SANDIA REPORT
SAND2008-6705
Unlimited Release
Printed March 2009

On Identifying the Specular Reflection of Sunlight in Earth-Monitoring Satellite Data

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Abstract

Among the background signals commonly seen by Earth-monitoring satellites is the specular reflection of sunlight off of Earth's surface, commonly referred to as a glint. This phenomenon, involving liquid or ice surfaces, can result in the brief, intense illumination of satellite sensors appearing from the satellite perspective to be of terrestrial origin. These glints are important background signals to be able to identify with confidence, particularly in the context of analyzing data from satellites monitoring for transient surface or atmospheric events. Here we describe methods for identifying glints based on the physical processes involved in their production, including spectral fitting and polarization measurements. We then describe a tool that, using the WGS84 spheroidal Earth model, finds the latitude and longitude on Earth where a reflection of this type could be produced, given input Sun and satellite coordinates. This tool enables the user to determine if the surface at the solution latitude and longitude is in fact reflective, thus identifying the sensor response as a true glint or an event requiring further analysis.

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1. INTRODUCTION

Satellites operated for a variety of Earth-monitoring missions field sensor types that are sensitive to time-varying radiation fluxes over a large range of wavelengths. These sensors detect a number of natural background sources including atmospheric phenomena such as lightning and meteors as well as astrophysical events like solar storms and gamma ray bursts. A commonly observed background signal for Earth-looking optical and near-infrared transient event detectors is the specular reflection of sunlight off of a water surface such that a satellite's sensor is illuminated. This type of reflection, commonly referred to as a glint, results in a brief and luminous flash appearing to come from the surface of the Earth. Consequently, it is important to be able to distinguish between these and other transient surface and atmospheric events.

In this report we describe ways of identifying glints by reviewing the radiative processes involved as the radiation travels from the Sun to the satellite sensor. We also describe a software tool written in the Interactive Data Language (IDL) that solves for the geographic coordinates on Earth where the conditions exist to produce a glint, given input Sun and satellite coordinates. The theory behind the software, the user interface, and the output data products are outlined. We also address future applications of this type of program to identify additional signals of similar origin.

2. RADIATIVE TRANSFER THEORY APPLIED TO GLINTS

The positive identification of a glint as the source of a sensor response can be accomplished by a few different means. Both the spectrum and polarization of radiation comprising a glint leave the imprint of the radiative transfer processes from emission at the solar photosphere to detection at the sensor and, depending on the capability of the sensor system, can possibly be used to distinguish between these and other phenomenon.

2.1. Properties of Reflected Optical and Infrared Solar Radiation

The radiation resulting in a glint begins with the spatially-integrated solar spectrum. Position dependent variations in the solar spectrum due to limb-darkening and sunspots are not considered here since any instrument capable of discerning these spatial variations must also have the ability to determine the location of the glint point, and can be identified via the method described in Section 3. The first-order solar spectrum is a blackbody radiator with a temperature of approximately 5800 K. Superimposed upon the blackbody spectrum are a number of absorption lines formed in the solar photosphere and atmosphere. Ultraviolet, optical, and near-infrared line absorption due to the ionization of H, He, O, C, Fe, Ca, Na, Mg, Ni, Ti are observed (see [1] for a comprehensive line list). The predominant absorption of radiation by the solar atmosphere is continuum absorption shortward of 1.7 μm, by the H^{-} ion. For wavelengths between 2 and 100 μm strong absorption features of CO, OH, and H_2O and a number of absorption lines from C, Na, Mg, and similar elements are also observed (see [2] for a review). Radiation with higher energy than the near-UV and lower than the near-IR are produced, especially in the solar atmosphere and corona, however, as will be outlined in the next section, radiation at these wavelengths is not transmitted through Earth's atmosphere and consequently need not be considered in the context of glints.

2.1.1. Atmospheric Extinction

Accurately characterizing the amount of atmospheric extinction (i.e., the sum of scattering and absorption that radiation experiences as it passes through the atmosphere) *in a general way* is impossible due to the dynamic nature of the abundance and physical properties of extincting components. Extinction by aerosols (continuum absorption by O_2 and O_3 and Rayleigh scattering primarily by N_2 and O_2) makes the atmosphere opaque at wavelengths shorter than 300 nm. In the visible portion of the spectrum atmospheric transmission is generally high (above 90%) with the exception of relatively narrow absorption features due to the rotation-vibration bands of O_2 and H_2O. Absorption by other aerosols, including sea salt and dust, can be significant in the optical and are strongly dependent on geographical location and atmospheric conditions. Beyond 1 µm, absorption by numerous molecules, but principally H_2O, results in strongly varying atmospheric transmission. From 1 to 25 µm water vapor renders the atmosphere opaque except for windows exploited by the J, H, K, L, M, N, and Q photometric bands that have very high (~90%) transmission.

Beyond 25 µm the atmosphere is opaque, and remains so out to 300 µm. At wavelengths longer than 300 µm the atmosphere again has transmission windows but at these wavelengths the solar blackbody flux has dropped by nine orders of magnitude compared with visible wavelengths, making glints unlikely to be observed.

While precise determination of atmospheric extinction is not possible without detailed information about the atmosphere at the time of observation, some generalizations can be made to estimate typical atmospheric conditions. Using estimates of the extincting components described above and an estimate of the total path-length through the atmosphere, the integrated extinction is:

$$f_{extincted} = f_{incident} \times 10^{(-2k \times \sec(z))}$$

where

$f_{extincted}$	=	atmosphere extincted energy flux exiting the atmosphere toward the satellite
$f_{incident}$	=	solar flux incident upon the atmosphere
$\sec(z)$	=	path-length through the atmosphere assuming a plane-parallel atmosphere
z	=	zenith angle
k	=	wavelength-dependent extinction value

The factor of 2 accounts for the total path-length through the atmosphere that radiation experiences, which is twice the extinction value from the Sun to the glint point since the radiation must pass through the same amount of atmosphere again from the glint point to the satellite. Typical values for k are 0.24, 0.16, 0.08, 0.04, and 0.032 at wavelengths of 360, 440, 550, 700, and 900 nm, respectively. Extinction at wavelengths longer than 1 µm is strongly dependent on surface elevation at the glint point and abundance of water vapor, and no generalization can be considered reliable. Note, the term 'flux' in this case refers to the astronomical convention (units of W m^{-2}), which is referred to as 'irradiance' in the radiometric convention. Also, the k value used here is different than that typically used to describe extinction by a factor of 2.5 because standard k values refer to the calculation of *magnitudes* of extinction rather than the calculation in flux units done here.

2.3. Reflection Spectrum of Water

Fresnel's equations can be used to determine the reflection spectrum of white light incident upon a smooth water surface. In contrast with the formation of the solar spectrum and atmospheric extinction effects, the reflection of radiation off of a water surface is not strongly dependent on the wavelength. The fraction of reflected light is strongly dependent on the zenith angle of incident radiation, with the fraction of reflected light being only a few percent up to zenith angles of 70° where there is a sharp upturn to 100% reflectivity at a zenith angle of 90°. Thus, to estimate the reflected spectrum of sunlight off of a water surface, the entire solar spectrum, including atmospheric absorption features, is simply scaled by the fraction of reflectivity.

Sensors with spectral capabilities or even broad-band filter sets can identify glints by the shape of the measured spectrum, since true glints will have the spectrum of the intrinsic solar spectrum with the addition of atmospheric absorption signatures.

2.4. Polarization of Reflected Sunlight

Unpolarized sunlight reflected from water surfaces will become predominantly linearly polarized (>50% polarization) in the direction parallel to the reflecting surface. The amount of polarization depends primarily on the zenith angle of incident radiation, but also has dependencies on the wavelength of light and the precise index of refraction of the reflecting water surface, as dictated by Fresnel's equations. The maximum value of 100% linear polarization is observed at Brewster's angle (an apparent solar zenith angle of ~53° for reflections of visible light off of water; see [3] for detailed discussion). This property can be used to distinguish glints from other transient events by employing sensors with polarization capability since most other phenomena will tend to be unpolarized.

3. FIND_GLINT.PRO

One approach to determining if a sensor response is a glint is to calculate the latitude and longitude on Earth where the Sun-Earth-satellite geometry is such that a glint could be observed, and then use a mapping utility to determine if there is a reflective surface at that location. If the sensor detecting an event that could potentially be a glint has imaging capability, the location of the glint solution can be compared with the location of the event of interest to further confirm if the event was a glint. The Interactive Data Language (IDL) program find_glint.pro was written for this task.

In practice, find_glint.pro is a wrapper program running a series of individual programs that calculate the solution glint point with incrementally increasing precision and outputs the solution location to the user. The program also creates a number of diagnostic plots and a .kml file readable by Google Earth that shows the location of the solution glint point and plots the projection of the angular size of the Sun around that point.

3.1. Glint Geometry

The underlying principle behind specular reflection is that the angle between the incident radiation and the normal vector of the reflecting surface of is equal to the angle of reflected radiation. Thus, to observe a glint the angular distance between the zenith (i.e., the point directly overhead for a given latitude and longitude) and the Sun as observed at the glint latitude and longitude must be exactly equal to the angle between the zenith and the satellite. Additionally the difference between the azimuthal angle (i.e., angle in the plane of the reflecting surface from due North to the object, measured in degrees East of North) of the Sun and the satellite must be exactly 180° at the glint latitude and longitude. Find_glint.pro solves for the latitude and longitude capable of producing a glint by finding the location that minimizes the difference between the zenith angles of the Sun and satellite, and simultaneously minimizes the difference of the azimuthal angles from 180°.

Determining the latitude and longitude of the glint point is relatively straight-forward under the assumption of a spherical Earth surface because the glint point is constrained to lie on a great circle passing through the subsolar and subsatellite points. For points on this great circle, all that needs to be calculated are the zenith angles of the Sun and satellite, and the point on the great circle where these angles are equal is the glint point.

However, a spherical approximation for the surface of the Earth is not a particularly good one. A much better approximation is that of the World Geodetic System 1984 (hereafter WGS84; [4]). The WGS84 model is an oblate spheroid with polar radius of 6356.752 km and equatorial radius of 6378.137 km. This Earth model, which takes into account the flattening of Earth due to centrifugal forces arising from its rotation, results in a geodetic latitude coordinate that is always greater than the geocentric latitude value for a given location on Earth, except for the poles and the equator where geodetic and geocentric latitudes are equal. Geodetic latitude measures the angle formed by the normal vector of the surface at a given position and a plane parallel to the equatorial plane passing through the given position (See Figure 1). Geocentric latitude measures the angle from the equatorial plane to a line from the center of the Earth through the given position. The difference between solution glint points using the spherical and WGS84 models is dependent on satellite altitude, but can be significant; the maximum difference between geocentric and geodetic latitude occurs at geodetic latitude = 45° and is 0.19°.

3.2. Zenith and Azimuthal Angle Calculations

Step 1 for find_glint.pro begins by accepting input coordinates for the Sun (geodetic latitude and longitude) and satellite (geodetic latitude, longitude, and altitude) at the command line. It is important to note that the Sun's geodetic latitude and longitude are very different than right ascension (RA) and declination (Dec), which are commonly used to describe the Sun's position. The Sun's geodetic latitude and longitude are the geodetic Earth coordinates where the Sun would be directly overhead, meaning they are dependent on the position of the Earth in its orbit around the Sun *and* the time of day. RA and Dec are coordinates for a spherical coordinate system, fixed with respect to the celestial sphere. Consequently the Sun's RA and Dec do not change significantly over the period of one day, and are only dependent on the position of Earth in its orbit over the course of a year.

Once the Sun and satellite coordinates are input they are converted from the geodetic system into the Earth-centered-Earth-fixed (ECEF) coordinate system. Next, a grid of test points is established so that the zenith distances and azimuths of the Sun and satellite can be calculated. Values representing the range of possible geodetic latitudes and longitudes (1° increments from -90° to 90° and 0° to 359°, respectively) are also converted to the ECEF system. Then, the declination angle from each test grid point to the satellite is calculated. The declination angle (Figure 2) is the angle from the satellite to a plane parallel to Earth's equator but passing through the test point. Unlike the declination angle coordinate used to describe the position of astronomical objects, the declination angle is dependent on both the latitude and longitude that the angle is being calculated from, since the satellite is in the near field unlike distant astronomical objects.

The hour angle of the satellite is calculated next. The hour angle is the angle from the meridian of the test grid point to the satellite, essentially the difference in longitude between the satellite and test grid point, but again is dependent on both the latitude and longitude of the test point because the satellite is in the near field (Figure 3). Once the declination angle and hour angle of the satellite have been found, a 2-dimensional coordinate system describing its position has been established. These same angles are also calculated from each test grid point to the Sun, however, these calculations are simplified since the Sun can be approximated to be at infinity, making the declination angle independent of position on Earth and the hour angle dependent only on the longitude of the test point.

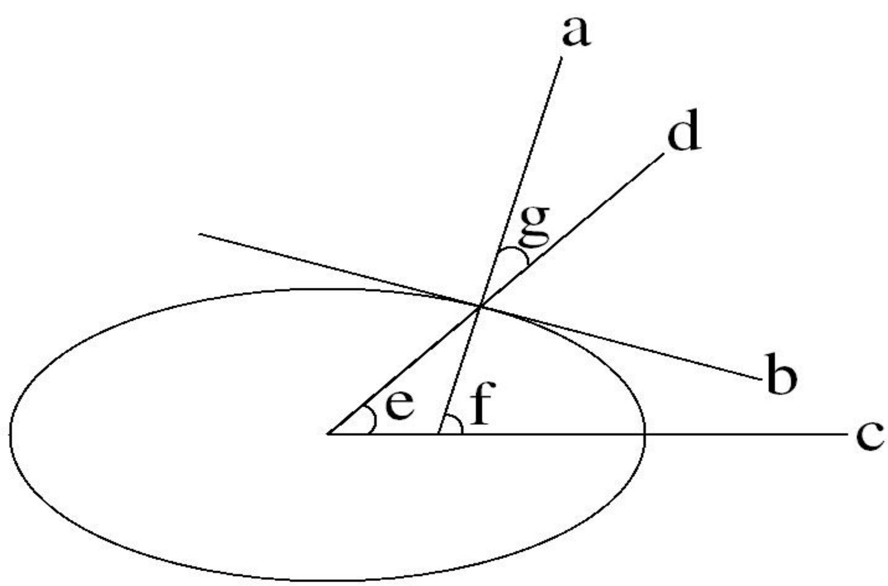

Figure 1: Diagram depicting the difference between geodetic and geocentric latitude. Vector (a) is normal to the surface at the test point. Plane (b) is the plane parallel to the surface at the test point. Plane (c) is Earth's equatorial plane. Vector (d) is the vector from the center of the Earth through the test point. Angle (e) is the geocentric latitude. Angle (f) is the geodetic latitude. Angle (g) is the difference between geodetic and geocentric latitudes at the test point.

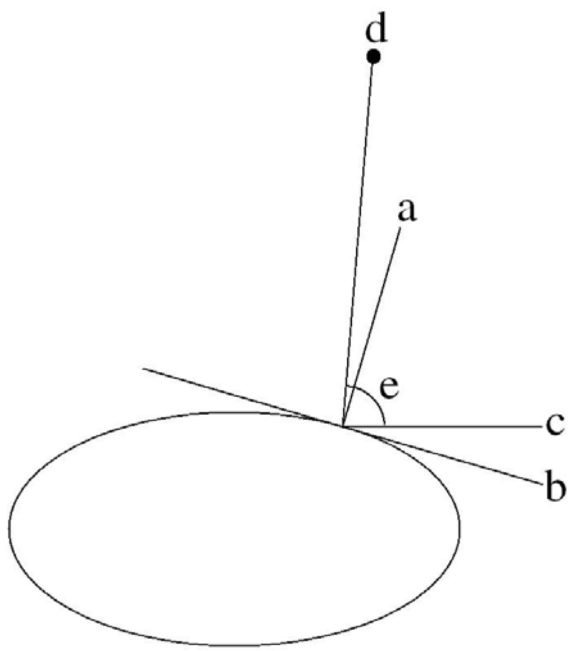

Figure 2: Depiction of the declination angle of a celestial object. The perspective is that of an exaggerated spheroidal Earth, viewed from the equator, with the North Pole oriented up. Vector (a) is the normal vector to the surface at the test point. Plane (b) is the plane parallel to the surface at the test point. Plane (c) is parallel to Earth's equatorial plane, but passes through the test point. Vector (d) is the vector from the test point to the celestial object in question. Angle (e) is the declination angle.

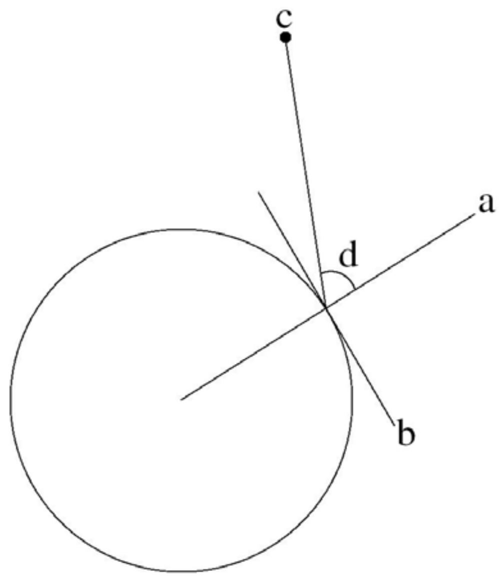

Figure 3: Depiction of the hour angle of a celestial object. The perspective is that of an exaggerated spheroidal Earth, viewed looking down at the North Pole from above. Vector (a) is the normal vector to the surface at the test point. Plane (b) is the plane parallel to the surface at the test point. Vector (c) is the vector from the test point to the celestial object in question. Angle (d) is the hour angle from the test point.

Once the declination and hour angles of the Sun and satellite are determined, the angular distance from the zenith at each test grid point to the Sun and to the satellite can be calculated, using the cosine formula [5]. The azimuthal angle of the Sun and satellite are then calculated using standard 3-dimensional geometry.

The routine has now determined two values, the zenith and azimuthal angles, for both the Sun and satellite at each test latitude and longitude on Earth. Again, the solution glint point will be where the zenith angle of the Sun is exactly equal to that of the satellite, and the azimuthal angles are different by exactly 180°. The final step is to find the combined minima of these two values. The absolute value of the difference between the zenith distances and the absolute value of the difference of the azimuthal angles from 180° are calculated. These values are divided by the maximum value found for each of them, such that the residual values range from 0 to 1 enabling us to consider the residual errors of the distance calculation and azimuth calculation on an equal scale. The square root of the sum of the squares of these two values is then calculated and the total residual difference is found. In practice there will be *two* points on Earth where the Sun and satellite will have equal zenith angles and difference in azimuthal angles of 180°. The true glint point is distinguishable from the other point by noting that for a glint to occur the Sun and satellite zenith angles must both be <90°, such that they are both above the local horizon. Thus, only locations where both the Sun and satellite zenith angles are ≤90° are considered in the final calculation where the minimum value of the total residual error is calculated, and only one of the two total minima found will be within this area. The latitude and longitude where this minimum in the residual error occurs is the solution glint point.

3.3. Adaptive Mesh Refinement

As detailed above, the residual error from the model of the satellite and Sun being at the same zenith angle and azimuthal angles different from 180° is calculated for each latitude and longitude on Earth on a grid of points at integer values of latitude and longitude. However, this grid size does not provide the desired precision since points separated by 1° in latitude and longitude are nearly 160 km apart at the equator. To calculate the glint point with higher precision and reasonable processing time the calculations described in Section 3.2 are repeated with increasingly smaller angular separation between test points, accomplished through a process similar to adaptive mesh refinement: The calculations described as Step 1 in Section 3.2 are performed and a solution is found. Step 2 creates a second grid, only 20° x 20° in extent with test points separated by 0.1° and centered on the solution coordinates of Step 1, and the calculations in Step 1 are repeated. A third and final grid, 2° x 2° in extent with test points separated by 0.01° and centered on the solution coordinates of Step 2 is created next and the calculations are run for a third time. The calculation in Step 3 is modified only slightly from Steps 1 and 2 in that an adjustment of the satellite position to correct for atmospheric refraction is performed (see Section 3.7.1 for a detailed discussion). The solution to the third step has an intrinsic precision (not including external sources of uncertainty, described in Section 3.5) of ±0.005° in latitude and longitude (approximately 0.56 km at the equator and decreasing as the cosine of the latitude).

3.4. Projection of the Solar Ellipse

The solution to Step 3, described above, yields the coordinates of the glint point where a ray leaving the center of the Sun would be reflected from, such that it would intercept the satellite sensor. However, because the Sun has a non-zero angular extent, with an angular diameter of roughly 0.5°, there are a range of latitudes and longitudes that can possibly produce a glint. Consequently, it is important to calculate the range of latitudes and longitudes that a ray leaving anywhere from the solar disk would intercept the satellite.

Step 4, and the final step in the routine, measures the projection of the solar disk around the central glint point (i.e., the range of latitudes and longitudes that could possibly create a glint considering the non-zero angular size of the Sun). This is done by running the calculation from Step 3 again, with the only difference being a box 1.5° x 1.5° is used to save computation time, and instead of using the Sun's coordinates, which depict the precise location of the center of the Sun, Step 3 is run sixteen times using coordinates representing sixteen points around the edge of the solar disk. The solution to Step 4 is a sixteen-sided polygon describing the glint region created by the full angular extent of the Sun. The size of the semi-major and semi-minor axes of the solar ellipse projection can vary from 0.1° to 0.75°, with the smallest angular extent occurring when the Sun and satellite are aligned in the sky, and the largest occurring when the Sun and satellite are opposite in the sky at the horizon.

3.5. The User Interface

Find_glint.pro was designed to be run by anyone with access to IDL, regardless of prior programming experience. To run the program five input values are needed: the Sun's geodetic latitude and longitude and the satellite's geodetic latitude, longitude, and altitude. Latitudes and longitudes must be in units of degrees, and the satellite's altitude must be in km. Longitudes in the western hemisphere can be input as either greater than 180° or negative values. At the command line the user enters the program name (i.e., find_glint), followed by the required inputs separated by commas, in the order listed above.

As an example, to find the location of the glint point given Solar latitude = -0.588° and longitude = -2.218°, and satellite latitude = -0.353°, longitude = 225.177°, and altitude = 35781.2 km the following would be input at the IDL command line:

```
find_glint, -0.588, -2.218, -0.353, 225.177, 35781.2
```

3.6. Program Outputs

3.6.1. Outputs to the Terminal

After entering the above command, a list of the compiled modules will be printed to the terminal. The find_glint.pro program compiles all subroutines it will use throughout the entire program at the beginning, which is different than the standard method of running an IDL routine where each subroutine is compiled as it is needed. Subroutines are all compiled together so that all of the messages stating which modules have been compiled are printed to the terminal in a single block, leaving the messages that find_glint.pro prints to the terminal more legible than they would otherwise be. After the block of messages stating which routines have been compiled is printed, a message stating "Calculating Rough Glint Location" is printed to the terminal. When the rough glint location is found (with test grid point separation of 1°; see Step 1 in Section 3.2) the coordinates are printed to the terminal. When Step 2 begins, a message is printed to the terminal stating "Calculating Better Glint Location", and when a solution is found the coordinates are printed to the terminal. Step 3 in Section 3.3 follows the same procedure, printing "Calculating Precise Glint Location" to the terminal, and the solution when it is found. As Step 4 in Section 3.3 proceeds it prints to the terminal which of the sixteen points it has calculated, e.g., "Calculating Glint Ellipse Point 9/16".

There are two statements that in certain situations will be printed to the terminal, which users should be on the lookout for. First is a statement regarding there being no place on Earth where both the Sun and satellite are above the horizon. Because of the non-zero size of Earth, there are Sun-Earth-satellite geometries where it is not possible for both the Sun and satellite to be above the horizon simultaneously. This occurs when the Sun and satellite are nearly 180° from one another in the sky. In this case an error message will be printed to the terminal and find_glint.pro will exit.

The second possible error message that the user should be aware of involves the correction for atmospheric refraction (see Section 3.6.1 for details). The correction applied to the satellite position to account for atmospheric refraction is only reliable for satellite zenith angles <80°. If the satellite zenith angle at the solution glint point is >80° the program will run to completion and provide a solution, but a message will be printed to the terminal warning the user that the solution may not be accurate.

3.6.2. Graphical Outputs

Several plots are created as find_glint.pro proceeds, enabling the user to ensure the solution it finds is reasonable. At the conclusion of Step 1 in Section 3.2 six plots are displayed. The left-most two plots (Figure 4) show a longitude and latitude map (in the x and y directions, respectively) with the color code representing the residual values of the azimuthal angle test (i.e., how close are the difference in azimuth angles of the Sun and the satellite to 180°). Very small numbers, represented by black in the color plot, are very small residuals meaning the azimuths of the Sun and satellite are nearly opposite, as required for a glint, while large numbers, represented by red, shows locations where the Sun and satellite are in the same direction in the sky making a glint unlikely.

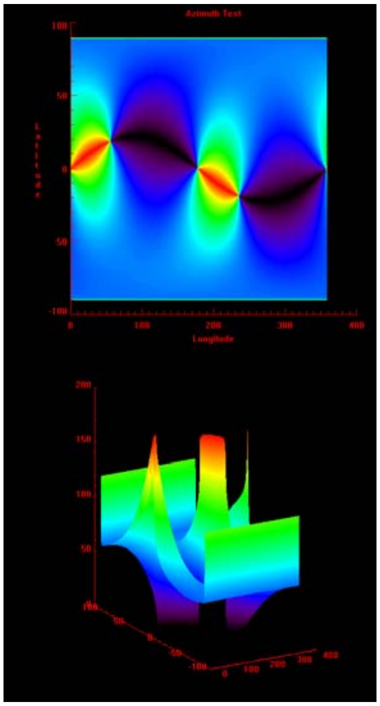

Figure 4: Sample plots showing the 'azimuth test' residual values as a function of longitude (x direction) and latitude (y direction). Dark points represent small residuals (i.e., the Sun and satellite azimuths are nearly 180° different from one another). The two plots show the same data from different perspectives. The top plot looks down at the xy plane from the +z direction. The bottom plot shows the same data with the z coordinate the residual value of the azimuth test.

The middle two plots (Figure 5) show a longitude and latitude map with the color code representing the residuals of the distance test (i.e., how close are the zenith distances of the Sun and satellite to being equal). Again, small residual values, represented by black, show locations where the Sun and satellite are at equal distances from the zenith. Large values, represented by red, show locations where the Sun and satellite are at very different zenith distances from one another, making a glint unlikely.

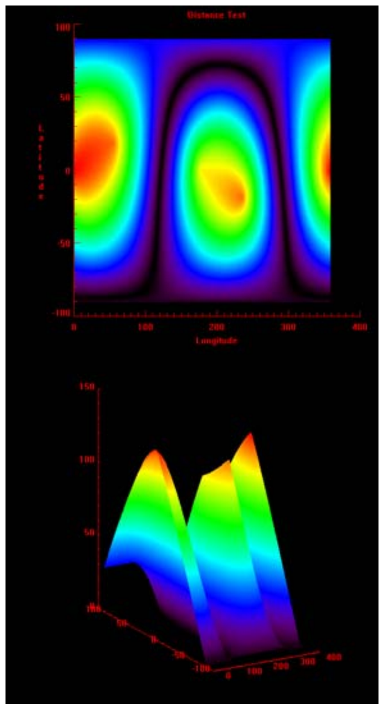

Figure 5: Sample plots showing the ‘distance test’ residual values as a function of longitude (x direction) and latitude (y direction). Dark points represent small residuals (i.e., the Sun and satellite are at equal zenith angles). The coordinates of the top and bottom plots are the same as Figure 3.

The right-most two plots (Figure 6) show the least-squares fit to the azimuth and distance tests. Very small values, represented by black, show locations where the Sun and satellite are at nearly equal zenith distances and have azimuths that are 180° different from one another. Large values, represented by red, show locations where zenith distances are very different and the difference between azimuthal angles is very different from 180°. Again, there will be two black spots on this plot, representing the minima of the least-squares fitting calculation, but only one of these will be the true glint point where both the Sun and satellite are above the horizon.

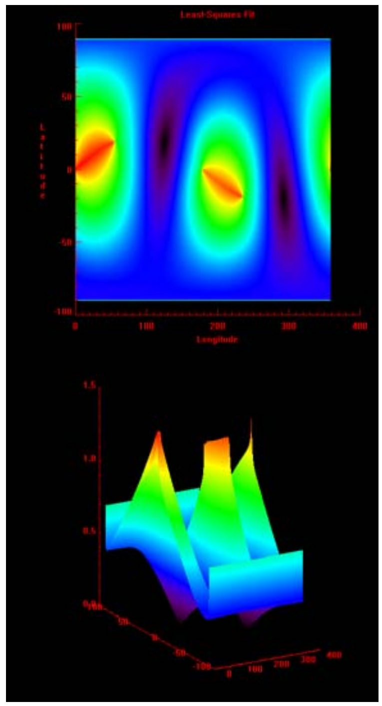

Figure 6: Sample plots showing the least-squares fit to the azimuth and distance tests (Figures 3 and 4) as a function of longitude (x direction) and latitude (y direction). Dark points represent small residuals (i.e., the Sun and satellite azimuths are nearly 180° different from one another and at equal zenith angles). The coordinates of the top and bottom plots are the same as Figure 3.

For each of the azimuth, distance, and least-squares fitting plots, the top plot shows the longitude and latitude on the x and y axes, looking down on the xy plane from the +z direction. The bottom plot shows the same data, only plotted from a different perspective with the value of the z coordinate being the numerical value of the minimization to the least-squares fit. These plots enable the user to more easily identify discontinuities and other subtleties that might not be easily interpreted in the top plot.

At the conclusion of Step 3 in Section 3.3 a second window is automatically created, and six more plots are drawn. These plots (Figures 7, 8, and 9) have exactly the same layout and meaning as those created for Step 1, but show the residual values for the calculations run with the finest grid size, with a total grid size of only 2° x 2° and a point-to-point grid spacing of 0.01°.

These plots are created so that the user can do a few checks to ensure the program is finding a reasonable solution. First, the user can look at the first plot, showing all possible values of latitude and longitude, and check that the rough glint solution found is reasonable given the input Sun and satellite coordinates. Second the user should ensure that one of the minima from the first plot is roughly centered in the second plot. The minima need not be directly in the center, however, if it appears the minima is at the edge of the least-squares fit plot, it is very likely that the adaptive mesh refinement failed, and the resulting solution will be incorrect

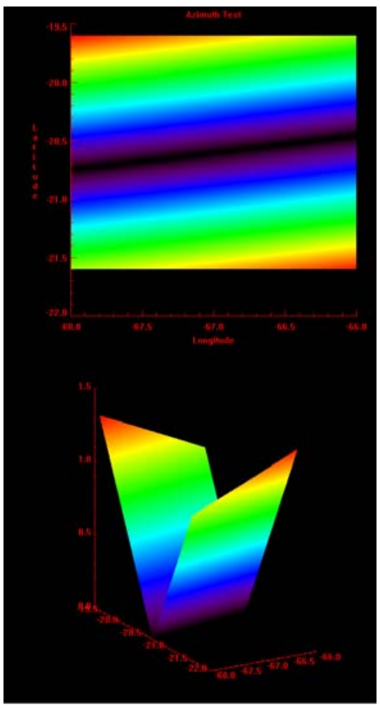

Figure 7: Same as Figure 4, but magnified to only show a 2° x 2° region around the solution glint point.

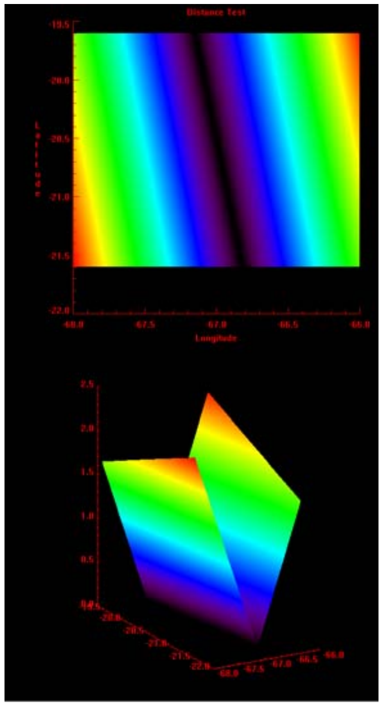

Figure 8: Same as Figure 5 but magnified to only show a 2° x 2° region around the solution glint point.

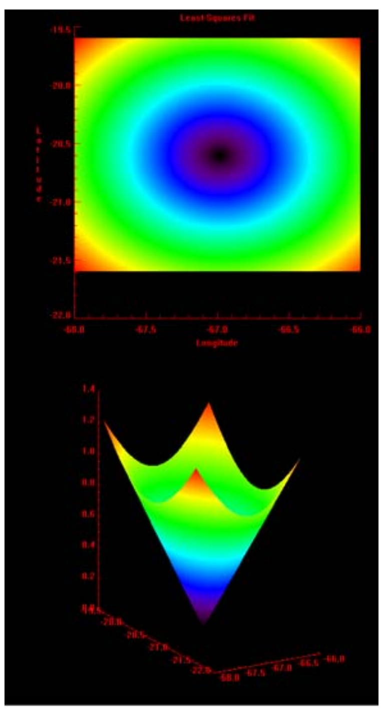

Figure 9: Same as Figure 6 but magnified to only show a 2° x 2° region around the solution glint point.

3.6.3 KML Output

The final , and likely the most useful, output from the find_glint.pro routine is a .kml file containing the locations of the 16 vertices of the polygon representing the projection of the solar ellipse, designed to be read by Google Earth. Upon opening the file Google Earth opens and the display is moved such that the solar ellipse is centered on the map. This utility is useful because it enables the user to determine whether the glint region might have been reflective at the time the glint was observed. Users should be cautious in strictly interpreting the Google Earth map, as seasonal variations can affect the amount of surface water or ice that is present (e.g. seasonal floodplains and ice flows) and the Google Earth map only represents a single image in time. Nevertheless, this utility has shown to be very useful in interpreting possible glint events. Figure 10 shows an example Google Earth map with the solar ellipse projection plotted.

Figure 10: Google Earth map showing an example solution for the glint ellipse. The glint ellipse is shown (grey ellipse with white border) in the center of this lake.

3.7. Sources of Uncertainty and Known Limitations

3.7.1. Sun and Satellite Position Uncertainty

There are a number of sources of uncertainty in the glint point solution that should be considered. The most easily identifiable sources are errors in the input Sun and satellite coordinates. Very high precision Solar coordinates for a given time are available from a number of sources, most notably the National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA/JPL) HORIZONS ephemeris generator [6]. However, the NASA/JPL ephemeris generator yields solar coordinates in the RA and Dec coordinate system, requiring the user to convert the coordinates to the geodetic system prior to use. Satellite Tool Kit (STK) uses the HORIZONS generator for stellar and planetary positions, but does its own internal conversion into several coordinate systems including the geodetic system, making it a very user-friendly tool.

The user must take care in knowing what corrections, if any, have been made to the Sun and satellite coordinates they input into find_glint.pro. For example, the HORIZONS ephemeris generator gives the absolute position of the Sun for the requested time. However, this position will not be where the Sun *appears* to be in the sky for two reasons. First, the light-travel time from the Sun to the surface of Earth is approximately 500 seconds. Thus, at any given instant the *apparent* longitude of the Sun lags behind the true longitude by approximately 2° (note, the Sun's latitude also changes with time, but so slowly as to be negligible in this case). The light-travel time to satellites, even those in relatively distant geosynchronous orbits, are less than a second, and can be considered negligible in this application.

The second correction that must be made to precisely determine the apparent position of the Sun and satellite is for refraction of sunlight through the atmosphere. The amount of refraction that radiation from the Sun will experience as it passes through the atmosphere is dependent on the altitude of the observer as well as the atmospheric conditions at the time (e.g., temperature, temperature gradient, pressure, abundance of water vapor; see [1] for a detailed description), but can be approximated by the equation:

$$R = R_0 \tan(z)$$

where

R = difference between the apparent and absolute zenith angles
R_0 = 0.016775° at 550 nm
z = zenith angle

The apparent zenith angle of the Sun is always smaller than the true value (i.e., the Sun always appears higher in the sky than it would be in the absence of an atmosphere). R_0 is dependent on atmospheric conditions and the wavelength of light being considered, and the above value is for demonstrative purposes only. This equation is only reliable for zenith angles up to 80°, since above this value the amount of refraction becomes strongly dependent on the atmospheric conditions at the time of observation. Consequently, a cautionary statement is written to the terminal by find_glint.pro if this angle is exceeded (see Section 3.6.1).

It is important to note that programs such as STK provide apparent positions, which have already corrected for both the light-travel time and estimated atmospheric refraction, while other programs may not have included these types of effects. Consequently, it is critical that the user be aware of what corrections have been made to the Solar and satellite positions that they input. Find_glint.pro assumes the solar coordinates have been corrected for, but that the satellite coordinates have not. It is also important that the user be aware that in situations where the satellite zenith angle is large, the solar zenith angle will also be large (again, because of the principle of specular reflection), making the estimated apparent positions of both the Sun and satellite inaccurate, leading to a large uncertainty in the final glint solution.

3.7.2. Time Dependence of Sun and Satellite Positions

Depending on the orbital parameters of the satellite in question, the rate of change of geodetic coordinates can vary dramatically. Of course, the geodetic coordinates of geostationary satellites are constant to first order, while the coordinates of low Earth orbit (LEO) satellites with orbital periods of ~90 minutes change at a rate of 4° minute^{-1}. Because geodetic satellite coordinates can change rapidly with time, determination of the precise time that the glint was observed is important in addition to the precision of the satellite ephemeris.

3.7.3 Terrain Elevation and Reflections from Cloud-Tops

Another source of uncertainty in the coordinates of the glint solution is due to terrain elevation. Because the true elevation of the Earth surface can vary significantly from the WGS84 model (up to 8.8 km at Mt. Everest), the ECEF coordinates for a given glint location can vary, affecting the declination and hour angles of the Sun and satellite. The effect of terrain elevation on the resulting glint point solution depends on the altitude of the satellite, but is generally very small, given that even at the maximum deviation of 8.8 km, the distance from the center of the Earth to the surface is only 0.1% different from the WGS84 value. For vehicles in medium Earth orbit, the maximum effect (i.e., a reflective surface located at the top of Mt. Everest) is only 0.01-0.02° and can be ignored. Note: because the Sun can be approximated to be at infinity, its declination angle is simply its geodetic latitude and neither its declination nor hour angles are dependent on the surface elevation at the glint point.

A similar uncertainty to that caused by terrain elevation is due to reflections from cloud-tops. Clouds can be highly reflective at visible wavelengths (exhibiting 70-95% reflectivity), and consequently are excellent candidates for the production of glint events. For small deviations such as elevation and clouds, the uncertainty introduced by elevation variation from the WGS84 approximation is linear with the deviation of the actual reflective surface from the WGS84 surface. Under the assumption that cloud-top surfaces are plane-parallel to the Earth surface directly below them, the uncertainty in the location of a glint solution can be up to 0.04° for cloud altitudes up to 18 km. It is important to note that it is possible for glints to be created by cloud surfaces not plane-parallel to the Earth surface below them. In this case the solution to the glint location is wholly unreliable. Fortunately, glints are generally created by reflective surfaces several kilometers in extent, and it would be exceedingly uncommon for a cloud feature of this size and flat enough to generate a glint to be in any orientation other than parallel to the Earth surface below it.

4. Future Applications: Glints from Near Field Surfaces

In addition to terrestrial water surfaces and cloud-tops, other surfaces can produce glints. Satellites passing into the field of regard of the satellite observing the glint are another common source of glints, and the ability to identify these events would provide a useful tool for the satellite community. Because the geometry involved is very different from that of terrestrial glints the current form of find_glint.pro cannot be used to estimate the locations of these types of events. However, future iterations will likely include this capability. There are additional subtleties that must be considered when estimating the location that the glint originated from.

Reflections from satellite surfaces are very different than Earth surfaces, because the vector normal to the plane of reflection can be in any orientation, whereas the vector normal to Earth's surface is directly opposite the local force field (i.e., the sum of the gravitational and centrifugal forces). This makes determination of the location of the satellite creating the glint a very different type of problem since there is not a unique solution to the Sun-reflector-sensor geometry capable of producing a glint as there was in the Earth case. In practice, the position of the reflecting satellite can be anywhere within the field of regard of the satellite detecting the glint, and more precise determination requires sensors with imaging capability, or careful consideration of instrumental sensitivity, sensor field of regard, satellite surface areas and reflectivities, and solar luminosity at the relevant wavelengths for the sensor. Taking into account all of these properties can possibly enable the user to narrow the range of distances from the satellite detecting the glint to the satellite producing it as a function of the size and material properties of the reflecting surface, but additional constraints are required to find a single solution for the glint location.

5. SUMMARY AND CONCLUSIONS

We have presented a review of the radiative processes involved in the formation of glints toward the goal of confidently identifying the source of these events. We identified the key spectral properties of the Sun and Earth's atmosphere. Glints can be confidently identified as the source of a sensor response if the spectral properties of the response match that of the solar spectrum scaled by the amount of atmospheric extinction the radiation experiences. While the solar spectrum is constant in time to first order, the amount of atmospheric extinction is dependent on the properties of the atmosphere (temperature, pressure, composition, abundance of dust, sea salt, and water vapor, etc.), the surface elevation at the glint location, and the zenith angle of the Sun at the time of observation. These variables make precise determination of the amount of extinction very difficult, but reasonable estimates can be made relatively easily. Sensors with spectral capability or even broad-band filters can distinguish between glint events and other signals by comparing the spectral signatures of the event with that of the atmosphere extincted solar spectrum.

We discussed a second method of identifying glints from other signals, which involves measuring the polarization of the radiation triggering a sensor. We addressed the polarization properties of reflected radiation and described the expected fractional polarization of a glint. The polarization of the radiation causing a sensor response can be used to positively identify a glint from another source since most other observable phenomena are expected to produce unpolarized flashes.

A robust method of identifying glint events in the absence of spectral or polarization capability of the sensor is by finding the Sun-Earth-satellite geometry capable of producing a glint. If the sensor in question has imaging capability the location of the event in the sensor's field of view and the solution glint location can be compared to verify its origin. In the absence of imaging capability, the glint solution can be compared with mapping utilities to determine if the surface at the location is reflective. We describe this method of glint identification, and the software tool find_glint.pro, written for this application.

Finally, we briefly discuss another type of glint event: the reflection of sunlight off of a satellite passing within the field of regard of the satellite observing the glint. Because of the large range of altitudes at which satellites operate, finding the precise glint location is a much more difficult problem than that on Earth's surface. However, considering the properties of the sensor detecting the glint can enable the user to narrow the range of possible locations of the reflecting satellite. A future version of the find_glint.pro program will work to solve this problem.

ACKNOWLEDGEMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

NOMENCLATURE

Azimuth	angle measured along the horizon eastward of north
Declination	equivalent of latitude and measured in degrees north or south of the observer
Extinction	attenuation of radiation energy flux due to scattering and absorption processes
Geodetic	latitude coordinate based on the normal vector to the surface
Geocentric	latitude based on the vector from the center of Earth through the observation point
Glint	specular reflection of sunlight off of a reflective surface to a sensor
Hour angle	angle between a celestial object and the observers meridian
Meridian	great circle passing through the zenith and intersecting the horizon due north and south
Zenith	the point on the celestial sphere directly above the observer

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