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ANALYSIS OF THE EFFECTS OF EARTH SHADOWING ON GNSS SATELLITE ORBITS

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Abstract. Precise positioning by GNSS might incur some error when one or more of the satellites that are being observed happen to be in Earth shadow – in eclipse. This effect might be worsened if the Earth is passing through a period of stormy solar weather. It is therefore of considerable interest to be able to examine satellite orbital degeneration while in eclipse compared to when not in eclipse.

This paper develops the connections between the methods of describing the motions of the Sun and GNSS satellites in, respectively, the astronomical and the Earth-centred systems. On this basis, tools are prepared for determining and predicting when individual satellites are, or are not, in eclipse, leading further to more advanced tools for predicting eclipse seasons in advance. Additionally, some experiments are described comparing predicted orbits with observed satellite orbits under both eclipse and non-eclipse conditions.

In conclusion this paper describes how the normal modern high precision land surveyor should take account of the eclipse phenomenon in planning measurement missions.

Keywords: GNSS satellites, eclipse, solar weather.

1. Introduction

Positioning and navigation using satellites remains a process of three-dimensional triangulation, where it is necessary to know or measure the positions of sufficient satellites together with the distance to those satellites. Providing knowledge of the satellites' instantaneous position on orbit is the responsibility of the Space Control Segment, in the sense that appropriate parameters are uploaded to the satellites for subsequent broadcasting to terrestrial receivers. Thus, those receivers need to be equipped with the firmware necessary to decode the incoming parameters and then to carry out the necessary computations.

Measuring the distance to the satellites is done indirectly, by recording the time of arrival of discrete elements of the incoming signal which also describe the time of their departure from the satellites. These time measurements are made using timepieces which themselves carry some error with them. The error in the satellite timepieces is relatively predictable and parameters describing them are broadcast by the satellites. The timing error in the terrestrial receiver is meanwhile unknown, and, since the necessary timepiece is normally somewhat less precise than those in space, cannot be easily predicted. Therefore, sufficient satellites are observed simultaneously to be able to develop the instantaneous clock error as one of the positioning unknowns.

All of the above therefore depends on a series of predictions for each satellite – predictions of the satellites' orbital movement, and predictions of the behaviour of the satellites' clocks. It is the behaviour of the satellites' orbits which is of interest here.

As already indicated the Space Control Segment prepares the necessary orbital predictions and uploads them to the satellites at regular intervals. Clearly, at the time of upload, the orbital parameters can be expected to be relatively accurate. With the passage of time towards the next update, however, the accuracy of the predictions can be expected to decay to some degree. Nevertheless, this decay in orbit prediction accuracy is of no concern to the average navigator and recreation user. Indeed, it may normally be of little importance to all but the most advanced users seeking the best possible accuracy.

The reasons for the decay in orbit prediction with time can be summarised as being a combination of residual errors in the modelling of the geo-potential surface at orbit altitude, coupled with the effects of various forms of radiation that are impinging on the satellite. Of the latter, the various forms of solar radiation perhaps dominate. However, the actual cause of the decay is of less concern to the high precision user. The degree to which the user's positional accuracy is degraded is much more of interest. Further, the high precision user is naturally interested in developing procedures to avoid decay where possible.

Serious research and monitoring of solar activity is very well established because modern society's infrastructure has certain serious vulnerabilities to solar storming. Over recent years, space weather forecasting and warning systems have become available, and records of activity are in the public domain. Thus, it is not difficult to determine from recent records whether and when solar storms have impacted on the Earth.

Meanwhile, aside from and yet complementary to the activities of the Space Control Segments, the International GNSS Service publishes precise *a posteriori* orbital information based on a worldwide geodetic tracking network. Certain comparisons can thus be made.

In particular, it might be logically assumed that orbit disturbance due to solar pressures would not take place when the satellite is in shadow – in eclipse. Here, of course, the satellite can find itself in the Moon's shadow and/or the Earth's shadow. Either way, it is suggested that some shielding from solar radiation and wind effects might be expected. The question is – how much difference can this make to precise terrestrial positioning. Further, if the positioning accuracy is significantly degraded, is it now becoming timely for precision users to follow space weather forecasting services, and to avoid measuring their positions at times of high risk.

Additionally, it must be remembered that the satellites are effectively powered by sunlight, supported by batteries. Once a satellite disappears into shadow, then the systems for orienting solar panels towards the Sun become, perhaps, slightly confused and start to hunt. At the same time, orienting the satellites in their correct attitude towards the Earth is also to a degree dependent on input from solar panel array orientation towards the Sun. Thus, while in eclipse, not only is the satellite draining power while it continues to hunt for the Sun, it may also be drifting slightly out of its correct orientation, thus introducing potential errors due to offsets between the satellite's centre of gravity and the electrical centres of its various transmitting antenna.

Another aspect of the argument is that investigating positioning decay caused by using or not using eclipsed satellites will provide a relatively simple indication of the seriousness or otherwise of these concerns.

2. Description of the Issue and Assumptions

The primary focus of this study, then, is to determine whether using eclipsed satellites is "safe" under solar storming conditions.

Put another way, by comparing observed position with well established "known" position, the following questions can be asked:

- Is the accuracy of high precision positioning degraded when observing while solar storming effects are impacting the Earth?
- Is the degree of degradation worsened by including the observations to eclipsed satellites?
- As a general question, should eclipsed satellites be avoided as a matter of routine for high precision positioning?

For the purposes of this study, it was decided to make a number of assumptions. These are justified by bearing in mind the distances involved between Sun and Earth, between Earth and satellites, and the relatively slow apparent motion of the satellites (orbiting roughly twice per solar day). Additionally, the assumptions simplified the computing processes considerably. Meanwhile, it was thought that further more precise computations could be undertaken if necessary for periods of time where these studies indicated that there was some significant phenomena to be studied further.

The assumptions, then. were:

- That the distance from the Sun to the Earth is constant at 149597890 km;
- That the Sun's face as seen is circular;
- That the Sun's radius is 1392000 km;
- That for the purpose of computing the shape of the Earth's shadow at satellite orbit altitude:
  - The Earth is actually spherical in shape;
  - That the Earth's radius is 6378 km;
- Finally, that the orbits followed by the satellites are in fact circular.

3. Computation Strategy for Defining the Earth's Shadow Zone

Determining whether or not orbiting satellites are in eclipse clearly requires a definition of the area in space which is eclipsed. In its very simplest form, this area can be thought of as a circular surface produced by the intersection of the umbral cone with the geopotential surface on which a given satellite is riding. If then the boundaries of this surface can be defined in the form of conventional 3D Earth-centred coordinates, then simple comparison with satellite coordinates at epoch will immediately show whether the satellite is eclipsed. It is thus not necessary to be concerned with the shape of the actual surface – it is the surface's boundary which is of interest.

The strategy selected required input following the above named assumptions. The computing process was then:

- Establish the Earth centred coordinates of the centre of the Earth's shadow at satellite orbit altitude:
  - Using polynomials for solar ephemerides, extract the latitude of the point on the Earth's surface where the Sun is at the zenith at epoch. The longitude of that point is of course the equivalent of 12 hours local mean time.
  - Change the sign of latitude, and add 180° to the longitude to obtain the latitude and longitude of the point on the Earth's surface opposite the previous point.
  - Add the altitude of the satellite orbit to the Earth's radius to obtain the latitude, longitude and height of the satellite.
  - Convert these to Earth centred three dimensional (3D) coordinates.
- Establish the radius of the shadow plane at satellite altitude, noting that two radii were extracted here, one for full shadow (umbra) and one for proportional shadow when some part of the Sun's limb would still be visible to the satellite (penumbra):
  - Compute the convergence of the shadow cone due to the difference in radius between the Sun and the Earth.

– Then compute the radius of the shadow plane.

4. Determining Satellite Positions at Epoch

The simplest method of determining satellite positions on orbit is by extraction from *a posteriori* precise data developed by the International GNSS Service (IGS). These data files (having the "sp3" format) are in the public domain, and present actual measured positions as Earth centred three-dimensional coordinates at 15 minute intervals, both for GPS and for GLONASS. Thus, so long as a 15 minute interval is satisfactory for the purposes of this type of study, then orbit positions can be directly extracted.

If however more frequent orbital positions are required, then, these must be interpolated between the data points given in the IGS data files. However, the satellite orbit paths are not rectilinear, and therefore it is appropriate to use a Lagrange interpolation. It has been recommended that 8 data points will be sufficient for accurate interpolation.

The final step in determining whether a satellite is in eclipse is to compute the distance between the satellite at epoch and the centre of the shadow zone at satellite altitude. This is a simple matter of three- dimensional Pythagoras. If that distance is smaller than the radius of the umbra zone, then the satellite is in eclipse.

5. Data Collection and Formats

Numerical data for the periods selected for this investigation was collected from a number of sources. The periods selected were in the first instance periods during which there was minimal registered and recorded solar activity. Subsequently, test periods were selected to coincide with significant solar storming events. The data sources were:

- Polynomials describing the Sun's motion were sourced from the Star Almanac for Land Surveyors. These polynomials provide for the computation of the Sun's declination ("Dec") and the difference between the Greenwich hour angle of the Sun and Universal Time ("E") at any epoch throughout the calendar year.
- Precise satellite ephemerides for GPS and GLONASS were downloaded from the CDDIS data centre which supports the International GNSS Service (IGS), as mentioned already.
- One hour observation and navigation files – also at one second intervals and in RINEX format – were additionally retrieved from the records maintained at the Gjøvik University College's reference station (GJOV) at latitude 60° 47' 22.2" N, longitude 10° 40' 50.3" E, or X-3066670.0470, Y-578381.1270 and Z-5544140.8300.

6. Analysis of Evaluation of Solar Eclipse on Ground Positioning

The algorithms for computing eclipse periods were first tested by means of hand computations in order to provide validation results. Thereafter, appropriate program routines were drafted to perform the various functions described earlier. The routines were finally connected together in a full program that was thoroughly tested and then compiled into an executable form. All programming work was done using the FBIde program editor into the Quick Basic programming system.

Systematic examination of records of solar activity showed that there were a number of moderate to strong events during the second half of the last full Solar Cycle – during 2003, 4 and 5. Since then, however, there have been few significant events, and it is well documented that the current Cycle appears to be late and slow in starting. Nevertheless, two periods of minimal activity were selected during 2010 – 01 to 11 March and 01 to 18 September. Observational, solar polynomial and precise ephemeris data for these periods were collected for the above mentioned stations.

Observational data for the GJOV station for the selected storm periods during 2003-5 were also extracted.

Having captured the necessary and or available data, processing sequences were carried out. The first task was to determine during those periods whether – and if so which, when and whether they were visible over a 15° elevation cut-off – there were satellites going through Earth shadow during their orbits.

The Leica Geo Office (LGO) software (version 7) was then used for further processing. In all cases, one-hour sessions were processed using one-second observations, with the 15° elevation cut-off angle. Naturally, rigorous checks were performed to ensure that all processing used the correct ellipsoidal parameters, projection definitions, antenna offset values and antenna heights over their respective monuments. Additionally, separate confirmation was sought and obtained from the Norwegian Mapping Authority that the three-dimensional coordinates recorded in their RINEX headers were correct.

The process that was carried out for both stormy and not-stormy periods was to compute single point dual frequency code positions in order to determine the degree of their variation with and without storming. (The LGO software does not include the ability to compute single point phase positions.)

The same process was then repeated but this time first having ensured that eclipsed satellites would not be taken into the processing during the hourly sessions when they were in shadow. The aim here was to compare the hourly variations with and without eclipsed satellites.

7. Test Results

The aim of this research was to find out any significant differences in position. In other words, to look at the ground position variations between stormy and no-stormy periods with and without eclipsed satellites.

The coordinates were developed by single point, which were computed using Leica Geo Office software, version 7. Results of the storm days and no-storm days with eclipsed satellites are presented in table 1 and 2.

Table 1. Storm days with eclipsed satellites

	X, meters	Y, meters	Z, meters
Average	3066675.3849	578381.2175	5544140.5616
SD Average	1.5804	1.0484	3.1063
Max Value	3066678.6167	578383.0976	5544146.8621
Min Value	3066672.5181	578379.2614	5544134.1954
Range	6.0986	3.8362	12.6667

Table 2. No storm days with eclipsed satellites

	X, meters	Y, meters	Z, meters
Average	3066674.9527	578381.3312	5544140.9584
SD Average	1.1725	0.3589	1.2141
Max Value	3066678.4790	578382.1785	5544144.3119
Min Value	3066673.0480	578380.9433	5544138.4992
Range	5.4310	1.2352	5.8127

The same process was made for storm and no-storm period but without eclipsed satellites. Results of the test are presented in table 3 and 4.

Table 3. Storm days without eclipsed satellites

	X, meters	Y, meters	Z, meters
Average	3066675.5171	578381.0441	5544140.5501
SD Average	1.3508	1.3886	1.9440
Max Value	3066677.8909	578383.0063	5544143.8645
Min Value	3066672.2441	578377.8902	5544136.6457
Range	5.6468	5.1161	7.2188

Table 4. No storm days without eclipsed satellites

	X, meters	Y, meters	Z, meters
Average	3066674.8735	578381.1788	5544140.9238
SD Average	1.1175	0.3517	1.1414
Max Value	3066678.1468	578382.3603	5544144.0107
Min Value	3066672.9485	578380.4384	5544138.4206
Range	5.1983	1.9219	5.5901

As the results show, in stormy and no-stormy periods with eclipsed satellites, the range between maximum value and minimum value is significantly different. In stormy and not-stormy periods but without eclipsed satellites results are very close.

8. Conclusions and Recommendations

The evidence suggest that under conditions where there is no solar storming the removal of observations to satellites that are in Earth shadow (eclipse) makes no significant differences to single point positions. This is seen by examining post-processed observation over many days with and without eclipsed satellites.

Under solar storm conditions, however, similar examinations indicate that removing eclipsed satellites from post-processing appears to improve the quality of resulting positions. In other words, without eclipsed satellites the ground position is more reliable.

It is suggested that this could be because eclipsed satellites are not being so much diverted in their orbital paths as the others, and are therefore introducing a non-random element into what otherwise should be expected to be a random Gaussian distribution.

On the other hand, these results are based on extensive single point positioning using code observations. Clearly, differential phase processing will provide significantly more precise ground positions. Much of the effects of solar storming might be expected to be eliminated, thus making it more difficult to detect eclipse distortion.

Nevertheless, the evidence reported here suggests that under solar storming conditions it would be wise to avoid using observations to eclipsed satellites.

Two practical consequences emerge:

- For post-processing, removing eclipsed satellites is easily done. RTK systems mostly do not at present allow for removing individual satellites from observation while in the field.
- Secondly, removing eclipsed satellites requires knowledge of which satellites will be in eclipse, and when. Computation of eclipse periods is not normally included in conventional mission planning software.

More reliable conclusions are being developed by comparing further processings of single points and phase vectors under solar storming conditions. A separate investigation is also being made to compare broadcast and precise orbit positions under solar storming.

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