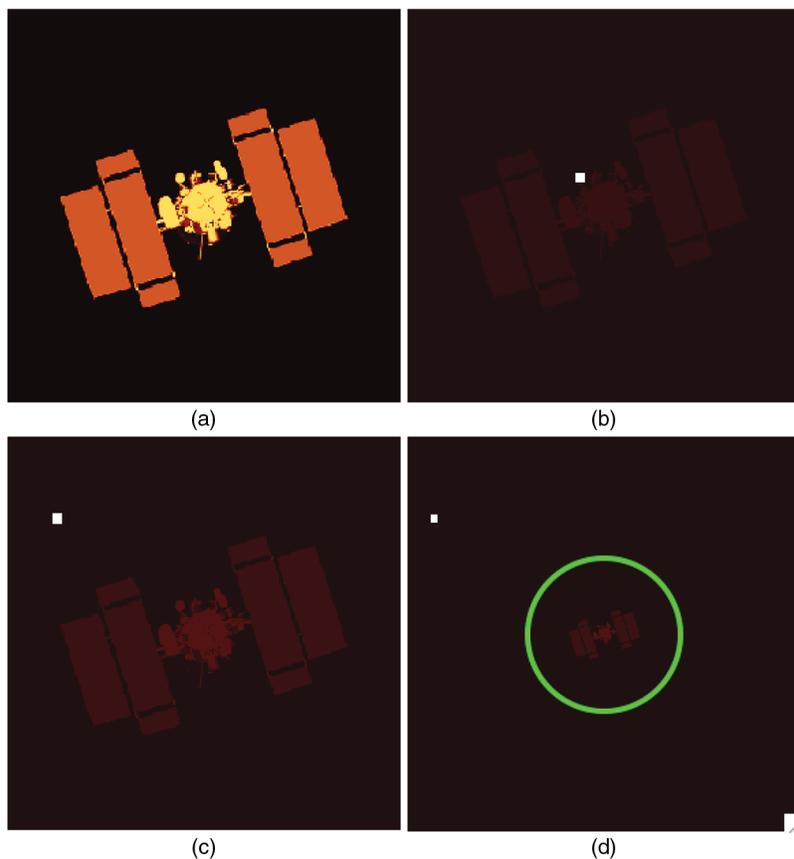
**Fig. 3** The top left panel (a) shows the schematic of a glintchen observation, showing an increase of 50% in the flux level around UT = 04:42. The right panel (b) shows that the time when the specular reflection of the sun (yellow) is seen on Earth (blue) fixes the orientation of the structure. For an observation obtained at UT = 04:42, the observer on Earth detects the glintchen which was not detected at an observation taken at UT = 04:00. The bottom left panel (c) shows in the upper sub-panel the spectrum during glintchen (green, UT = 04:42) and the spectrum before glintchen (black, UT = 04:00). The bottom sub-panel shows the difference between the glintchen spectrum and the spectrum outside glintchen (blue) which, when compared to the spectrum of white paint (red), shows a good agreement, thus, revealing the composition of the glinting surface.

**Size:** The size of the glinting structure can be inferred from the brightness. This calculation is more constrained when combined with the *albedo* as indicated by the composition.

These parameters are derived from the photometry alone. The important missing datum for each glinting structure is where the structure is located on the bus. Observing the position of a glinting structure on the geosat may or may not be important. If the geosat and the configuration of structures are known, the position of a glinting structure may be determined without imaging. However, changes to the spacecraft structure would be of great interest. For example, imaging an antenna showing that it is not pointing toward Earth would be valuable in diagnosing why a loss of communication has occurred. Changes in multiple glintchen, due to adjacent structures, would be evidence of a collision that caused structural deformation.

In addition, if the satellite is previously unknown or uncharacterized, knowing the position of structures on the bus might be a helpful clue to the function of those structures. This, in turn, could assist in understanding the mission of such an unknown geosat should other data prove ambiguous.

Another vital use of imaging is to determine if the glinting structure is indeed on the geosat. As Fig. 4 illustrates, imaging can detect very close debris or an unknown small companion satellite. These nearby structures may not be detected by optical observations because they may be too close to the geosat of interest or too relatively faint to be seen directly by a single telescope. Under regular to good atmospheric conditions, we expect to be able to resolve structures separated by more than  $\sim 1$  arcsec ( $5 \mu\text{rad}$ ) without adaptive optics which corresponds to 175 m at the geostationary distance. For fainter, smaller structures, the distance at which they can be detected with a single telescope may be even larger, because it becomes harder to disentangle



**Fig. 4** A geosat image<sup>17</sup> as seen outside of glintchen (a), and three possible images during glintchen; the glintchen is due to a structure on the geosat (b); the glintchen is due to a separate satellite in the field of view (c); the glintchen is due to a separate satellite not in the field of view of the optical interferometer (shown in green), but still close enough that the photometric monitoring cannot image it as a separate object (d).

them from the glare of the geosat. Furthermore, in the case of an unknown satellite, it may be silent, in which case, it would not be detected by radio observations. This extremely valuable knowledge, the possible presence of a close companion, is the unique contribution of the imaging. There is no other way to gain evidence indicating this situation. It should be borne in mind that the glintchen seen in Figs. 1 and 2 may already be indicating the presence of shadowing satellites.

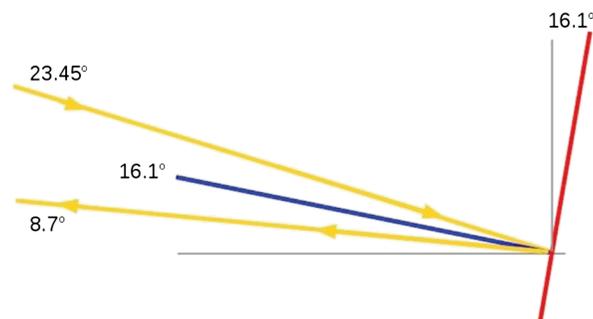
The above discussion demonstrates the utility of glintchen observations. The glintchen isolate individual small structures on the geosat and permit measurement of various characteristics that otherwise cannot be performed. Normally, the light from a small structure is lost in the light from the much larger satellite body. During a glintchen, the increase in the flux from a small structure allows its light to be analyzed separately from the normal flux. In the spectral realm, the light from the individual small structure may be sufficiently bright to allow the determination of the composition of that structure. In the imaging realm, the fringes from that structure are brought out of the constant background (the background due to the resolved geosat bus and solar panels) so that the placing of the structure, whether on the bus or close to it, can be determined. These combined data would be a valuable tool to diagnose problems with known geosats, to determine the function of unknown geosat, and as a tool to detect nearby unknown satellites.

## 6 Limitations

While glintchen can be exploited to yield information not otherwise available, there are five limitations inherent in the phenomenon which include orientation, repeatability, duration, homogeneity, and size variability. The first four affect photometric measurements as well as imaging while the last limitation is relevant only for imaging.

First, the structure may not be at an orientation that causes glintchen. For example, a structure in Fig. 4 could be rotated about a horizontal line, so that sunlight (incident on the page from the viewer's direction) would be reflected up or down, and miss the Earth entirely. The Earth's angular diameter, as seen from a geosat, is approximately 17.6 deg. Figure 5 shows an incoming ray with the Sun at its maximum declination of 23.5 deg. In order to intercept the earth, the reflected ray cannot be more than 8.8 deg from the Earth's equatorial plane. This requires that the normal to the surface not be more than 16.1 deg above or below that plane. The real limits, for any observer, are slightly less depending on the latitude. Figure 5 makes it clear that if the observer is on the equator, the maximum tilt is  $23.45 \text{ deg} / 2 = 11.7 \text{ deg}$ . The value of 16.1 deg is an absolute limit as no site can see glintchen from surfaces tilted more than that.

There is a limit in the perpendicular (east to west) direction as well. For a satellite directly overhead, any surface with a normal that is tilted less than 45 deg away from the line toward the center of the Earth will generate a glintchen. For a satellite on the horizon, the amount of tilt still



**Fig. 5** Schematic view of a ray (yellow) being reflected from a surface on the geosat (red). The plane of the sky is represented by the vertical gray line and the reflecting surface is inclined by 16.1 deg relative to this plane. The blue line shows the direction normal to the reflecting surface. Earth is located to the left of the horizontal gray line. In this configuration, the Sun is at its maximum declination of 23.45 deg, and the figure illustrates the maximum inclination a reflecting surface can have (16.1 deg), in order for the reflected ray to be less than 8.7 deg off the Earth's equatorial plane and still be intercepted somewhere on the Earth's surface.

ranges over 90 deg, but from 8.7 deg on one side to 81.3 deg on the other side of the line toward the Earth's center, the limit of 81.3 deg is geometrically correct, however, as a practical matter, anything tilted over 60 deg suffers from severe foreshortening.

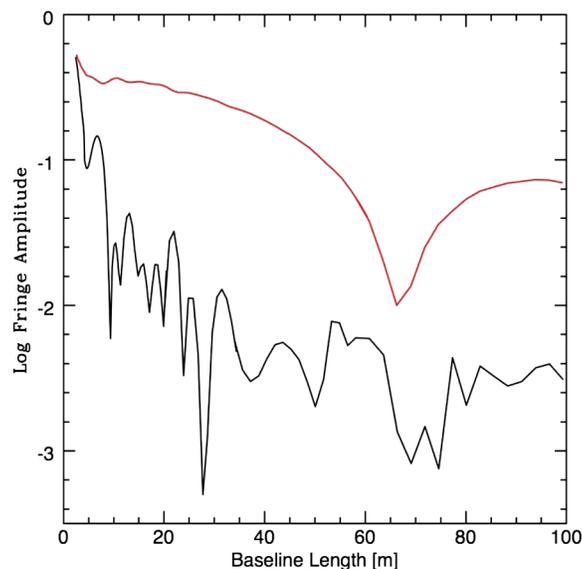
A second limitation on the glintchen phenomenon is that a glintchen from a particular structure will occur for only a few consecutive nights clumped in two seasons, typically about a week long. As with a major glint, the occurrence of a glintchen depends on the declination of the Sun and that can change by 0.4 deg per night at the equinox. However, unlike a major glint, the tilt of the structure can cause the glintchen to occur near an extremum in solar declination. In that case, the two glintchen seasons can be very close together and then the structure would be invisible for more than 10 months. This will have a major effect on the development of an efficient observing strategy, as discussed in Sec. 7. The important fact is that no structure can be imaged on demand when relying on glintchen.

The third limitation is that glintchen last only a short portion of the night. While the glintchen seen in the examples in Figs. 2 and 3 last 30 min or more, a perfectly flat surface would produce a glintchen lasting only 2 min.

A fourth limitation on glintchen is that while each individual structure glints for only a week or so, different structures at different orientations can glint at any time throughout the year and throughout the night. To sample the full range of available solar phase angles requires six months, from solstice to solstice and even these are not sufficient to make glintchen from every structure on the geosat.

Finally, a fifth limitation, that affects only imaging, is the relatively huge increase in surface brightness of the glinting structure as compared to the rest of the satellite. A glinting structure as bright as the rest of the satellite could easily be smaller by a factor of 100. While the glintchen aids in the fringe tracking, it tends to blind the optical interferometer so that it cannot see the rest of the satellite. In order to place the glinting structure on the geosat, it is necessary to see some background structure to connect all the different structures seen to glint at different times.

We show, in Fig. 6, two sets of fringe amplitudes corresponding to the satellite images on the top row of Fig. 4. The black line shows the fringe amplitudes for the satellite outside glint. The red line shows the fringe amplitudes for the case where a glinting structure, with a diameter of  $\sim 0.6$  m, has as much flux as the rest of the satellite. Comparing the two datasets, we see that, during a glintchen, the interference fringes are dominated by the small glinting structure, especially on long baselines. However, we find that the shorter baselines still show some of the



**Fig. 6** Fringe amplitude, as a function of baseline length, for a satellite outside glint (black) and when a small structure, with a diameter of  $\sim 0.6$  m, is glinting with as much flux as the rest of the satellite (red). The images used to calculate these fringe amplitudes are shown in the top row of Fig. 4. The baselines are in the North to South direction and rotated by 6 deg towards the East. Observations are simulated for the wavelength of 850 nm.

structure seen in the dataset without the glintchen. The amount of information about the satellite's large scale structure that can be recovered from the short baselines depends on the area and relative brightness of the glinting region. This information is important to pinpoint the position of the glinting structure relative to the body of the satellite.

Due to this limitation, glintchen have been considered, when considered at all, as, at best, nuisances and, at worst, fatal to efforts to image small details on satellite. A glintchen can interrupt the long integrations needed to find fringes from these same small features. The very increase in surface brightness that renders a glintchen visible can also make it useless. The situation when glintchen is useful depends on the size of the glinting structure and its brightness relative to the rest of the satellite. Another solution to the problem posed by the large increase in surface brightness will be presented in the next section.

## 7 Efficient Observing Strategy

The limitations presented in the previous Section imply that glintchen are of little use in the observation of geosats. While the smallest structures on a geosat can be analyzed no other way, it would seem that each geosat must be observed full time by a dedicated interferometer. The surface brightness issue would appear to render imaging of glintchen pointless in any case.

A clever observation strategy can deal with the surface brightness issue and improve the number of glintchen observed by at least two orders of magnitude. The enabling concept is the realization that the glintchen are somewhat repeatable from night to night for at least a few nights. Thus, repeated photometric observations of many geosats can be performed with a dedicated single-aperture telescope one evening, the observed glintchen cataloged, and then an interferometer can be efficiently scheduled on a subsequent night. Because the photometric data are an integral part of the analysis and yield spectra as well as time of occurrence, duration, and magnitude of each glintchen, these observations are needed in any case. Measurements of these data contemporaneous with the imaging observations are desirable, however, those can be obtained with a relatively small and simple auxiliary telescope scheduled to observe the same geosat as the interferometer.

From any site, approximately 100 geosats are visible. Ideally, each would be measured photometrically in multiple bands at a tempo sufficiently fast to obtain repeated observations over an interval short enough to catch any glintchen. This can be done if a series of long/shortpass filters can be used to separate the light onto separate detectors and measure all the bands simultaneously. The process is also helped if the field is sufficiently large as, then, multiple geosats can be measured simultaneously. However, the telescope must be able to move quickly along the geo belt, settle, obtain data on a satellite, and then move on to the next field. Considering that this photometric telescope can be relatively small and cheap, an obvious partial solution is to employ multiple telescopes.

What is an appropriately short interval between photometric observations of a geosat? As stated previously, a perfectly flat surface would produce a glintchen lasting only 2 min. While the observed glintchen are all far longer than this, this minimum interval would look like a proper goal.

Clever scheduling can also deal with the issue of the extreme surface brightness of a glintchen. Looking at the glintchen in Figs. 1 and 2, it is noted that these glintchen do not "switch on" instantaneously. Rather, there seems to be some rise time that looks to be on the order of a minute. If the interferometer attempts to image the geosat during the first few seconds of the glintchen, there should be an interval during which the surface brightness of the glinting area is bright enough to produce measurable fringes but faint enough not to overwhelm the rest of the signal. If sufficient signal can be obtained, the glinting structure can be placed on the geosat image. Likewise, this should be possible during the decay of the glintchen. Thus, far from being only a nuisance, the glintchen can yield information on some small structures in a short observation.

Another solution, applicable in some cases, is the use of the differential phases technique as suggested by the results presented in Fig. 2.<sup>18</sup> If a glintchen is markedly fainter over an interval of

the spectrum, light in that band will still be sensitive only to the large spacecraft bus. The fringe contrast and, particularly, the phase difference between different parts of the spectrum would still allow the place of the glinting structure to be determined. A “white” glintchen, meaning a glint that is equally bright throughout the optical, would not produce a differential phase as a function of wavelength and this technique would not be applicable.

When the glintchen observed by photometric telescopes during an evening are cataloged, they can be used to schedule subsequent observations with the interferometer. Like the photometric telescopes, the interferometer must be able to quickly acquire an object, obtain the data, and then reconfigure for the next object. Reconfigure means not only pointing the apertures but also repositioning the delay lines. Currently, the NPOI requires ~5 min to switch from object to object. A shorter interval is desirable as glintchen from different satellites will occur at random intervals. However, it certainly will be impossible to observe all available glintchen on one night. Because each glintchen occurs on several nights, near coincidences can be handled to some degree.

## 8 Conclusion

Glintchen are small glints that allow the flux from small structures to be isolated and the structures to be analyzed in some detail. In particular, they enable conventional Michelson interferometers to image details as small as 0.2 m on geosats. Conventional photometry can be used to learn much about these structures, however, only imaging can unambiguously determine the position of these structures on the spacecraft bus. Imaging is beneficial for diagnosing changes on a known satellite, for determining the structure and function of an unknown satellite, and, most importantly, it is invaluable for detecting a companion satellite.

There are a number of challenges to be met. The utility of glintchen, both photometrically and in imaging, is limited by the lack of glintchen from some structures, the short intervals (both in terms of nights per year and minutes per night) during which glintchen occur, and the possibility of glintchen occurring at any time throughout the year rather than in a single week-long season. These issues mean that a geosats must be monitored at a rapid cadence and the prospects for imaging may also be uncertain due to the large surface brightness of a glinting structure.

When taken at face value, these issues seem to suggest that a single optical interferometer would be needed to monitor each geosat. However, clever scheduling can resolve most of these issues. Using auxiliary photometric telescopes, glintchen can be cataloged and used to generate an efficient observing schedule for the interferometer on a later night. Timing of interferometric observations may be extremely critical in order to obtain fringes while the surface brightness of the glinting surface is still low enough not to swamp the dynamic range.

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