

# Chapter 3

## Using Accelerometer Data as Observations

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**Abstract** By established convention, non-gravitational accelerations measured on-board satellites are not treated as genuine observations in the “observed minus computed” sense, like other data types. Instead, they appear as an additional perturbation on the right hand side of satellite dynamics and accelerometer calibration factors (scaling, biases) play the role of dynamical parameters. The more logical method would be to treat them conceptually in the same manner as other kinds of measurements, like SLR (satellite laser ranging), GPS or inter-satellite ranging. This alternative method has been investigated and compared to the conventional method. Benefits and disadvantages are discussed and the performance of the conventional and the new method is assessed in the context of gravity field recovery, for a simulated scenario and using real-world CHAMP and GRACE mission data.

### 3.1 Introduction

In the context of gravity field recovery, modern satellites such as CHAMP (Reigber et al. 2002), GRACE (Tapley et al. 2004) and GOCE (Rummel et al. 2002) carry on-board accelerometers. In combination with star tracker data it is thus possible to provide measured surface accelerations in the inertial frame for orbit integration and to separate non-conservative from conservative forces.

Parameter adjustment from measurement data runs along the well-established “observed minus computed” routine. From the actual observation data, a modeled observation is subtracted that depends on parameters. The “true” values of those parameters are not known; therefore the difference (residuals) is nonzero. A linearization process yields the design equations, which are transformed into normal equations in

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order to obtain corrections in the parameters. This is the classical approach for various geodetic measurement types such as satellite laser ranging (SLR), GPS, altimetry or inter-satellite ranging.

Somewhat surprisingly, the prevailing method to process satellite on-board accelerations is significantly different. After a pre-processing step of the “raw” data that amounts to closure of data gaps, outlier removal or re-sampling, the acceleration vector is inserted “as is” into the right hand side of the differential equation of satellite motion. It replaces the “classically” used sum of modeled surface accelerations: air drag, solar radiation pressure and albedo. The adjustable parameters the acceleration vector depends on, namely biases and scaling factors, take the role of dynamical parameters of satellite motion. An observation equation for the observation type “surface acceleration” does not exist in this approach. In the following, we will call this the “conventional method”.

The more intuitive procedure would be the above-mentioned “observed minus computed” adjustment technique. The “observed” part comprises the measured on-board accelerations. The “computed” part is the sum of modeled values for air drag, solar radiation pressure and albedo. In the accelerometer observation equation, two types of solve-for parameters appear. First, the accelerometer calibration factors (scaling, biases). Second, scaling factors separately for air drag, radiation pressure and albedo. On the right-hand side of the satellite differential equations, the surface accelerations are *not* the measured values, but rather the sum of the models for air drag, solar radiation pressure and albedo. Despite the fact that this approach is more logical than the established conventional method, it was apparently never seriously investigated. We will do this here, and show its benefits and impacts in the context of gravity field recovery.

The conventional method of real accelerometer data processing has of course clear advantages. Satellite dynamics are much simpler, as the only dynamical parameters the surface accelerations depend on are the accelerometer biases and scale factors. Also, e.g. modeled air drag is only as good as the models for the underlying air densities, and there are effects that cannot be properly represented by models at all. An example would be rapid density variations around the poles, where ionized particles collide with molecules of the upper atmosphere (polar light crown).

However, there are many points that are more appropriately addressed by the alternative method proposed here. The most important are the following:

- Handling of measurement noise: In the conventional approach, we suppose that there is no noise at all. If this is not true, the formal accuracies of the solved parameters obtained from the overall adjustment are too optimistic.
- Handling of data gaps: As the accelerometer data vector is inserted “as is” into the right hand side of the equation of motion of the satellite, a stream of gapless data must exist on the integration time grid. If the accelerometer has severe data gaps the consequence is a cumbersome cutting of the integrated orbital arcs.
- The measured surface accelerations must be 3D vectors in the conventional approach, as they appear directly on the right hand side of the satellite dynamics. In the alternative setting, we have no original accelerometer data in the satellite

dynamics, but only model forces, thus it plays no role if we observe e.g. the along-track channel alone. A good example for that is CHAMP. Here the radial channel of the accelerometer is essentially flawed. It would be desirable in that case to have the liberty to entirely omit the radial channel, and to use only along-track and cross-track values.

In the following, we show how the alternative method performs in the context of gravity field recovery when compared with the conventional method. In order to see what we can gain in ideal conditions, we first discuss a simulated GRACE-like scenario (two tandem satellites, GPS and K-band Satellite-to-Satellite (SST) tracking) first. We will then look at real-world examples for CHAMP and GRACE.

### 3.2 Test of the Alternative Method in a Simulated Environment

A first assessment of the new approach was obtained with the simulation of a GRACE-like configuration: two coplanar satellites with on-board GPS receivers, accelerometers and star trackers connected by a microwave inter-satellite link. The time horizon of the simulation was 28 days and was realized in the following way:

- The orbit elements at the begin of the integration were chosen such that the initial orbit heights were about 350 km, the along-track separation 200 km and the inclination of the orbit plane  $89^\circ$ .
- Both satellites were integrated with a step size of 5 s over the whole 28 days. The simulated surface accelerations were the sum of the three model components
  - DTM air drag model by Barlier (Berger et al. 1998),
  - Solar radiation pressure model with a shadow transition function, and
  - The Knocke albedo model (Knocke 1989).
- Furthermore, simulated star tracker data were derived from nominal attitude (yaw steering) in the form of “attitude quaternions”.
- Orbital, surface acceleration and attitude quaternion data sets were then divided into 28 batches of one day length, and the one-day LEO (low earth orbiter) orbits were combined with real-world GPS SP3 files to generate artificial GPS code and phase as well as K-band range rate measurements. All data were endowed with appropriate measurement noise of 30 and 3 mm rms for GPS code and phase, respectively, and  $0.05 \mu\text{m/s}$  rms for the K-band link.
- Simulated (from modeled values) accelerometer data were provided alternatively with noise-free as well as with  $10^{-9} \text{ m/s}^2$  noise on all three channels (radial, along-track, cross-track).

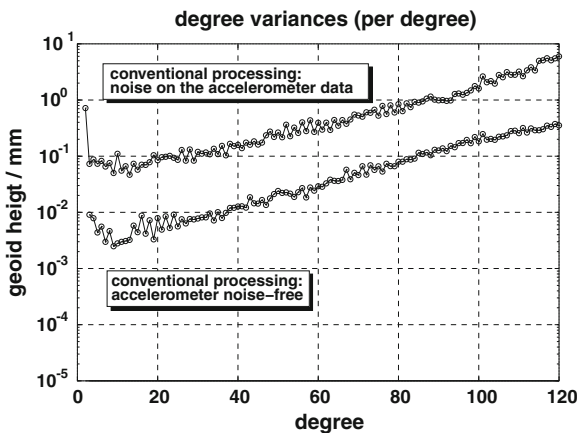
In the recovery step, the one-day batches of simulated data were fed to LEO screening orbits of one day length each. First, with the parameters of the initial gravity field fixed, the LEO orbits were adjusted to fit the measurements as close as possible. Second, arc-wise normal equations, now with gravity field expansion

coefficients free, were produced and added, and the resulting normal equation was inverted. For the derived adjusted gravity field degree variances (per degree) of the geoid differences versus the “true” gravity field of the simulation were computed and plotted in order to assess the quality of the solution.

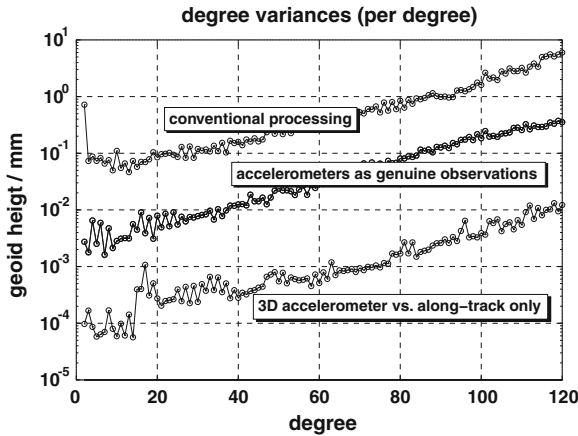
To test the new method versus the established method, several recovery scenarios were realized.

1. The conventional recovery strategy, with noise-free simulated accelerometer data. Accelerometer biases and scaling factors were estimated for all three spatial directions. Both scaling factors and biases were linear functions with one solve-for parameter at the beginning and one at the end of the arc.
2. The conventional recovery strategy, however with noise added to all three spatial channels of the accelerometer data.
3. Recovery with accelerometer measurements according to the new method. On the right hand side of the satellite dynamics, the surface forces are provided by models, and the model parameters are adjusted (indirectly) from the GPS and the K-band measurements and (directly) from the accelerometer data. In addition to the calibration factors for the accelerometers, one scaling factor each for the air drag, the solar radiation pressure and the albedo models for both satellites were adjusted.
4. Recovery according to the new method, however not for all three spatial channels, but only using the along-track channel of the on-board accelerometers.

The results of recovery scenarios 1 and 2 are depicted in Fig. 3.1. It is quite obvious that the conventional recovery method cannot cope appropriately with noise on the accelerometer data. The error degree variance curve for the noisy-data case is more than an order of magnitude above the curve for noise-free data.



**Fig. 3.1** Degree variances of the differences between the recovered and the true gravity field in the simulated GRACE scenario. In both cases, the adjustment procedure is the same. The *upper curve* results if white noise of  $10^{-9}$  m/s<sup>2</sup> rms is added to the accelerometer data



**Fig. 3.2** Degree variances of the difference between true and recovered gravity field (*upper two curves*) and of the difference between the scenarios where the whole 3D surface acceleration vector and only the along-track channel has been processed (*lowermost curve*). Note that the *middle curve* actually is made of two curves superimposed so closely that they cannot be separated visually (see text)

The uppermost curve in Fig. 3.2 is the same as the upper curve in Fig. 3.1 showing the conventional recovery with noisy accelerometer data. The middle curve in Fig. 3.2 results from the alternative method. By treating accelerometer measurements as genuine observations, the noise on the accelerometer data is taken into account in the correct manner, and the curve of error degree variances is lowered almost to the level of the case where the recovery has been performed with the conventional method with noise-free accelerometer data. Actually, in the middle we have two curves, namely for the case where all three spatial components of the accelerometer data vector are observed as well as the case where only the along-track channel is processed. Both curves are so close that they appear as one, however they actually differ. The lowermost curve is the degree variance plot of their difference. We may therefore conclude that most of the information about the surface forces is contained in the along-track channel alone.

A notable disadvantage of the alternative processing method is a considerable increase in processing time. As accelerometer data feature as genuine observations, they appear in the budget of data that have to be processed, and their number can be considerable. Whereas we have, for both satellites, some 40000 GPS measurements with 30 s data step size, and 17280 K-band 5-second range rate data per day, we can expect, at a integration step size of 5 s, for 3 spatial measurement channels and two satellites,  $(86400/5) \times 3 \times 2 = 103680$  additional (accelerometer) measurements per arc in addition to the original 57000 GPS and K-band observations. The situation is somewhat ameliorated when only the along-track channel is processed. The additional data amount here to some 35000 per day. Still, this is almost as much

as the number of GPS data alone, so even in this case we can expect the processing time to be two times as long as for the conventional technique.

### 3.3 Test of the Alternative Method with Real-World CHAMP Data

One month (August 2008, containing 29 usable days) of CHAMP GPS and accelerometer data were processed according to the standards of the GRACE release 05 products (Dahle et al. 2012) along the lines of the conventional and the alternative method. There were altogether 583103 GPS code/phase observations (30 s step size) and 751680 accelerometer measurements (3 axes with 10 s step size). For the alternative method, only the along-track accelerometer channel was observed, resulting in 250560 measurements of the type “surface acceleration” in addition to the GPS data. For the alternative method, the rms value of the adjusted surface acceleration model data to the observed data was around  $5.5 \cdot 10^{-9} \text{ m/s}^2$ , which conforms well to the nominally reported  $3 \cdot 10^{-9} \text{ m/s}^2$  accuracy of the CHAMP accelerometer (Grunwaldt and Meehan 2003).

The adjustable parameters for the conventional method were chosen as follows:

- Two accelerometer scaling factors per day in every spatial direction.
- Accelerometer radial biases: 40 min step size (approximately one half-revolution).
- Accelerometer cross/along-track biases: 93 min step size (one per orbit)
- Thruster misalignment parameters.
- Empirical accelerations in the radial direction: once-per-rev cosine and sine terms.

The many parameters for the radial channel are necessary as the accelerometer data of that channel are known to be inherently flawed for CHAMP (Perosanz et al. 2003; Loyer et al. 2003).

For the alternative processing method, the surface acceleration was assumed to be the sum of the three model components:

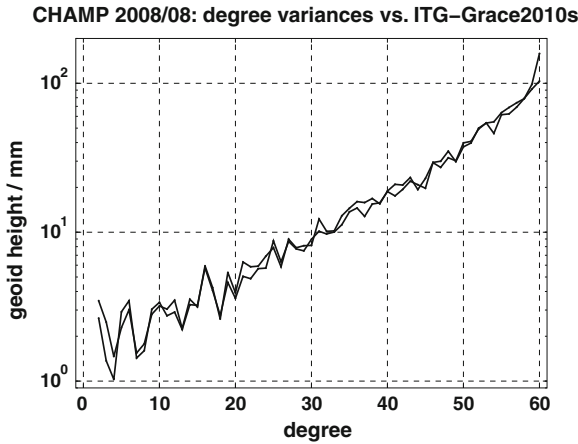
- Jacchia-Bowman air drag model 2008 (Bowman and Tobiska 2008)
- A solar radiation pressure model with a shadow transition function
- The Knocke albedo model (Knocke 1989)

From all three model accelerations, only the air drag and the solar radiation parts were endowed with adjustable scaling factors:

- The air drag scaling factor is a time-dependant polygon with 3 min step size.
- The solar radiation pressure is scaled by one global parameter.

Figure 3.3 shows the degree variances of the differences of the gravity field solutions of the conventional and the alternative method versus the static gravity field ITG-Grace 2010 (Mayer-Gürr et al. 2010).

The alternative method is obviously capable to reproduce the results of the conventional method using only one third of the accelerometer data (along-track), albeit



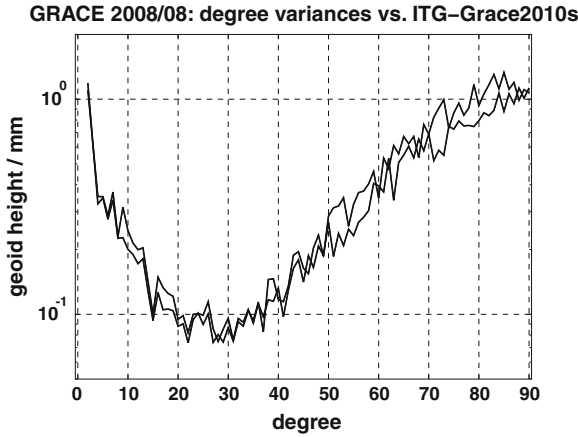
**Fig. 3.3** Degree variances of the differences between adjusted CHAMP gravity fields and the ITG-Grace2010s static gravity field. The two close and nearly coinciding curves correspond to the conventional and the alternative recovery method

at the expense of increased processing time and an increase of arc-specific parameters: for the air drag model scaling factors were estimated all three minutes, resulting in 480 additional parameters per day.

### 3.4 GRACE Scenario with Real Data

The results of the same month (August 2008, with 31 usable days) are presented here analyzing GRACE data according to the standards of the GRACE release 5 products (Dahle et al. 2012). The gravity field adjustment is based on 1019610 GPS code/phase measurements and 492631 K-band range-rate inter-satellite observations, as well as 2977776 measurements of the on-board accelerometers (2 satellites, 3 spatial axes, 5 s sampling). The calibration of the accelerometers was handled such that the scaling factors were fixed to one, and biases were estimated with a step size of one hour. The measured surface accelerations were modeled as a sum of air drag, solar radiation pressure, Earth albedo and revolution-periodical empirical accelerations in all three spatial directions. The models for air drag and albedo are almost the same as in the CHAMP case. We estimated scaling factors for solar radiation pressure and air drag; the former globally, the latter as a polygon with 6 h stepping size. Furthermore, we estimated cosine/sine amplitudes for the empirical accelerations, with frequencies of 1/rev and 6/rev. The amplitudes of the former were assumed to be polygons with 45 min stepping size, the latter to be polygons with 15 min step size.

Again the new method is capable to produce an adjusted gravity field with a quality that is at least as high as the one achieved with the conventional method, as can be



**Fig. 3.4** Degree variances of the difference compared to the static model ITG-Gace2010, for the conventional and the alternative recovery method. Both curves have not been separately labeled, as they almost coincide

seen in Fig. 3.4. From the way how the measured surface accelerations are modeled it can be inferred that for every arc of one day length we have 1548 auxiliary solve-for parameters. Thus the inflation of the parameters vector inherent to the alternative method stays within reasonable limits.

### 3.5 Conclusions

The established method for the processing of satellite on-board accelerometer measurements has been compared with a novel approach that fits logically more into the framework of the general treatment of measurement data. The method has been assessed in the context of gravity field recovery. Results have been presented for a simulated GRACE-like scenario as well as for a month of real-world GRACE and CHAMP data. It has been established that the method copes correctly with noisy accelerometer measurements, which is not the case for the conventional method. In the real-world case it can at least produce adjusted gravity fields of the same quality level as the established approach. It has been demonstrated that for the alternative method, it is not necessary to process the entire three-dimensional surface acceleration vector; instead using the along-track channel alone is sufficient. Disadvantages are a certain increase of arc-specific parameters and a growth of processing time, but both are in a range that can be handled. The results all in all are somewhat sobering, as it was not possible to surpass the performance of the conventional approach, however, there is some promise that this can be achieved by further investigation of alternative parameterization of the surface acceleration models and by dedicated



techniques for de-correlation of the gravity field parameters on the one hand and the arc-wise dynamical parameters on the other.

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