Non-conservative GNSS orbit modeling and its impact on geodetic time series

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1. INTRODUCTION

GNSS is a vital space technique for reference system realization. However navigation satellite orbits do not contribute to the definition of the datum of the International Terrestrial Reference Frame. The reasons reside in the sensitivity of the large satellite structures to direct and indirect solar radiation pressure.

GNSS orbit modeling deficiencies cause peculiar patterns observed in Satellite Laser Ranging (SLR) residuals, which were first noted by Urschl et al. (2008) and are presented in Fig. 1. In addition, orbit related frequencies were identified in geodetic time series such as apparent geocenter motion by Hugentobler et al. (2006) and station displacements derived from GNSS tracking data by Ray et al. (2008), shown in Fig. 2 and Fig. 3. Particularly an anomalous frequency of 1.04 cpy was found, corresponding to a period of about 350 days which is very similar to the "GPS draconitic year", the repeat period of the Sun with respect to the satellite constellation, see also Fig. 5.

A probable candidate for radiation pressure mismodeling is related to Earth albedo radiation consisting of visible reflected light and infrared emitted radiation, an effect that is currently not yet included in the computation of most analysis center contributions to the IGS final orbits. Furthermore, as albedo radiation depends on the position of the Sun with respect to the satellite, it is also a good candidate for causing the observed anomalous frequency in the geodetic time series.

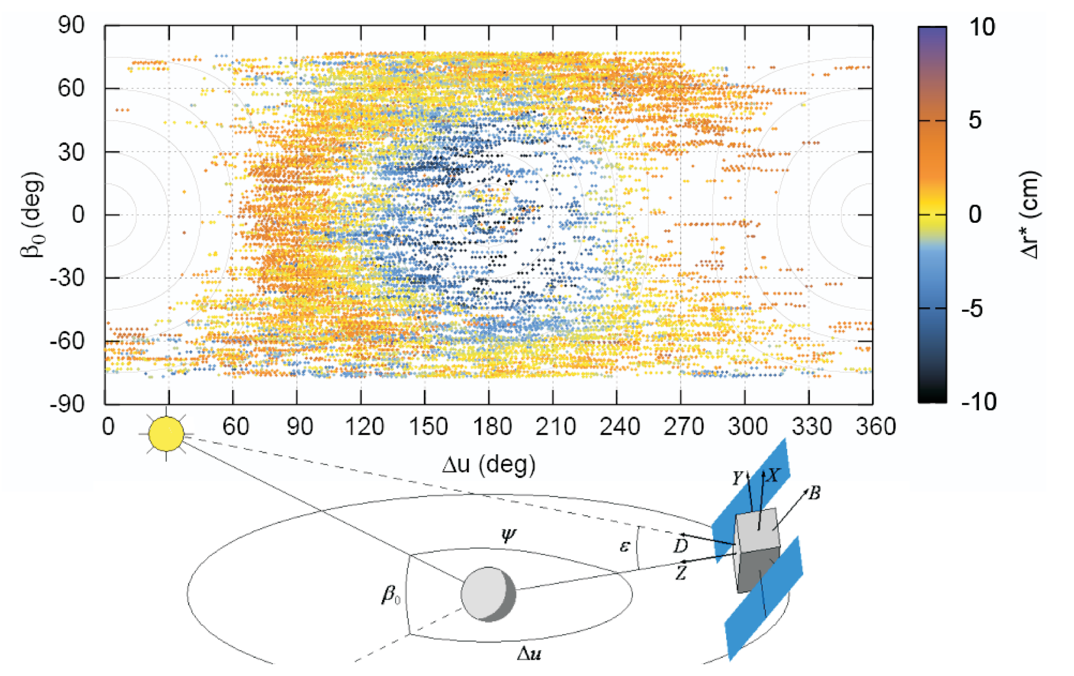

Fig. 1. SLR range residuals minus mean value for the GPS satellites SVN35 and SVN36 derived from CODE final orbits. Residuals plotted in a Sun-fixed reference frame, Urschl et al. (2008). The angle ψ satellite-Earth-Sun is related to the orientation of the Sun with respect to the satellite and its orbit by $\cos\psi = \cos\beta_0 \cos\Delta u$.

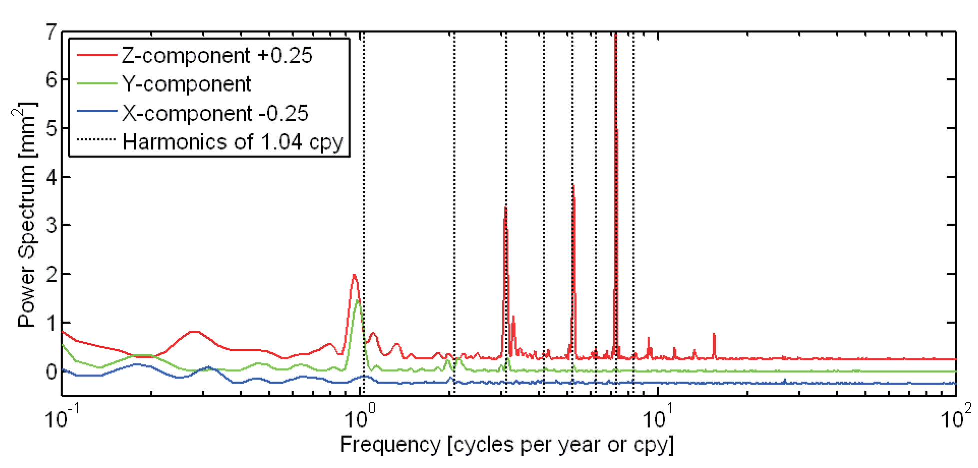

Fig. 2. Power spectrum for daily geocenter coordinates estimated from 2000.0 to 2009.0.

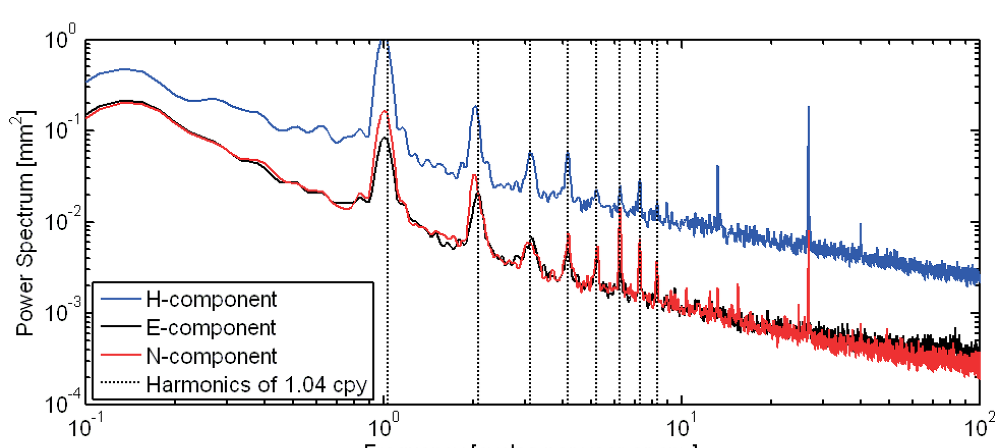

Fig. 3. Power spectrum for GPS daily station position estimated from 2000.0 to 2009.0. More than 200 IGS sites with at least one year of data.

2. ALBEDO MODELING

The irradiance received by an artificial satellite, due to the Earth's reflected (visible) and emitted (infrared) radiation, is calculated by:

1. Determination of solar irradiance received by each surface element of the Earth.
2. Computation of the irradiance received by the satellite based on the reflectivity and emissivity coefficients (from NASA's CERES project) of the surface element.
3. Integration of irradiance over all surface elements visible to the satellite.

The irradiance at the satellite position is then used to compute the acceleration acting on the satellite by using:

1. Box-wing model based on Fliegel et al. (1992).
2. Nominal attitude, i.e., navigation antennas always pointing to the Earth and solar panels always pointing to the Sun.
3. Block specific dimensions and optical properties.
4. Thrust due to navigation antennas.

The acceleration acting on a GPS satellite is shown in Fig. 4 as a function of the satellite position along the orbit, however Earth radiation and satellite models primarily depend on the angle ψ shown in Fig. 1. More details of the models can be found in Rodriguez-Solano et al. (2010).

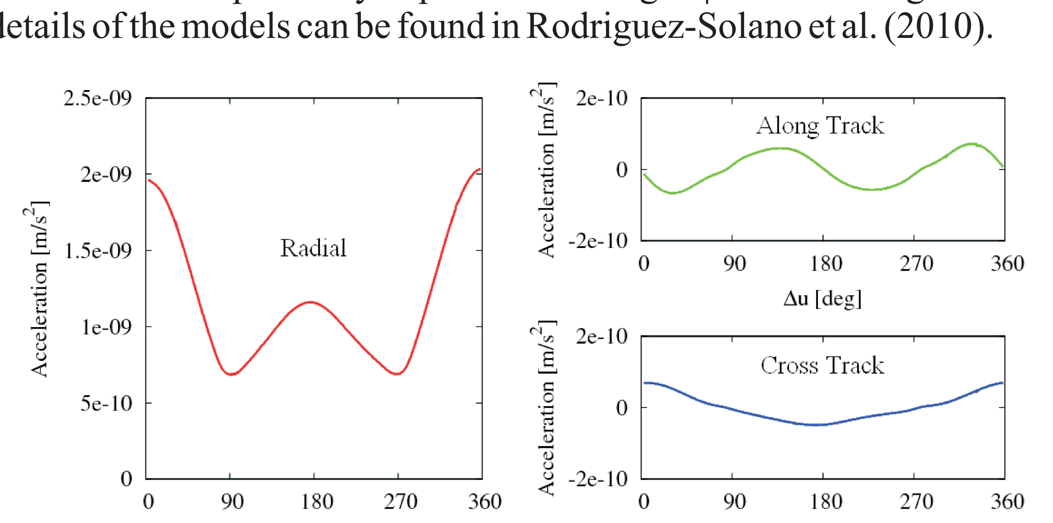

Fig. 4. On-orbit acceleration acting on the GPS satellite SVN36 for β_0=20.2° due to albedo radiation. Note that for 90°<Δu<270° the satellite mainly sees the non-illuminated part of the Earth.

3. IMPACT ON GPS SATELLITE ORBITS

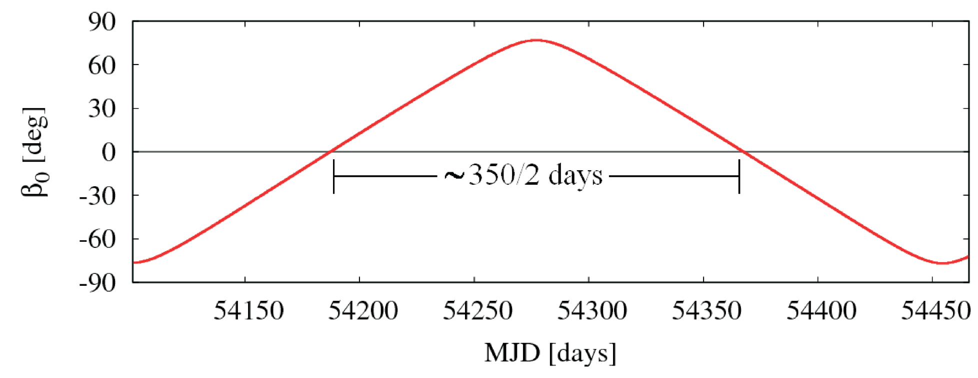

Fig. 5. Sun elevation angle (β_0) above the orbital plane for SVN36 and year 2007.

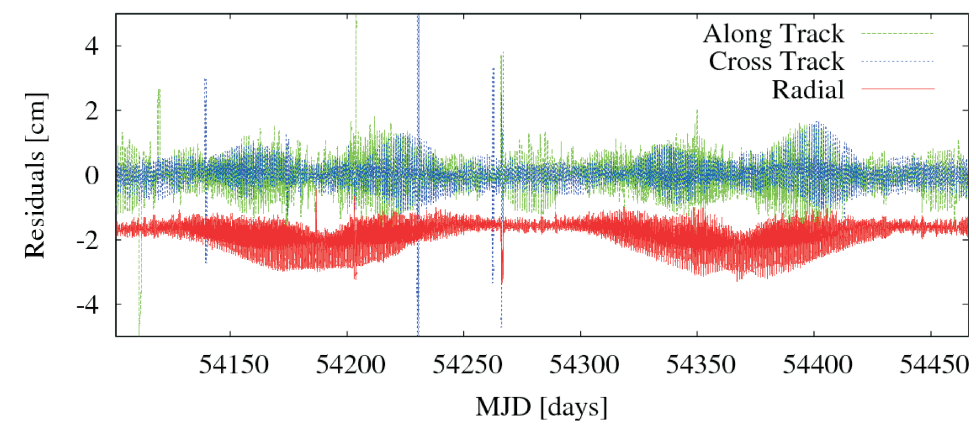

Fig. 6. Residuals of GPS orbits (albedo minus no albedo) for SVN36 and year 2007.

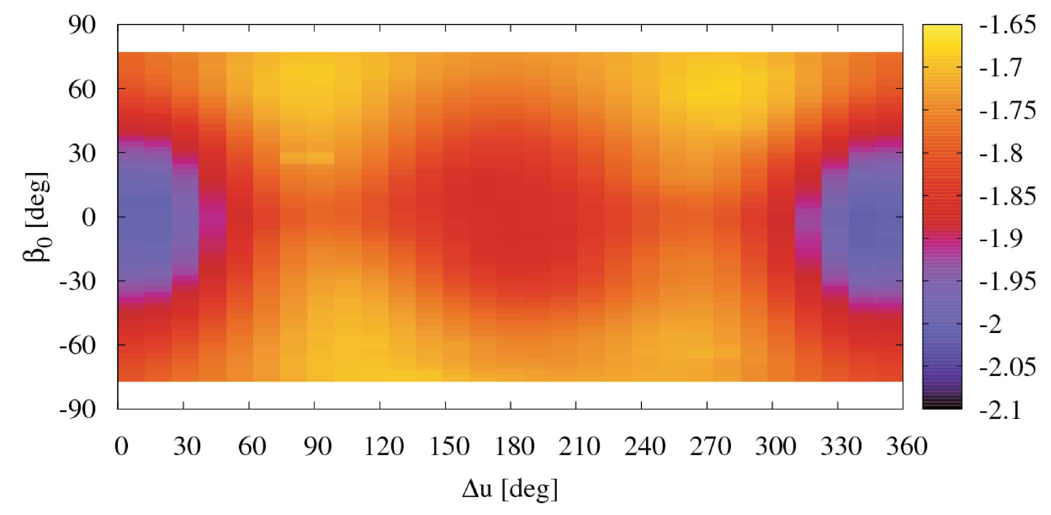

Fig. 7. Radial residuals in cm of GPS orbits (albedo minus no albedo) for SVN36 and year 2007 in a Sun-fixed reference frame.

The acceleration induced by albedo radiation was introduced in the estimation of GPS satellite orbits, by employing the processing scheme of the CODE (Center for Orbit Determination in Europe) with the Bernese GPS Software, see for example Steigenberger et al. (2010). In total one year (2007) of GPS tracking data from about 190 IGS stations was analyzed.

Fig. 6 shows the differences between the orbits that include albedo radiation and orbits determined with no albedo for SVN36. As one prominent feature one can observe the radial offset between the orbits. As already noted by Ziebart et al. (2007) this effect reduces the aberrant SLR - GPS anomaly by 1-2 cm. The reason for this radial reduction of the orbits 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.

Note also the dependency of the radial orbit residuals (Fig. 6) with respect to the Sun elevation angle above the orbital plane (β_0) plotted in Fig. 5. Consequently this kind of perturbation should have a main repeat period close to half of the "GPS draconitic year", that is about 350/2 days.

The radial orbit differences are plotted in a Sun-fixed reference frame in Fig. 7. We observe a significant radial deformation of the orbits as a function of satellite position with respect to the one of the Sun that resembles the pattern observed by Urschl et al. (2008) in Fig. 1 for SLR residuals 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 in Fig. 1. Note, however, that such a pattern is not present for a simple satellite model without solar panels, where we would see a minimum in the radial acceleration for 90°<Δu<270° instead of a local maximum in Fig. 4.

4. IMPACT ON GEODETIC TIME SERIES

The impact of the albedo radiation on the geodetic time series was studied by computing the geocenter and global station coordinates for 9 years of GPS tracking data (2000.0 to 2009.0), as it is done by CODE.

Although the orbit residuals have a repeat period close to half of the "GPS draconitic year", there is no significant difference in the spectra of the geocenter by including this type of acceleration. As shown in Fig. 8 the impact of albedo in the geocenter position is of similar magnitude for the X, Y and Z components, while the geocenter power spectrum at the orbit related frequencies (Fig. 2) is much higher for the Z component.

In the case of ground station positions we find a more significant effect from albedo radiation, as shown in Fig. 9, at the submillimeter level. Specially the North component is affected and its variability has a clear pattern over one year, with a visible main frequency of around 6 cycles per year. Therefore we find a reduction in the power spectrum of the station coordinates mostly in its 6th peak as one can note in Fig. 10. In the East and Height components the pattern is similar but of lower magnitude and the impact in the spectrum is consequently less significant.

The reason for the small impact on the power spectra could be that there is still a non-modeled effect on the GPS orbits, which is larger than the albedo radiation and which also has a periodicity of 350 days. A probable candidate for orbit mismodelling is then the direct solar radiation pressure. On the other hand, Ray et al. (2008) suggested that the anomalous frequency observed in the GPS time series could be caused by near-field multipath.

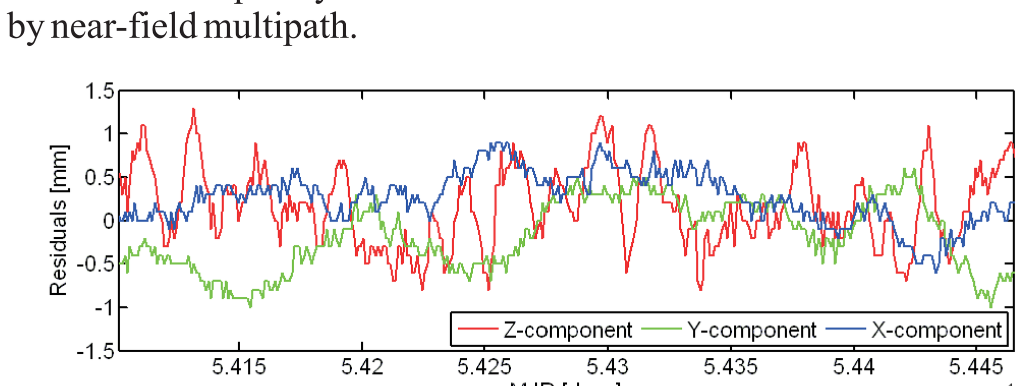

Fig. 8. Change of geocenter position due to albedo, year 2007.

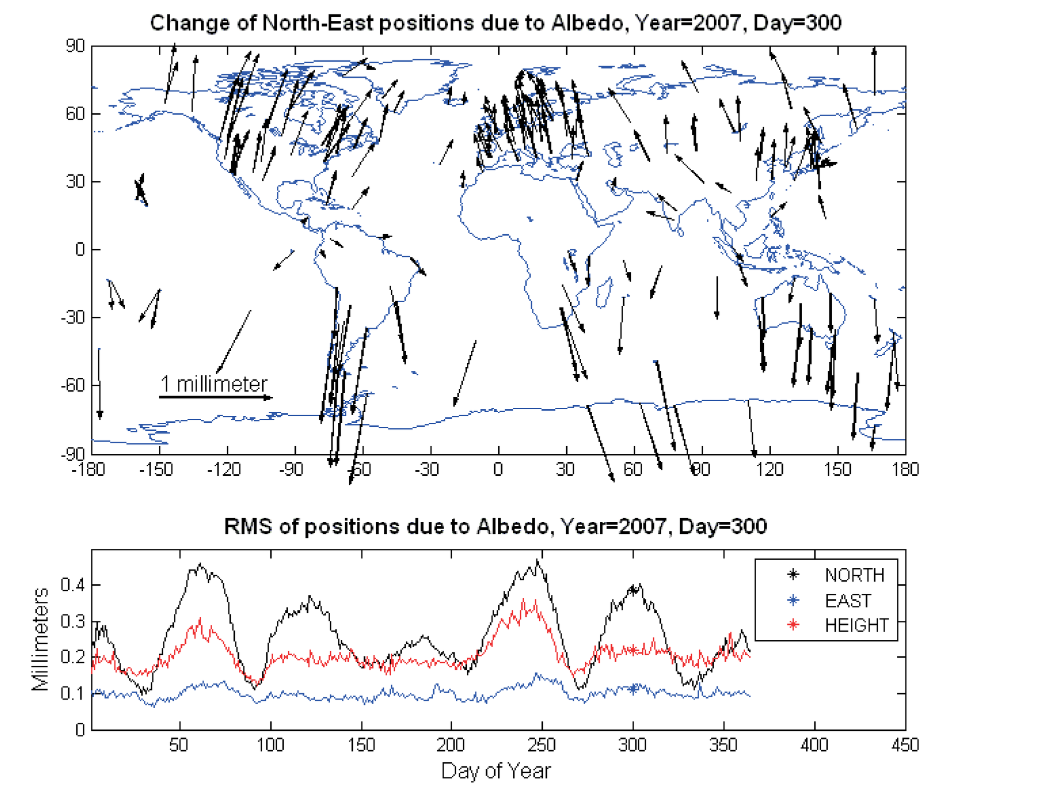

Fig. 9. Change of daily station positions (North and East) due to albedo for day 300 of 2007 and their respective RMS for the complete year.

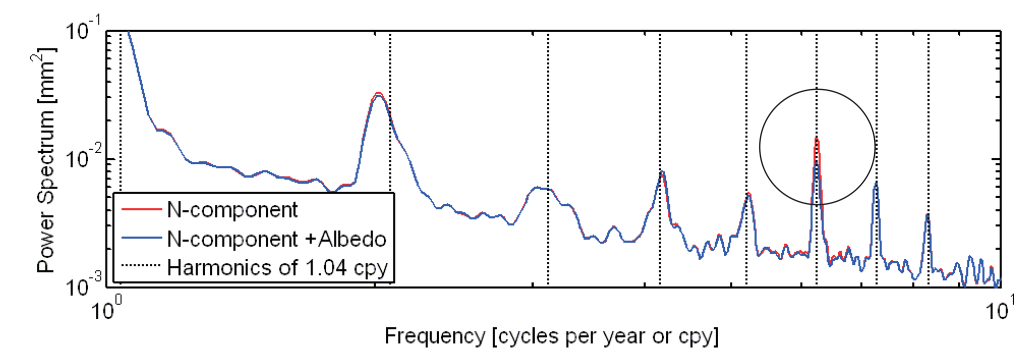

Fig. 10. North component power spectrum, with and without albedo.

5. SOLAR RADIATION PRESSURE

To compensate the effect of solar radiation on GPS satellites, we have estimated 5 empirical parameters per satellite and per day. These parameters are: three constants in the D, Y and B directions (Fig. 1) and two periodic (once per revolution) in the B direction. This is the ECOM model (Beutler et al., 1994). Moreover no a priori model was used. Previously the ROCK models (Fliegel et al., 1992), based on detailed structure and optical properties of the satellites, were used as a priori information. Nowadays no model or purely empirical models are used due to the lower performance of the ROCK models.

From the 9 years reprocessed data without albedo, the 5 empirical parameters were extracted and the average computed as a function of β_0 and for all satellites of the same type. The obtained acceleration is compared with the ROCK model for Block IIA in Fig. 11. Note that the ECOM model does not adjust to the Δu dependency of the ROCK model.

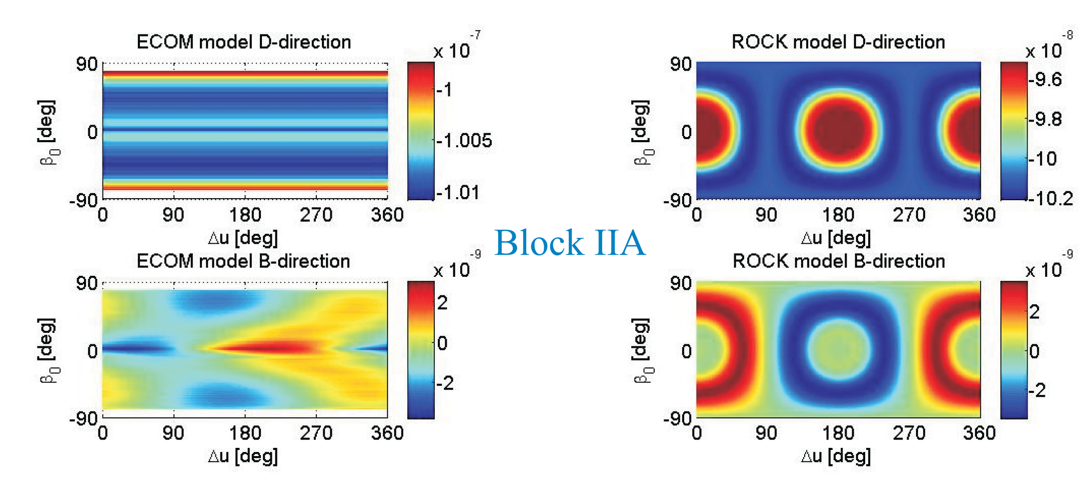

Fig. 11. Comparison of acceleration in m/s^2 between ECOM and ROCK.

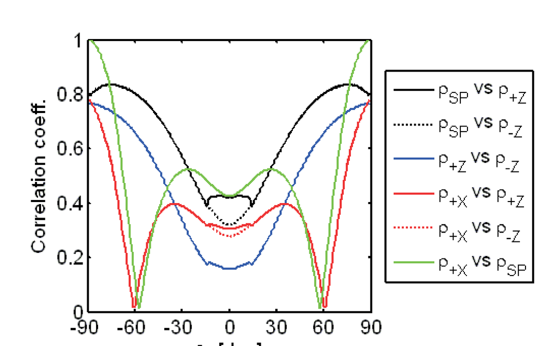

Fig. 12. Correlation between the fraction of reflected photons (ρ) of the surfaces of a box-wing model. SP: solar panels, see also Fig. 1.

In this context a box-wing model capable of adjusting to the GPS tracking data by considering the shape of the satellite and the physical interaction between the surfaces and the radiation is being investigated. In Fig. 12 the correlation between the fraction of reflected photons (ρ) at different surfaces as a function of β_0 is shown, assuming known areas for the four main satellite surfaces.

6. CONCLUSIONS

The acceleration caused by albedo radiation has a non-negligible effect on the orbits of GPS satellites, this effect is mainly a mean reduction of the orbit radius by about 1 - 2 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 (Fig. 7) has similarities to the pattern found by Urschl et al. (2008), see Fig. 1. The size of the effect is, however more than a magnitude smaller. Nevertheless, albedo may have the potential to explain a part of this behavior.

The results of our study 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.

The impact of Earth radiation pressure on the geocenter and ground station positions is on the submillimeter level. The largest effect is found for the North component of the ground stations, presenting a periodic pattern which reduces mainly the 6th peak of the North power spectrum.

However, the main peaks of the power spectrum of geodetic time series at the anomalous frequencies (harmonics of 1.04 cpy) computed from GPS tracking data remain yet without an explanation. One of the possible candidates that could reduce this anomaly is related to the solar radiation pressure. For further investigations a box-wing model with adjustable optical surface properties is currently being developed by our research team at TUM.

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