# GRACE AS GEODETIC PRECISION SPACE LABORATORY


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## 1 – GRACE PENUMBRA TRANSITIONS

Transitions of the GRACE satellites through Earth penumbra offer a unique opportunity to study the changing accelerations due to solar radiation pressure. This includes the strong effects of **refraction and absorption** of solar light reaching the satellite along rays through the Earth atmosphere. Penumbra transitions also allow validating **advanced solar radiation pressure modeling**. They stand out as very distinct and sharp features in the accelerometer signals along all three axes (Fig. 1), because the other contributions to non-gravitational accelerations – in particular the residual air drag – tend to change more slowly.

We compare accelerometer time series for typical transitions with radiation modeling based on the approach of Vokrouhlicky et al. (1993). We model refraction due to a polytropic atmosphere for single rays originating from surface elements of the solar disk. Numerical integration leads to the total solar radiation field acting on the satellite surfaces. We use this to compute radiation pressure accelerations for a 8 surface satellite model with known reflectivity coefficients. Fig. 1 shows the total acceleration for all surfaces.

Results match the **timing and shape** of observed acceleration change well, much better than with models which do not account for the atmosphere. In Level-1B ACC1B acceleration products (35mHz low-pass filtered) the penumbra signals are slightly smoothed. We also compare with the sharper acceleration changes derived from 10 Hz Level-1A data (applying heater switching spike corrections). The match demonstrates the good quality of radiation modeling. It also helps to validate the accelerometer data, e.g., it allows a rough validation of the instrument scale factors. However, the model seems to slightly overestimate the total acceleration change. Results could be further improved by adjusting the given surface reflectivity coefficients.

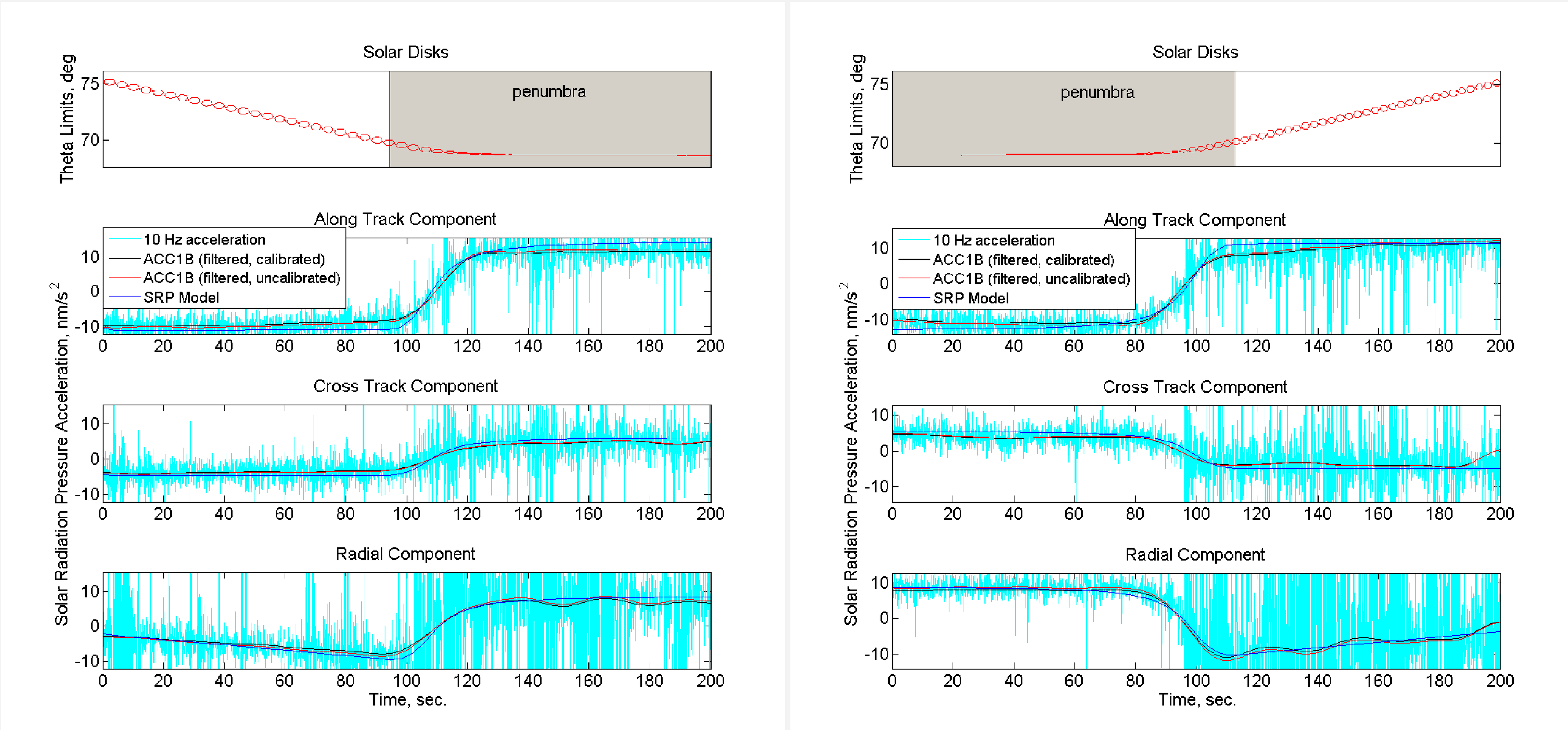


Fig. 1: Solar radiation pressure acceleration during shadow entry (left) and exit (right) of GRACE B on Jan 2nd 2008. A comparison of solar radiation pressure model, 10Hz accelerometer data after heater switching spike correction and the Level-1B 1Hz accelerometer data is shown. The top panel shows the size of the solar disc as seen from the satellite

## 2 – THE COMPLEXITY OF GRACE POINTING VARIATIONS

How accurate the two GRACE satellites point to each other varies in time with very distinct features related to the autonomous onboard attitude and orbit control system (AOCS). Some of these features have consequences for mission operation and science results. The AOCS keeps roll-pitch-yaw variations with respect to the line of sight to the other satellite - obtained from two star cameras and orbit data - within deadbands (currently max. 4.8 mrad or ~1000 arcsec). This is achieved using magnetic torquers and cold gas thrusters if needed. The applied control strategy leads to residual rotation in characteristic multiples of the orbital frequency with periods around 200 seconds early in the mission and around 300 seconds (particularly in pitch – Fig. 2) after changes in control parameters in 2004 (G-A) and 2005 (G-B). Other features include pointing oscillations after simultaneous blinding of both cameras by sun and moon, and jumps when the number of star cameras used for attitude post-processing changes as well as when switches of the AOCS primary star camera occur. The quality and smoothness of control (and also gas consumption) depends on which of the two cameras is used by the AOCS.

The observed pointing variations contain both real variations and errors of star camera measurement and calibration. Errors coming from the different attitude information provided by the two star cameras are known to reach up to 1 mrad but are not well studied so far. Re-analysis of calibration parameters for the star cameras and the K-band antenna is currently ongoing in the GRACE Science Data System.

Long and continuous attitude and pointing time series as in Fig. 2 help to understand the **complexity and dynamics** of the mission. The typical features offer opportunities to validate the overall sensor system. The **corrections** currently used for gravity field processing do not fully remove the contributions of pointing variations to the inter-satellite ranging observable. This leads to error contributions in the gravity field solutions (Horwath et al.,2011).

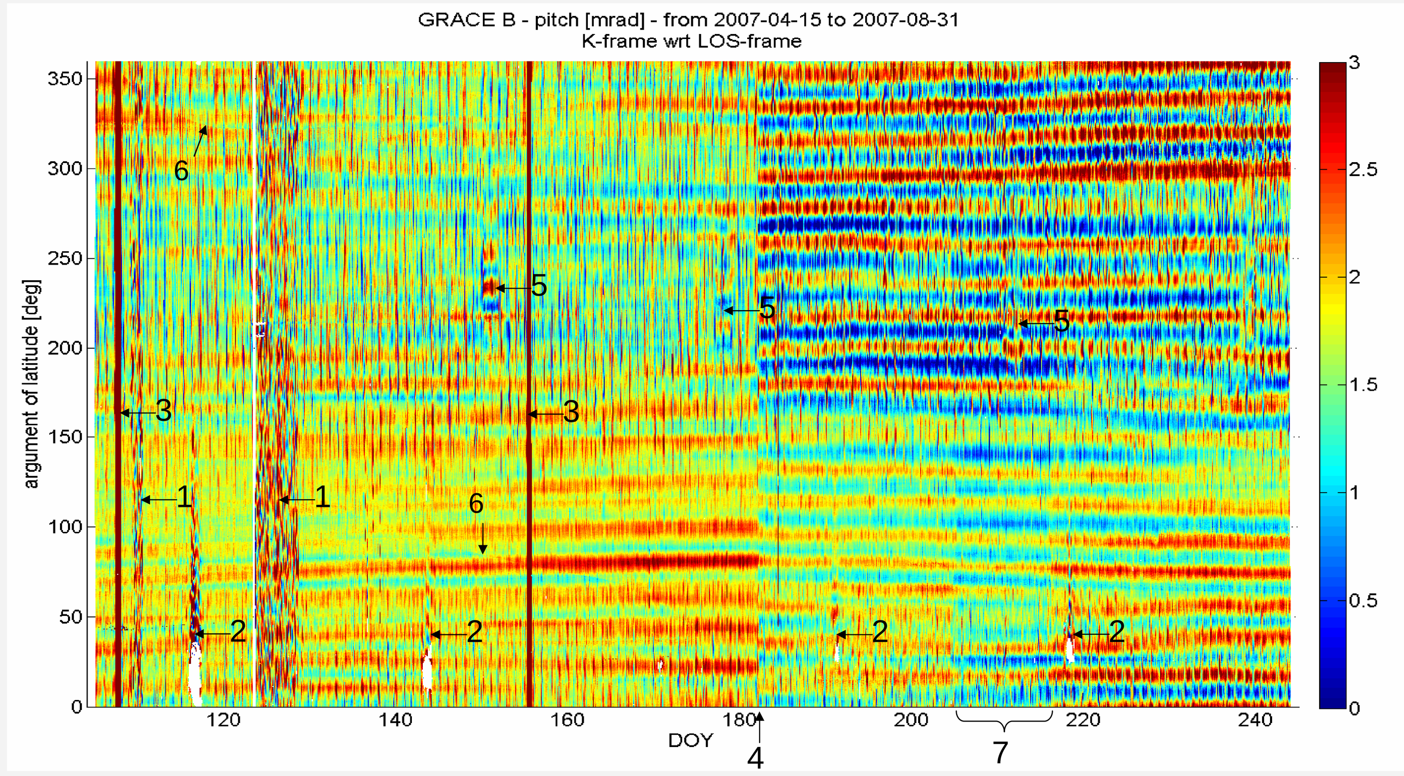


Fig. 2: Typical features in inter-satellite pointing variations, here G-B pitch Apr-Aug 2007: 1 – star camera and IMU simultaneous operation; 2 – simultaneous Sun and Moon intrusions in both star camera heads; 3 – center of mass calibration maneuver; 4 – AOCS primary star camera switch (β' = 0); 5 – AOCS primary star camera switch due to moon intrusions into FoV; 6 – switch from dual to single star camera mode (SCA1B); 7 – disabling of suplemental heater lines, SCA/ACC alignment changed (QSA)

## 3 – GRACE "TWANGS"

On GRACE, 'twangs' are damped acceleration oscillations lasting several seconds which are strongest in the radial accelerometer component of both GRACE satellites. Analysis have revealed a strong geographical distribution (e.g. magnetic field, fig. 3) of the twangs, whereas this distribution is furthermore depending on seasonal and local time variations as well as on insolation angle onto satellite planes. The distribution can furthermore be broken down according to the energy and possibly also oscillating behaviour of the twang signal. We are currently building tools to extract and classify twang types according to oscillation shape and energy. Analysis about twangs may provide opportunities to learn about the interactions of spacecrafts in GRACE altitude with their atmospheric and magnetic environment.

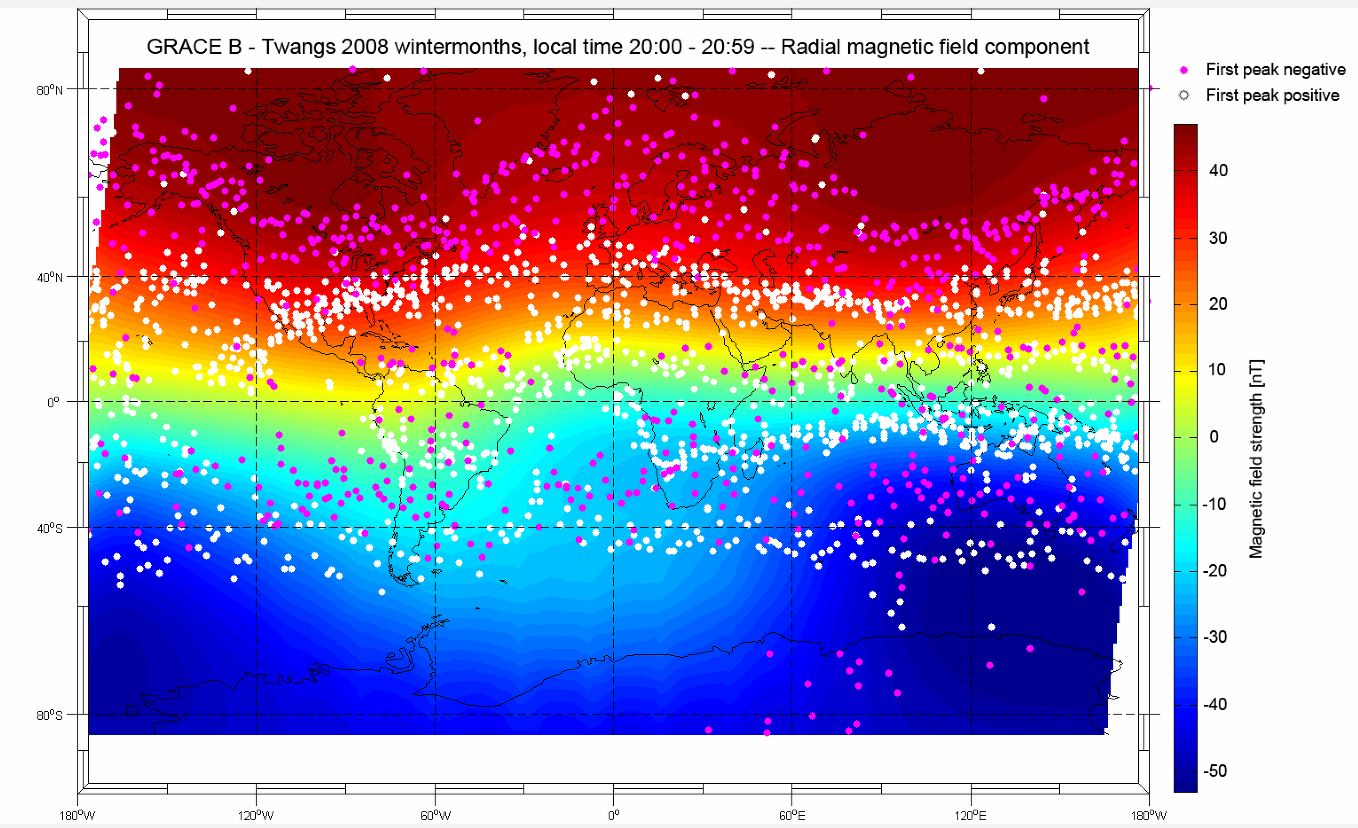


Fig. 3: Global distribution of twangs in accelerometer data of GRACE B in wintermonths of 2008 at a local time between hours 18 and 19 and the radial component of the Earth magnetic field (Peterseim et al.,2010)

## 4 – HIGH FREQUENCY CONTENT OF ACCELEROMETER OBSERVATIONS

The accuracy of GRACE data is often assumed to be homogeneous. For accelero-meter observations, this does not match reality well. The high frequency content above 35 mHz (Fig. 4) is strongly variable. Most or all of it is probably related to the satellite platform and its environment. Some effects are related to solar radiation hitting, e.g., the nadir side of the spacecraft. Others occur at certain locations along the orbit. Again others depend on local time. Further analysis is needed to constrain possible sources.

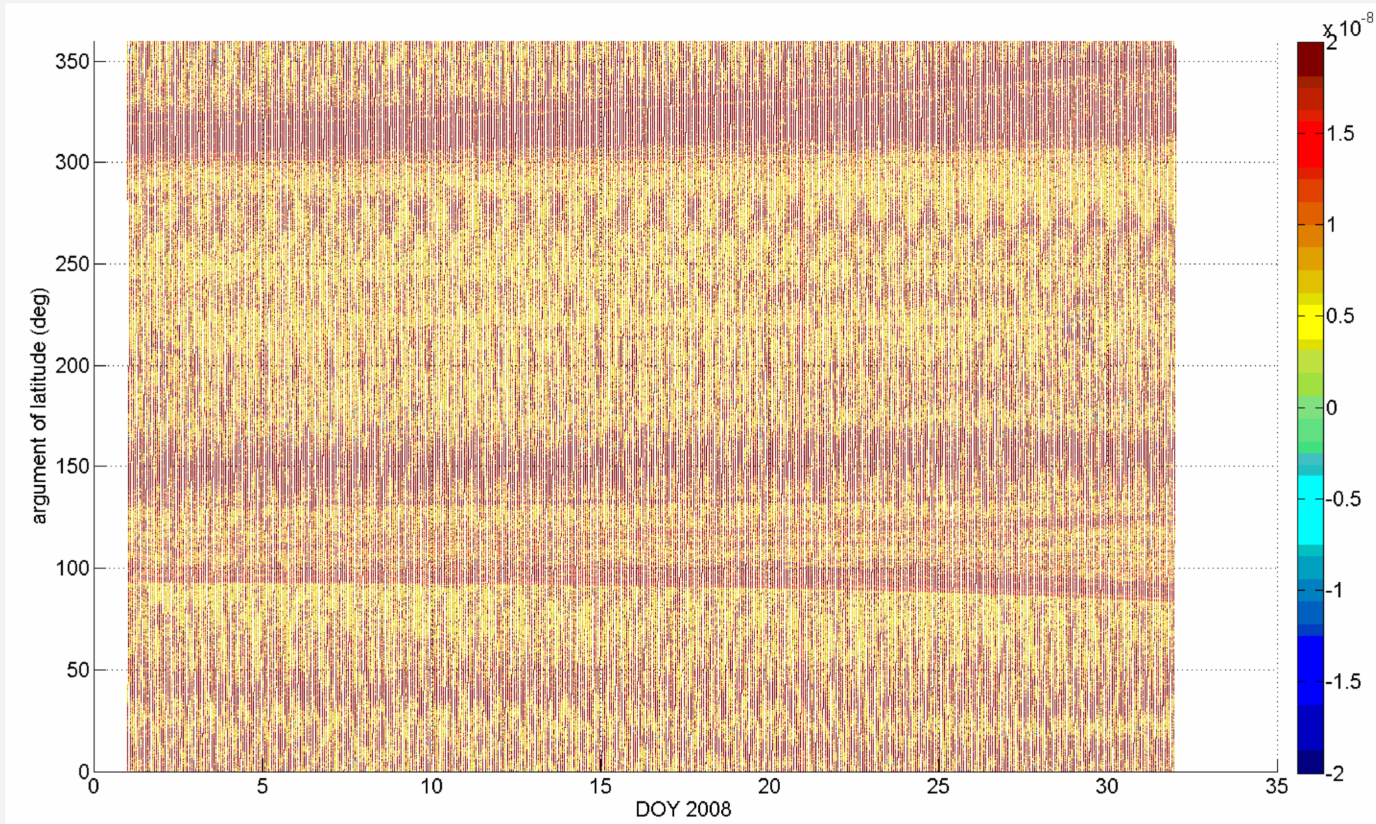


Fig. 4: GRACE-A 35 mHz high-pass filtered radial accelerations [ms$^{-2}$] with 10 Hz sampling based on Level-1A accelerometer data after heater switching spike correction

## 5 – CONCLUSIONS

**The GRACE twin satellite formation and its sensor system (K-Band inter-satellite ranging, accelerometers, star cameras, GPS) offer many opportunities for further research on satellite dynamics and space sensor validation. Some of them are:**

- **to validate radiation pressure modeling, satellite surface reflectivity, and atmospheric refraction modeling,**
- **to validate sensors (e.g., by comparing attitude information from star cameras, gyros, accelerometers),**
- **to validate the sensor system, including pointing corrections,**
- **to validate satellite platform properties, to diagnose platform events, and to explore effects related to the satellite environment (such as twangs and oscillations),**
- **to validate precise orbit determination,**
- **to validate gravity field processing, e.g., by investigating correlations between residuals and pointing variations.**

**The length of the data time series (now 9 years) with very high temporal resolution is a particular strength for such investigations. The use of recurring or regular signal contributions (such as penumbra transitions, AOCS characteristic periods, star camera switches, etc.) as test signals could be further extended.**

## 6 – REFERENCES


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