Impact of Albedo Radiation on GPS Satellites

C. J. Rodriguez-Solano, U. Hugentobler, P. Steigenberger
Institute for Astronomical and Physical Geodesy,
Technische Universität München, Arcisstraße 21, 80333 Munich, Germany

Abstract. GPS satellite orbits available from the International GNSS Service (IGS) show a peculiar pattern in the SLR residuals at the few centimeter level that is related to radiation pressure mismodeling. Part of the mismodeling may be attributed to neglecting the solar radiation reflected and re-emitted from the Earth, the albedo radiation, as most IGS analysis centers do not yet take into account this radiation pressure component. In this study the relative importance of different albedo model constituents is analyzed. The impact of nine albedo models with increasing complexity is investigated using one year of global GPS data from the IGS tracking network. The most important model components are the solar panels of the satellites while different Earth radiation models have a minor impact on orbits at GPS altitudes. Albedo radiation has the potential to remove part of the anomalous SLR residual pattern observed by Urschl et al. (2008) in a Sun-fixed reference frame.

Keywords. Precise orbit determination, GPS orbits, albedo radiation

1 Introduction

Satellite Laser Ranging (SLR) to the two GPS satellites SVN35 and SVN36 that are equipped with laser retro reflectors arrays (LRA) shows a consistent bias relative to the IGS final orbits of 4 – 5 cm which has been called the GPS-SLR orbit anomaly. Urschl et al. (2005), Urschl et al. (2008), and Ziebart et al. (2007) found indications that this bias could be due to the Earth radiation impacting the satellites, an effect that is currently not yet included in the computation of most analysis centers contributing to the IGS final orbits.

Consequently there is an increasing interest in the scientific community that uses GPS for very precise applications to understand the impact that the Earth radiation has on GPS satellites orbits. There is an interest in developing models that are of sufficient fidelity to represent the characteristics of the Earth albedo effect on GPS orbits but simple enough for easy implementation and handling.

In the literature different ways to construct Earth radiation and satellite models are given. Analytical descriptions of the Earth radiation acting on artificial satellites have been developed, see Borderies and Longaretti (1990). The mathematical model used in our study was developed by Knocke et al. (1988). This model assumes that the Earth reflects and emits radiation in a purely diffuse way like a Lambertian sphere, and any specular reflection is assumed to have a small contribution to the irradiance received by a satellite. The model was constructed for latitude-dependent terrestrial surface reflectivity and emissivity but can easily be adapted to constant surface properties or to properties derived from satellite measurements. Using such a model and Earth reflectivity and emissivity satellite data from the CERES (Clouds and the Earth's Radiant Energy System, Wielicky et al., 1996) and ERBE (Earth Radiation Budget Experiment, Barkstrom,1984) missions, Ziebart et al. (2004) computed the irradiance of the Earth that reaches the GPS satellites. More sophisticated models, like the one of Martin and Rubincam (1996) used information from the ERBE mission to consider a more accurate phase function for radiation reflected on the Earth's surface than the Lambertian scattering law.

Regarding the satellite models, one can find in the literature many works dealing with the interaction of the satellites with solar radiation pressure, see, e.g., Sibthorpe (2006). These existing models can be adapted for the case of Earth radiation interacting with GPS satellites. For example Fliegel et al. (1992) and Fliegel and Gallini (1996) have made public the optical properties and dimensions of the different GPS satellite blocks, together with the physical description of the effect of radiation on the surface of the satellites. Ziebart et al. (2005) have developed sophisticated satellite models for GPS satellites. In a study based on several days of global GPS tracking data Ziebart et al. (2007) demonstrated the impact of albedo radiation, including microwave antenna power thrust, on GPS satellite orbits and showed a reduction of the GPS-SLR anomaly – the anomalous SLR range bias to IGS orbits – by 2 cm. In a different approach based on the adjustment of GPS measurements for constructing radiation pressure models, we find the empirical models developed by Springer et al. (1999) and Bar-Sever and Kuang (2004).

This study aims not at the development of the most sophisticated albedo models but at the identification of the relative importance of different albedo model constituents. The impact of nine albedo models with increasing complexity was investigated using one year of global GPS data (2007) from the IGS tracking network. These models include different Earth radiation models starting from a simple analytical representation of the Earth's visible and infrared radiation to a radiation model derived from satellite measurements, and different satellite models from simple cannon-ball to box-wing models with different surface properties. Details on the models may be found in Rodriguez-Solano (2009).

2 Models

2.1 Earth Radiation Models

The irradiance received by an artificial satellite, due to the Earth's reflected (visible) and emitted (infrared) radiation, is calculated by introducing three main assumptions: the Earth behaves like a Lambertian sphere, the radiation is reflected or emitted at its surface and there is a global conservation of energy, i.e., all the energy received by the Earth from the Sun must also leave it (as reflected or emitted radiation). To compute the irradiance received by the satellite, first the solar irradiance received by each surface element of the Earth visible by the satellite is determined. Then the irradiance received by the satellite based on that element's reflectivity and emissivity is computed. Finally, integration over all surface elements provides the irradiance at the location of the satellite.

Reflectivity and emissivity coefficients of surface elements of the Earth were obtained from monthly satellite data from NASA's CERES project (Kusterer, 2009) to construct our most sophisticated model of the Earth radiation. A simplified version of the model considers only a latitude-dependency of the coefficients obtained from CERES data. Finally, the most simple model considers a globally constant albedo of $\alpha = 0.3$ and an emissivity of $\varepsilon = 1 - \alpha$ for the entire Earth.

Assuming that the Earth's irradiance reaches the satellite just in radial direction (a reasonable approximation if the satellite's distance is much larger than the Earth's radius) allows us to perform the integration over the visible illuminated surface of the Earth analytically. This most simple albedo model is very easy to implement by one line of source code.

In total four Earth radiation models with increasing complexity were tested. E1: a model based on analytical integration over the Earth's surface assuming a constant albedo; E2: a model based on numerical integration over the Earth's surface considering constant albedo; E3: a numerical model with latitude-dependent reflectivity and emissivity of the Earth's surface elements; E4: a numerical model adopting time-dependent reflectivity and emissivity from CERES satellite data.

2.2 GPS Satellite Models

Different satellite models were constructed to describe the interaction with the radiation coming from the Earth. These models are mainly based on the work of Fliegel et al. (1992) and Fliegel and Gallini (1996) that provide dimensions and reflectivity ν and specularity μ for the surface elements of GPS satellites. Since the irradiance consists of a visible and an infrared component, the optical properties of the surfaces must be known also for the infrared. For this study the infrared properties were assumed to be $\nu = 0.2$ and $\mu = 0.5$ for all types of satellites and surfaces. This choice is justified by the necessity of the satellites to dissipate heat into space, the surfaces thus having a high emissivity for thermal radiation. The infrared specularity was adopted based on the assumption that the surfaces reflect equally in a diffuse and in a specular way. These assumptions were necessary since the properties reported by Fliegel et al. (1992) and Fliegel and Gallini (1996) are just for radiation in the visible part of the spectrum.

The simplest adopted model was a cannon-ball type satellite model assuming constant cross-section and average optical properties. A simple analytical box-wing model was constructed adopting nominal attitude with the satellite's solar panels oriented perpendicular to the Sun and the navigation antenna pointing to the center of the Earth. The acceleration for this analytical box-wing model assumes that irradiance from the Earth has only a radial component. Finally, a box-wing model was constructed where the irradiance was not only considered to be radial but coming from the full disc of the Earth seen by the satellite. This was called the numerical box-wing model, since no analytical expressions can be obtained.

To summarize, three satellite models were tested: S1: the cannon-ball model; S2: the analytical box-wing model considering only radial albedo irradiance; S3: the numerical box-wing model. We also distinguish between satellite models with average optical properties and properties equal to the published block-specific values (B). Finally we took into account the thrust of the navigation antenna (A) as reported by Ziebart et al. (2004), which gives an extra acceleration in the radial direction, comparable in magnitude to the effect of Earth radiation.

3 Results

A number of models were available for tests. The developed Earth radiation and satellite models were combined to obtain a sequence of models with increasing complexity, see Table 1. No a priori direct solar radiation pressure model was used for most experiments but five solar radiation pressure parameters were estimated for each orbit determination step. Nevertheless, tests including the ROCK models (see Fliegel et al., 1992, and Fliegel and Gallini, 1996) were done with the most sophisticated albedo model (ALB-9) as well as – for comparison – without any albedo model (ALB-R). Finally, tests including antenna thrust were executed (ALB-8 and ALB-9).

Table 1. Selection of Earth radiation and satellite models

Test #	Abbreviation	Complexity change
ALB-R	E0-S0-R	No albedo, ROCK a priori
ALB-0	E0-S0	No albedo, no ROCK a priori
ALB-1	E1-S1	Simplest albedo models
ALB-2	E2-S1	Num. (const. albedo) model
ALB-3	E2-S2	Box-wing analytical model
ALB-4	E3-S2	Latitude-dependent albedo
ALB-5	E4-S2	Incorporating CERES data
ALB-6	E4-S2-B	Block-specific properties
ALB-7	E4-S3-B	Box-wing numerical model
ALB-8	E4-S3-BA	Including antenna thrust
ALB-9	E4-S3-BA-R	With a priori ROCK model

3.1 Acceleration on the Satellites

Figure 1 shows the radial, along track and cross track accelerations for the models ALB-1 to ALB-8 as a function of the longitude along the orbit, measured from the sub-solar point. The angle $\Delta u = 0°$ thus corresponds to the point along the orbit that is closest to the direction to the Sun. The figure covers one revolution of SVN36 for an elevation of the Sun above the orbital plane of $\beta = 20.2°$.

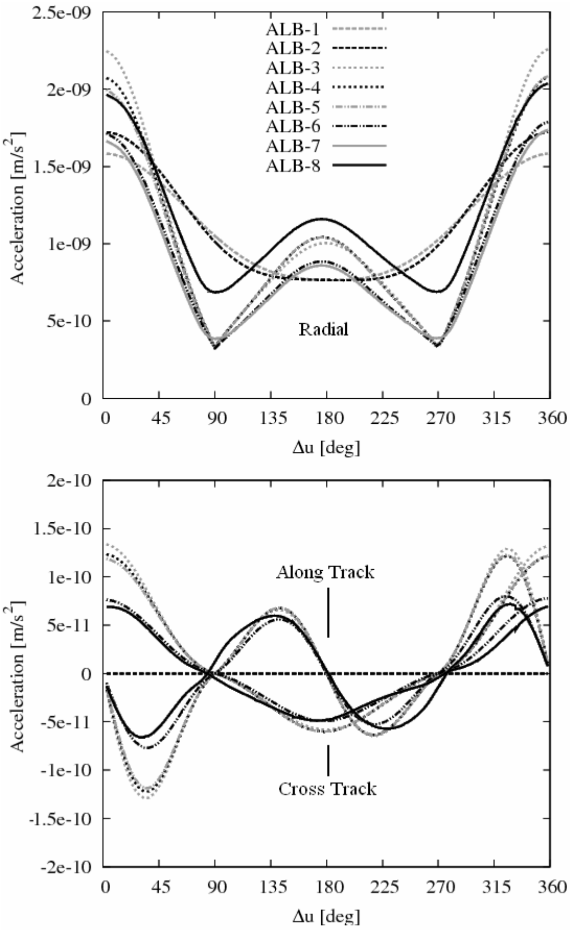

Fig. 1 Acceleration for selected models (β=20.2°), SVN36.

For the cannon-ball models ALB-1 and ALB-2 the radial acceleration is simply proportional to the albedo irradiance. The maximum is reached with the satellite above the side of the Earth that is illuminated by the Sun while the minimum is found above the night side of the Earth. Adding the solar panels to the satellite model (ALB-3) changes the picture drastically as the satellite's cross section as seen from the Earth varies much during one satellite revolution. The minima are reached when the geocentric directions to the satellite and to the Sun are at a right angle, where exposure of the solar panels to Earth radiation is minimal. A secondary maximum is found above the night side of the Earth where the solar panels are maximally exposed to the Earth's infrared radiation.

Further improvement of the Earth radiation models including latitude-dependent albedo (ALB-4) or time- and position-dependent reflectivity and emissivity from CERES data (ALB-5) has no significant impact on the acceleration. The use of block-specific optical properties (ALB-6) has a noticeable impact while the use of the numerical box-wing model (ALB-7) changes the curves just around $\Delta u = 90°$ and $\Delta u = 270°$, eliminating the sharp cusps of the analytical box-wing model. Finally, as expected, the antenna thrust (ALB-8) causes a radial offset of the acceleration.

For the along track and cross track components of the acceleration we can observe differences between models, too. The albedo acceleration in these two components is, however, an order of magnitude smaller than in the radial acceleration. Finally, note that the magnitude of the total acceleration is around 1×10^{-9} ms^{-2} and thus of the same order as the Y-bias effect, see, e.g., Springer et al. (1999).

3.2 Impact on the Orbits

After evaluating the acceleration induced by albedo radiation for a single orbital revolution of GPS satellites, the impact on orbits estimated using global GPS tracking data was studied. The processing scheme of the CODE (Center for Orbit Determination in Europe) was employed with the Bernese GPS Software (Dach et al., 2007) to analyze one year (Jan. to Dez. 2007) of GPS tracking data of about 190 globally distributed IGS stations (Dow et al., 2009). In fact, cleaned single difference files with fixed ambiguities from the CODE contribution to the IGS reprocessing (Steigenberger et al., 2009) were used to determine daily GPS orbits for each of the described albedo models estimating six orbital parameters and five empirical solar radiation pressure parameters as well as one stochastic pulse in the middle of the arc. For each run one of the albedo models listed in Table 1 was implemented.

The orbit differences between successive solutions are appropriate to identify the factors that are essential for a proper modeling of the albedo effect for GPS satellites. Table 2 lists differences between orbits computed with different albedo models in radial, along track, and cross track directions in millimeters for SVN36. Mean and standard deviation of the differences were computed for one year.

Table 2. Mean and standard deviation of orbit differences for different albedo models over one year for SVN36 in mm.

Difference	Radial	Along track	Cross track
ALB-1 – ALB-0	-16.4 ± 1.6	0.6 ± 2.3	0.2 ± 0.9
ALB-2 – ALB-1	0.4 ± 1.0	0.5 ± 2.1	0.0 ± 0.6
ALB-3 – ALB-2	1.5 ± 3.6	3.8 ± 5.5	-0.0 ± 5.2
ALB-4 – ALB-3	0.1 ± 0.8	-0.4 ± 2.2	0.0 ± 0.6
ALB-5 – ALB-4	-0.9 ± 1.2	-0.0 ± 2.5	-0.0 ± 1.2
ALB-6 – ALB-5	2.0 ± 1.1	-1.0 ± 2.4	-0.0 ± 1.1
ALB-7 – ALB-6	0.3 ± 0.8	0.1 ± 2.0	0.0 ± 0.3
ALB-8 – ALB-7	-4.7 ± 0.7	-0.1 ± 2.0	0.0 ± 0.1

Figure 2 shows the differences between the orbits based on the box-wing model with CERES Earth radiation model (ALB-8) and orbits determined with no albedo model (ALB-0) for SVN36 for the entire year 2007.

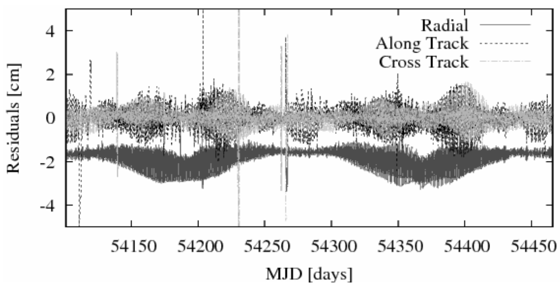

Fig. 2 Orbit differences for models ALB-8 – ALB-0 for satellite SVN36 for the year 2007.

As one prominent feature we observe the radial offset (ALB-1 – ALB-0) that is common to all albedo models with respect to orbits computed without albedo model. As already noted by Ziebart et al. (2007) this effect reduces the aberrant SLR-GPS anomaly by 1–2 cm. The reason is that GPS measurements, being essentially angular measurements due to required clock synchronization, mainly determine the mean motion of the satellite. As a matter of fact, a constant positive radial acceleration (equivalent to a reduction of GM) decreases the orbital radius according to Kepler's third law.

The second important feature are the increased differences per revolution in all three components between orbits determined with a cannon-ball (ALB-2) and with a box-wing model (ALB-3) exhibiting themselves by a significantly increased standard deviation in Table 2 and a temporally correlated pattern displayed in Figure 2 that is mainly due to the box-wing model. As already observed for the accelerations, the box-wing satellite model represents an essential key element of any albedo model. Refinement of the Earth radiation model from constant albedo (ALB-3) to latitude-dependent albedo (ALB-4) or to CERES derived surface properties (ALB-5), on the other hand, does not have an important impact on the orbits. Obviously GPS satellites are high enough such that varying surface albedo is averaged out over the visible illuminated surface area of the Earth.

We may, finally, represent the radial orbit differences in a Sun-fixed reference frame as a function of longitude Δu along the orbit, measured from the sub-solar point and the elevation β of the Sun above the orbital plane, see Figure 3 for the same example represented in Figure 2. We observe a significant radial deformation of the orbits as a function of satellite position with respect to the position of the Sun that resembles the pattern observed by Urschl et al. (2008) for SLR residuals of GPS satellites on the night-time side of the Earth. The amplitude of the effect is, however, only about 2 mm compared to the 5 cm effect found by Urschl et al. (2008). Note, however, that such a pattern is not present for a cannon-ball satellite model.

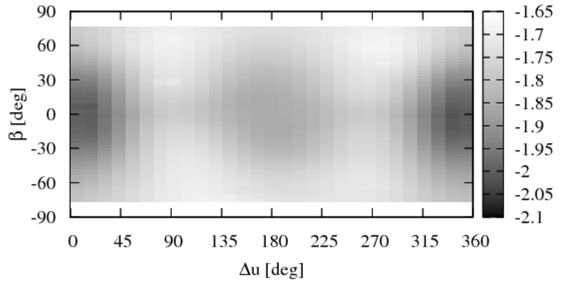

Fig. 3 Radial residuals (in cm) between the models ALB-8 and ALB-0 for SVN36 in a Sun-fixed reference frame.

Finally, an external validation of the different orbit solutions can be accomplished by performing an SLR validation for the satellites SVN35 and SVN36 that are equipped with LRAs. Results in form of mean, root mean square (RMS) and standard deviation of SLR residuals over the entire year 2007 are presented in Table 3.

Table 3 SLR residuals for SVN35 / SVN36

Test #	Mean [cm]	RMS [cm]	Sigma [cm]
ALB-R	-3.24 / -3.45	4.83 / 5.02	3.58 / 3.64
ALB-0	-2.36 / -2.61	3.62 / 4.16	2.75 / 3.24
ALB-1	-0.80 / -1.07	2.86 / 3.42	2.75 / 3.25
ALB-2	-0.92 / -1.13	2.95 / 3.48	2.81 / 3.29
ALB-3	-0.99 / -1.38	2.91 / 3.49	2.73 / 3.21
ALB-4	-0.98 / -1.35	2.90 / 3.49	2.73 / 3.22
ALB-5	-0.92 / -1.29	2.89 / 3.48	2.74 / 3.23
ALB-6	-1.12 / -1.46	2.96 / 3.55	2.74 / 3.23
ALB-7	-1.15 / -1.48	2.97 / 3.55	2.74 / 3.23
ALB-8	-0.68 / -1.01	2.82 / 3.38	2.74 / 3.23
ALB-9	-1.51 / -1.84	3.37 / 4.02	3.02 / 3.57

The results confirm what was already found from Table 2. The solutions with albedo (ALB-8 resp. ALB-9) show a radial bias with respect to solutions without albedo (ALB-0 resp. ALB-R) that is about 16 mm reduced. About 5 mm thereof are due to the antenna thrust. It is interesting to note that the solutions involving the ROCK a priori solar radiation model (ALB-R and ALB-9) show a larger bias as well as a larger standard deviation for both satellites. This is an indication that there is a problem with the ROCK model for Block II/IIA satellites, a conclusion that requires further investigation. A small change in bias is observed when implementing block-specific instead of typical optical properties.

As expected Table 3 shows that the introduction of a box-wing model slightly reduces the standard deviation of the residuals while no significant change is observed when changing the Earth radiation model. Even the simplest analytical model (ALB-1) behaves astonishingly well in terms of standard deviation of SLR residuals. This is probably an indication that a significant fraction of albedo (apart from a bias) can be absorbed by the estimated empirical and stochastic parameters.

4 Conclusions

The acceleration caused by Earth radiation pressure has a non-negligible effect on the orbits of GPS satellites. The acceleration has a similar order of magnitude as the so-called Y-bias. The effect of this acceleration on the GPS orbits is mainly a mean reduction of the orbit radius by about 1 cm. The radial orbit differences obtained by considering an albedo model based on a box-wing satellite model show a prominent dependency of the satellite's position with respect to the direction of the Sun. The corresponding pattern has similarities to the patterns found by Urschl et al. (2008) in SLR residuals for SVN35 and SVN36. The size of the effect is, however more than a magnitude smaller. Nevertheless, albedo may have the potential to explain part of this behavior. The results of the study, based on one year of GPS tracking data, clearly indicate – consistently with the findings of Ziebart et al. (2007) – that albedo radiation as well as antenna thrust should be considered for high precision GPS orbit determination. Mandatory is the inclusion of the solar panels into the satellite model. The details of the Earth radiation seem, however, to have a minor effect at GPS satellite altitude.

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