Atmospheric densities derived from CHAMP/STAR accelerometer observations

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Abstract

The satellite CHAMP carries the accelerometer STAR in its payload and thanks to the GPS and SLR tracking systems accurate orbit positions can be computed. Total atmospheric density values can be retrieved from the STAR measurements, with an absolute uncertainty of 10–15%, under the condition that an accurate radiative force model, satellite macro-model, and STAR instrumental calibration parameters are applied, and that the upper-atmosphere winds are less than 150 m/s. The STAR calibration parameters (i.e. a bias and a scale factor) of the tangential acceleration were accurately determined using an iterative method, which required the estimation of the gravity field coefficients in several iterations, the first result of which was the EIGEN-1S (Geophys. Res. Lett. 29 (14) (2002) 10.1029) gravity field solution. The procedure to derive atmospheric density values is as follows: (1) a reduced-dynamic CHAMP orbit is computed, the positions of which are used as pseudo-observations, for reference purposes; (2) a dynamic CHAMP orbit is fitted to the pseudo-observations using calibrated STAR measurements, which are saved in a data file containing all necessary information to derive density values; (3) the data file is used to compute density values at each orbit integration step, for which accurate terrestrial coordinates are available. This procedure was applied to 415 days of data over a total period of 21 months, yielding 1.2 million useful observations. The model predictions of DTM-2000 (EGS XXV General Assembly, Nice, France), DTM-94 (J. Geod. 72 (1998) 161) and MSIS-86 (J. Geophys. Res. 92 (1987) 4649) were evaluated by analysing the density ratios (i.e. “observed” to “computed” ratio) globally, and as functions of solar activity, geographical position and season. The global mean of the density ratios showed that the models underestimate density by 10–20%, with an rms of 16–20%. The binning as a function of local time revealed that the diurnal and semi-diurnal components are too strong in the DTM models, while all three models model the latitudinal gradient inaccurately. Using DTM-2000 as a priori, certain model coefficients were re-estimated using the STAR-derived densities, yielding the DTM-STAR test model. The mean and rms of the global density ratios of this preliminary model are 1.00 and 15%, respectively, while the tidal and latitudinal modelling errors become small. This test model is only representative of high solar activity conditions, while the seasonal effect is probably not estimated accurately due to correlation with the solar activity effect. At least one more year of data is required to separate the seasonal effect from the solar activity effect, and data taken under low solar activity conditions must also be assimilated to construct a model representative under all circumstances.

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Keywords: Atmospheric density observation; Thermosphere model; Orbit determination; Accelerometer calibration

1. Introduction

1.1. Atmospheric density modelling

Semi-empirical atmospheric density models, such as DTM-94 (Berger et al., 1998), DTM-2000 (Bruinsma and Thuillier, 2003) and MSIS-86 (Hedin, 1987), predict atmospheric temperature and density as a function of altitude, latitude, local solar time, day of year, and parameters related to the state of atmospheric heating. Besides their use in atmospheric studies, these models in particular are employed in satellite precise orbit determination in order to compute the atmospheric drag force. Their accuracy is at the 15–20% (1σ) level for the predicted total densities and at the 6–10% (1σ) level for the predicted temperatures (Bruinsma and Thuillier, 2003).

Due to the absence of a rigorous physical basis, semi-empirical models (as opposed to the general circulation models) rely heavily on the assimilated density and temperature data. Predictions under conditions for which no or (too) few data were available, or inaccurate data were assimilated, may be significantly in error. The data sets that are nowadays available are not of homogeneous
Table 1

<table>
<thead>
<tr>
<th>Data set</th>
<th>Used by:</th>
<th>$F_{10.7}$ range</th>
<th>Altitude (km)</th>
<th>Latitude (°)</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGO-6 T</td>
<td>Thuillier et al., 1977</td>
<td>2,3</td>
<td>140–160</td>
<td>230–270</td>
<td>−90; 90</td>
</tr>
<tr>
<td>DE-2 T</td>
<td>Spencer et al., 1981</td>
<td>1,2,3</td>
<td>150–230</td>
<td>225–600</td>
<td>−90; 90</td>
</tr>
<tr>
<td>AE-E T</td>
<td>Spencer et al., 1973</td>
<td>1,3</td>
<td>70–220</td>
<td>140–500</td>
<td>−30; 30</td>
</tr>
<tr>
<td>DE-2$^b$ He</td>
<td>Carignan et al., 1981</td>
<td>1,2,3</td>
<td>150–230</td>
<td>400–1000</td>
<td>−90; 90</td>
</tr>
<tr>
<td>AE-E$^b$ He</td>
<td>Pelz et al., 1973</td>
<td>1,3</td>
<td>70–160</td>
<td>300–600</td>
<td>−30; 30</td>
</tr>
<tr>
<td>DE-2$^b$ O</td>
<td>Carignan et al., 1981</td>
<td>1,2,3</td>
<td>150–230</td>
<td>275–575</td>
<td>−90; 90</td>
</tr>
<tr>
<td>AE-E$^b$ O</td>
<td>Pelz et al., 1973</td>
<td>1,3</td>
<td>130–160</td>
<td>300–475</td>
<td>−30; 30</td>
</tr>
<tr>
<td>DE-2$^b$ N$_2$</td>
<td>Carignan et al., 1981</td>
<td>1,2,3,4</td>
<td>150–230</td>
<td>225–400</td>
<td>−90; 90</td>
</tr>
<tr>
<td>AE-E$^b$ N$_2$</td>
<td>Pelz et al., 1973</td>
<td>1,3</td>
<td>70–100</td>
<td>140–250</td>
<td>−30; 30</td>
</tr>
<tr>
<td>DTM$^b$ ρ</td>
<td>Barlier et al., 1978</td>
<td>2,3</td>
<td>70–170</td>
<td>225–1000</td>
<td>−90; 90</td>
</tr>
<tr>
<td>CACTUS ρ</td>
<td>Villain, 1980</td>
<td>2,3</td>
<td>70–80</td>
<td>225–500</td>
<td>−30; 30</td>
</tr>
<tr>
<td>CHAMP ρ</td>
<td>4</td>
<td>70–220</td>
<td>200–450</td>
<td>−90;90</td>
<td>1–5%</td>
</tr>
</tbody>
</table>

$^a$Absolute precision.

The numbers given in the second column show whether the following atmospheric density models assimilated the data: 1 = MSIS-86, 2 = DTM-94, 3 = DTM-2000, and 4 = DTM-STAR.

quality, and in certain cases they are biased because the instrumental calibration parameters could not be accurately determined. Moreover, they all have limited geographical (for example, due to orbital inclination) and/or temporal coverage (for example, only during high or low solar activity). A description of the main data sets is given in Table 1 in support of the aforementioned data imperfections.

The CHAMP mission profile is particularly interesting for upper atmosphere studies: it will provide good geographical coverage over a period of 5 years. The 87° orbit inclination ensures a nearly complete latitudinal coverage, while the solar local time is completely sampled (0–24 h) approximately every 4 months. The initial altitude in July 2000 was 454 km, but it will be 200 km at the end of its nominal 5-year mission. Furthermore, over that nominal mission time period the instrument STAR (cf. Section 2.1) will take measurements under solar activity conditions ranging from maximum (2000–2001) to minimum (2005). This is important taking into account the heterogeneity of the density database available nowadays, of which the main contributions were shown in Table 1. The last line of Table 1 shows coverage and precision of the STAR-derived density data set, under the assumption of a nominal mission scenario. Such a data set would constitute the most complete one and be among the most valuable contributions in terms of precision. In the present study, the first CHAMP atmospheric density data set usable for modelling purposes is derived and analysed.

1.2. Organization

The function and specifications of the STAR accelerometer, the data it delivers and their calibration are discussed in Section 2. In order to calibrate the STAR data and extract the part due to atmospheric drag, characteristics of the CHAMP spacecraft and the precise determination of its trajectory in time have to be addressed. Section 3 concerns the two precise orbit determination approaches used in case of CHAMP. Section 4 describes the density retrieval procedure. Section 5 presents the results of comparisons of DTM-94 (Berger et al., 1998), DTM-2000 (Bruinsma and Thuillier, 2003) and MSIS-86 (Hedin, 1987) with the STAR densities. The STAR-derived atmospheric densities, combined with a molecular nitrogen data set, are used to re-estimate DTM-2000 model coefficients. The resulting test model, and in particular the density structures it predicts, is analysed in Section 6. The conclusions of this study are given in Section 7.

2. The CHAMP mission and the STAR accelerometer

2.1. CHAMP: the spacecraft and its mission profile

The challenging minisatellite payload (CHAMP) spacecraft was launched in July 2000, and the mission is managed by the GeoForschungsZentrum (GFZ) in Potsdam, Germany. The primary mission objectives are: mapping of the magnetic and gravity fields of the Earth, and monitoring of the ionosphere and troposphere. One of the secondary objectives and the subject of this study is the monitoring of thermospheric density. The following instruments are included in the payload in order to achieve the objectives: two fluxgate magnetometers, an Overhauser magnetometer, a digital ion-drift meter, a GPS receiver for orbit determination and limb sounding of the atmosphere, a laser retro-reflector array, and the STAR accelerometer (Spatial Triaxial Accelerometer for Research). STAR is the contribution from CNES (Centre National d’Etudes Spatiales) to the CHAMP mission, but it was developed by ONERA (Office National d’Etudes et de Recherches Aerospatiales).
Fig. 1 gives a representation of the satellite, with the magnetometers fixed to the boom, the digital ion drifter meter fixed to the front panel, and the GPS Precise Orbit Determination (POD) antennae on top and at the rear of the spacecraft. The CHAMP orbit configuration and specifications are as follows:

- Initial altitude: 454 km; orbit inclination: 87.3°; mean eccentricity: 0.003.
- Length: 8.33 m (boom: 4.04 m); height: 0.75 m; width: 1.62 m.
- Initial mass: 522 kg (boom: 20 kg).

Assuming a nominal mission scenario, the orbit altitude will be 250 km after 5 years of operation. This altitude will be attained by natural decay, and when necessary, through additional orbit corrections (by two cold gas thrusters). The satellite tracking is assured by a Turbo Rogue GPS receiver, provided by NASA/JPL, while a laser retro-reflector array has been mounted as well. The nominal satellite attitude is with the boom aligned with the tangential component of the RTN local satellite frame (radial, tangential, and normal directions; see Section 2.1), which is in the flight direction. This attitude is actively maintained, within 2° (control error < 0.1°), by three magneto torquers as well as six pairs of cold gas thrusters. The thrusters are mounted in such a way that torques are generated with minimum resulting translational forces. Star cameras provide the necessary attitude measurements (quaternions) with a 2″ accuracy.

STAR, which measures the non-gravitational accelerations acting on the satellite, the GPS system and the satellite laser ranging (SLR) network provide the necessary data for the precise orbit determination (POD) and the recovery of the terrestrial gravity field. The same observations are also used in the derivation of thermospheric density. Therefore, a large part of the data processing procedure is the same as in gravity field modelling and the subjects POD, perturbation modelling and estimation of the STAR calibration parameters must be addressed in this study. The gravity field model EIGEN-1S (Reigber et al., 2002), which was constructed using only 3 months of GPS high-low satellite-to-satellite tracking (SST), SLR and STAR data, currently represents the state-of-the-art satellite-only model (e.g. no terrestrial gravity data were assimilated). The gravity field coefficients were estimated simultaneously with the STAR calibration parameters, for which the a-priori values were determined by CNES in the framework of the CAL/VAL activities (Perret et al., 2001). This study benefits significantly from the EIGEN-1S gravity field model, the use of which improves the POD and the ongoing determination of the STAR calibration parameters.

2.2. The STAR accelerometer

2.2.1. The instrument

The STAR accelerometer consists of a sensor unit (SU), an interface and control unit (ICU), and the harness between boxes. The SU measures the non-gravitational accelerations acting on the satellite in an adequate range and frequency bandwidth. The ICU filters frequencies higher than 2.4 Hz employing a Butterworth filter and converts the analog signal from the SU to a digital one over 24 bits for each channel (three for linear accelerations and three for angular ones). Table 2 presents the (pre-launch) specifications of STAR in the measurement bandwidth of 10⁻²⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻㈠Edward Peirce et al., 2002), which was constructed using only 3 months of GPS high-low satellite-to-satellite tracking (SST), SLR and STAR data, currently represents the state-of-the-art satellite-only model (e.g. no terrestrial gravity data were assimilated). The gravity field coefficients were estimated simultaneously with the STAR calibration parameters, for which the a-priori values were determined by CNES in the framework of the CAL/VAL activities (Perret et al., 2001). This study benefits significantly from the EIGEN-1S gravity field model, the use of which improves the POD and the ongoing determination of the STAR calibration parameters.

**Table 2**

<table>
<thead>
<tr>
<th>In translation/rotation</th>
<th>Measurement range</th>
<th>Resolution (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>±10⁻⁴ m s⁻²</td>
<td>3 x 10⁻⁴ m s⁻²</td>
</tr>
<tr>
<td>Y</td>
<td>±10⁻⁴ m s⁻²</td>
<td>3 x 10⁻⁴ m s⁻²</td>
</tr>
<tr>
<td>Z</td>
<td>±10⁻³ rd s⁻²</td>
<td>5 x 10⁻³ rd s⁻²</td>
</tr>
<tr>
<td>Pitch, roll</td>
<td>±10⁻³ rd s⁻²</td>
<td>1 x 10⁻³ rd s⁻²</td>
</tr>
</tbody>
</table>
satellite is orbiting in its nominal attitude (i.e. yaw, pitch and roll all equal to zero), both frames are aligned with the classical \((R,T,N)\) orbital reference frame: \(R\) = radial, \(T\) = tangential (along-track) and \(N\) = normal (cross-track), but with the radial axis pointing upward.

2.2.2. The data

Pre-processing of the raw STAR acceleration measurements (level 1B data with 1 Hz sampling rate) is required in order to eliminate or correct anomalous data. These anomalies, spikes in particular, have large amplitudes, which have a significant impact on the mean of the data. Their occurrence has been correlated with events such as attitude manoeuvres, the on/off switching of heaters, and instrument and satellite data handling system reboots. However, a certain number of spurious signals remain unexplained to this day. Level-2 data have therefore been used in this study. These 10-s normal points are free from (spurious) spikes and accelerations related to attitude manoeuvres, which in case of STAR data analysis in view of density derivation is advantageous. However, when these data are used for orbit computation purposes, the non-gravitational acceleration acting on CHAMP will be erroneous due to the suppression of manoeuvres.

2.2.3. The calibration equation

Because the voltages required to suspend the proof mass under laboratory conditions are too high, the STAR accelerometer calibration parameters were not known at the time of launch. The calibration, i.e. the determination of an instrumental bias and scale factor per axis, is a key element for the success of the gravity mission as well as for this study.

The relationship between the surface accelerations \(a_{\text{surf}}\) acting on the satellite, the accelerations \(a_{\text{pm}}\) acting on the proof mass of the SU, and the output \(a_{\text{acc}}\) of the accelerometer can be expressed in an equation. The output \(a_{\text{acc}}\) depends on both the SU and the ICU. Both introduce a bias in the observations, and they may scale them. The calibration equation is as follows:

\[
a_{\text{pm}} = XB + XSa_{\text{acc}},
\]

where \(XS\) and \(XB\) represent the global bias and scale factor of the accelerometer observation due to the two components. The acceleration acting on the proof mass can be decomposed into the following components:

\[
a_{\text{pm}} = a_{\text{surf}} + a_{\text{the}} + a_{\text{ecc}} + a_{\text{Lorentz}},
\]

where \(a_{\text{surf}}\) is the surface acceleration due to atmospheric drag, solar and terrestrial (albedo and infrared) radiation pressure; \(a_{\text{the}}\) is the linear acceleration resulting from the attitude control thrusters mismatch and/or misalignment. Each of the six couples of thrusters induces a linear acceleration proportional to the thrust duration; \(a_{\text{ecc}}\) is the acceleration due to the offset of the proof mass relative to the satellite centre of mass, defined by the eccentricity vector \(E_{\text{ecc}}\). We can write

\[
a_{\text{ecc}} = \omega \wedge (\omega \wedge E_{\text{ecc}}) + 2 \omega \wedge \text{d}E_{\text{ecc}}/\text{dt} + \text{d}\omega/\text{dt} \wedge E_{\text{ecc}} + \text{d}^2E_{\text{ecc}}/\text{dt}^2 + E_{\text{ecc}} I_{\text{gg}},
\]

where \(E_{\text{ecc}}\) is the vector satellite CoM-centre of the accelerometer proof mass, \(\omega\) is the Earth’s rotation rate, and \(I_{\text{gg}}\) is the gravity gradient tensor. A specific analysis of the linear accelerations confirmed that the offset of the proof mass is within the specifications \((E_{\text{ecc}} < 2 \text{ mm})\), which means that \(a_{\text{ecc}}\) may be neglected, \(a_{\text{Lorentz}}\) is the acceleration originating from the Lorentz force acting on the charged proof mass. According to ONERA, the cage shields the proof mass from the magnetic field of the Earth and therefore the Lorentz force is non-existent. Orbit calculations in which the Lorentz force was modelled and the corresponding correction to the STAR measurements applied significantly deteriorated the orbit fit as compared with the no-Lorentz-force case. Thus, the Lorentz force is either not acting on the proof mass or it is much attenuated and undetectable.

2.2.4. Calibration procedure

The calibration parameters were estimated by means of CHAMP dynamic orbit adjustment (Section 3.2) and inversion of accumulated normal equations in a least-squares adjustment. The trajectory, obtained by numerical integration of the equations of motion in which the non-gravitational accelerations are provided by the accelerometer, is constrained by GPS tracking observations. Significant correlation between orbit parameters, accelerometer calibration parameters and gravity field coefficients has been demonstrated through simulation (Schwintzer et al., 2000). Furthermore, accurate calibration parameters can only be determined using an iterative process.

The calibration procedure consists of the following five steps, of which the steps (i), (i–v) or (iii–v) may be
iterated:

(i) CHAMP dynamic POD (to be discussed in Section 3.2) using the STAR data (calibrated with the first a priori values, obtained by comparison to models), GPS SST and SLR data. Computation of the partial derivatives of the gravity field coefficients and calibration parameters with respect to the orbit positions (1 normal matrix per arc). Accumulation of the normal matrices and inversion; this resulted at first in EIGEN-1S.

(ii) CHAMP reduced-dynamic POD (estimation of 362 empirical accelerations per day; to be discussed in Section 3.1), using only the GPS tracking data.

(iii) CHAMP dynamic POD using the STAR data (applying the most recently estimated calibration parameters) and the positions \((X, Y, Z)\) of the reduced-dynamic orbits as pseudo-observations. Computation of the partial derivatives of the calibration parameters with respect to the orbit positions (1 normal matrix per arc).

(iv) Accumulation of the normal matrices and inversion.

(v) Validation: CHAMP dynamic POD using the STAR data (calibrated with the \(\text{rst}\) a priori values, obtained by comparison to models), GPSSST, and SLR data. Computation of the partial derivatives of the calibration parameters with respect to the orbit positions (1 normal matrix per arc), which allows for another iteration in case the adjusted values are still too inaccurate.

Due to problems with the radial component (Perosanz et al., 2003), which have not been fully solved yet, the calibration parameters for this component are inaccurate and therefore these measurements were not used in this study. The following mean calibration parameters for the tangential and normal axes, with uncertainties of 1–2% for the tangential axis and at least 10% for the normal axis, were obtained after three iterations by analysing data in the period May–December 2001:

\[
T : \text{bias} = -0.296 \cdot 10^{-5} \text{ ms}^{-2} \text{ scale factor} = 0.833; \\
N : \text{bias} = -0.376 \cdot 10^{-6} \text{ ms}^{-2} \text{ scale factor} = 0.875. \tag{4}
\]

The validity of these parameters in 2000 and 2002 has been checked and confirmed, in part thanks to this study (as will be shown in Section 3.2).

3. Orbit computation

Precise CHAMP orbit solutions were determined using the CNES GINS software, which, together with EPOS from GFZ Potsdam, was used in the construction of the EIGEN-1S (Reigber et al., 2002) gravity field model. GINS numerically integrates the state vector at epoch (i.e. position and velocity at the beginning of the arc) using a detailed and accurate force model in order to predict the consecutive positions and velocities of the spacecraft. The force model includes the terrestrial and third-body (direct and indirect) gravitational perturbations, as well as atmospheric drag, and solar and terrestrial radiation pressure perturbations. The software is also used to estimate measurement corrections, such as SLR ranging biases or atmospheric propagation corrections.

The following sections describe two approaches used in precise orbit computation, namely the dynamic (D-POD) and reduced-dynamic (RD-POD) approaches. In a dynamic orbit computation, the trajectory of the spacecraft is predicted mainly relying on the force model. Errors in the force model can in part be corrected for, thanks to the tracking data, through the estimation of a limited number of scale factors and 1-cpr (one sinusoidal cycle per orbital revolution) terms. The purpose of a dynamic computation is not to obtain the most accurate spacecraft positions in an absolute sense, but the most accurate spacecraft positions achievable with a specific force model. Analysis of the measurement residuals may tell us which model (element) is in error. The model may then be improved through the computation of (linearized) observation equations linking the satellite tracking data to the model parameters, and the subsequent calculation of normal equations, followed by inversion. This method was for example applied in the construction of EIGEN-1S and the iterative procedure used to determine the STAR calibration parameters (Section 2.5).

However, when the most accurate orbit (position) is required, another approach is more appropriate. In order for this 'reduced-dynamic' technique to be valid, the tracking data must be more accurate than their reconstruction using the force model. In that case, a more accurate orbit can be computed by mainly relying on the observations instead of the force model. The large amount of precise CHAMP GPS tracking data allows for the estimation of empirical accelerations over periods of time much smaller than the orbital period. These empirical terms effectively absorb force model errors irrespective of their origin. The results of the computations, in terms of rms-of-fit and maximum of the measurement residuals, are presented in Sections 3.1 and 3.2 for RD-POD and D-POD, respectively.

3.1. Reduced-dynamic POD

The reduced-dynamic technique is in this study used with undifferenced CHAMP GPS SST data, which are processed in orbital arcs of 24 h. The SLR data are used to verify the orbit accuracy externally. The GPS satellite orbit and clock solutions of the International GPS Service (IGS) were used in this analysis. The quaternions, measured by the star trackers, are used to correctly orient the spacecraft in inertial space, and in particular the phase center of the GPS antennae and the laser retro-reflector with respect to the CoM. In the present study, RD-POD consists in estimating empirical accelerations due to gravitational and non-gravitational model errors and orbit manoeuvres projected on the along-track and cross-track directions. The dynamical and geometrical
models applied are presented in Table 3, and the estimated orbit-dependent parameters are given in Table 4. The most important source of orbit error, when the EIGEN-1S gravity field model is used, is due to the atmospheric drag model. These (high and low frequency) errors accumulate mainly on the along-track component; therefore, a constant along-track acceleration is estimated every 6 min in order to effectively absorb them. In the cross-track direction, a constant acceleration is estimated every 12 min and a 1-cpr term is adjusted in the radial direction.

The RD-POD gives the most accurate spacecraft (CoM) positions and smallest measurement residuals in this study. Thus, the orbit fit results and the orbits (positions) themselves can be used as references for dynamic orbit computations (Bruinsma et al., 2002). In particular, the orbits can be used as pseudo-observations in the dynamic orbit computation. This eases the computational burden significantly because the large amount of GPS-related corrections (Table 4) do not have to be estimated. The orbit fit statistics in the interval September 2000 through May 2002 are presented per year in Table 5. It was not possible to compute RD-POD orbits in the period 1 January through 15 May 2001 (no period 2 in Table 5) due to problems with the GPS data processing. Table 5 shows the steady progress in orbit accuracy, from approximately 10 cm rms of the SLR residuals in 2000 to 6.5 cm rms in 2002. Due to the upload of new software, the accuracy of the GPS measurements has also significantly increased over that period. This is demonstrated by both the decreasing mean rms of the range residuals and the smallest maximum rms, while the number of observations per arc increases.

### 3.2. Dynamic POD

The dynamic POD applies only the gravitational force models presented in Table 3. The tracking data in this case are the positions of the RD-POD orbits, and thus the geometrical model specific to GPS is not necessary, and SLR data are (again) used for validation. The non-gravitational accelerations are provided by the calibrated STAR measurements. The orbit parameterization, much alleviated compared to the RD-POD case, is given in Table 4. Additional accelerometer biases are estimated to accommodate small instrumental offsets with respect to the mean values given in Section 2.4. The dynamic POD approach is used in this study to verify the instrument STAR through analysis of the estimated additional bias parameters and to link the STAR measurements to the concurrent CHAMP geographical positions and non-gravitational model predictions, which are computed simultaneously. These are not used in the POD, but necessary to derive density from the STAR measurement, as will be explained in Section 4.1.

The average rms-of-fit to both the positions of the RD-POD ephemerides, of which the results of the fit are given in Table 5) and the SLR observations is 35 cm for the periods 1, 3 and 4 (periods defined in Table 5), with maximum values up to 80–100 cm for a few arcs in 2001.
Table 5

The results of the fit (mean rms, and maximum rms given between parentheses) of the GPS and SLR observations for the 1-day reduced-dynamic CHAMP orbits. Period 1 corresponds to 1/9/2000–31/12/2000, period 3 to 15/5/2001–31/12/2001 and period 4 to 1/1/2002–31/5/2002. For period 2, the GPS reduced-dynamic orbits could not be computed.

<table>
<thead>
<tr>
<th>Period</th>
<th>No. of arcs</th>
<th>GPS range (m)</th>
<th>GPS phase (m)</th>
<th>No. of GPS data per arc</th>
<th>SLR (m)</th>
<th>No. of SLR data per arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>0.940 (1.434)</td>
<td>0.006 (0.016)</td>
<td>26193</td>
<td>0.101 (0.265)</td>
<td>116</td>
</tr>
<tr>
<td>3</td>
<td>210</td>
<td>0.581 (1.822)</td>
<td>0.007 (0.030)</td>
<td>33219</td>
<td>0.082 (0.331)</td>
<td>101</td>
</tr>
<tr>
<td>4</td>
<td>136</td>
<td>0.547 (0.705)</td>
<td>0.007 (0.013)</td>
<td>34930</td>
<td>0.065 (0.236)</td>
<td>110</td>
</tr>
</tbody>
</table>

Fig. 3. The estimated corrections to the tangential bias for all used CHAMP arcs. The effect of an ICU switch (main to redundant) and two accelerometer reboots are indicated.

This average is rather high due to the use of STAR normal points (from which the manoeuvres have been filtered). Secondly, the STAR bias and scale factor both are not entirely constant due to instrumental causes, while here only a bias correction is estimated. The number of arcs is less than those obtained with the RD-POD technique because the accelerometer data were not used for days on which certain onboard events took place (i.e. switching between main and redundant board, calibration sequence, etc.). The average rms of fit to the approximately 100 SLR observations per day of 86 orbits in period 2 (1/1/2001 through 15/5/2001) is 12 cm.

Additional (with respect to the values given in (4)) accelerometer bias estimates exceeding $10^{-7}$ m/s² were assumed to be due to spurious STAR data, and the corresponding days were also eliminated. This caused 12, 4 and 3 arcs to be eliminated for the years 2000, 2001 and 2002, respectively. Although the orbit and the determination of the additional accelerometer biases is less accurate for period 2, a total of 86 days were processed. Fig. 3 displays the corrections to the mean tangential biases that were estimated for the CHAMP arcs that were used in the density derivation procedure. It can be seen that the uncertainty during period 2 is indeed highest. Table 6 presents the mean and rms values of the additional accelerometer biases for the four individual periods as well as for the entire period under analysis. The distribution of the estimated bias corrections is not random, but driven by the accelerometer and the data handling electronics on board of the spacecraft. Each time there was a switch between main and redundant electronics, the accelerometer bias parameters change. These events are known from the housekeeping data.

4. Density retrieval procedure

4.1. Total density computation

The atmospheric density is proportional to the drag and so to the acceleration measured with STAR. In order to isolate the drag component, the contributions due to radiation pressure (direct solar, Earth albedo and IR) have to be removed from the STAR measurements. The ‘observed’ total density, $\rho_{\text{STAR}}$, can be calculated by scaling the
density predicted with a model, \( \rho_{\text{model}} \), as follows (Bruinsma and Biancale, 2003):

\[
\rho^{\text{STAR}} = \frac{a^{\text{STAR}}_{\text{total}} - a^{\text{model}}_{\text{solar}} - a^{\text{model}}_{\text{albedo}} - a^{\text{model}}_{\text{IR}}}{a^{\text{model}}_{\text{drag}}} \rho_{\text{model}}. \tag{5}
\]

In this equation, \( a^{\text{STAR}}_{\text{total}} \), \( a^{\text{model}}_{\text{solar}} \), \( a^{\text{model}}_{\text{albedo}} \), \( a^{\text{model}}_{\text{IR}} \), and \( a^{\text{model}}_{\text{drag}} \) represent the accelerations measured by STAR, the modelled (direct) solar radiation pressure acceleration, the accelerations due to the Earth’s albedo and IR radiation, and the modelled drag acceleration, respectively. So despite the measurements, an accurate non-gravitational force model is required to derive the drag component at the few percent precision level. The modelling applied in this study has been given in Table 3, and is used in the orbit computations. A more detailed description of the drag modelling is given in the next section. This is necessary in order to establish the error budget of the density derivation.

At the altitude of CHAMP, atmospheric drag constitutes at least 95% of the force exerted in the along-track direction. The STAR calibration parameters for the tangential axis (which is very close to the along-track direction; see Section 1.2) are also determined best, as was stated in Section 2.4. Therefore, the density derivation is done using only the tangential component of the STAR measurements.

### 4.2. Atmospheric drag modelling

The expression for the atmospheric drag acceleration is as follows, where the index \( i \) (\( i = 1, 15 \)) represents a surface (modelled as a flat plate) of the CHAMP macro-model:

\[
a^{\text{drag}} = -\frac{1}{2} \rho \sum_{i=1}^{15} \left( C_{\text{D},i} \frac{A_i}{m} (\tilde{v} \cdot \tilde{n}_i) \cdot \tilde{v} + C_{\text{L},i} \frac{A_i}{m} (\tilde{v} \times \tilde{n}_i) \times \tilde{v} \right). \tag{6}
\]

In this equation, \( \rho \) is the atmospheric density, \( C_{\text{D},i} \) and \( C_{\text{L},i} \) are the drag and lift coefficients, respectively, \( A_i \) is the surface area of panel \( i \) of the macro-model, \( m \) is the spacecraft mass, \( \tilde{v} \) is its velocity vector relative to the atmosphere (which is assumed to be co-rotating with the Earth), and \( \tilde{n}_i \) represents the unit vector normal to panel \( i \). The atmospheric density is predicted using the DTM-2000 model (Bruinsma and Thuillier, 2003).

The drag and lift coefficients, which give a measure of the momentum exchange between the satellite surface and the colliding particles, are modelled under the assumptions of hyperthermal free-molecular flow and accommodated diffuse re-emission of the neutral atmospheric particles according to Cook (1965). The first assumption is based on the value of the molecular speed ratio \( s \) (satellite speed/most probable molecular speed), which is always larger than 5 for CHAMP. Therefore, we may neglect the random thermal motion of the atmospheric molecules, i.e. we consider the flow as hyperthermal. Experiments have shown that the re-emission mechanism is dependent on surface temperature: it was found to be diffuse for a surface at room temperature, whereas it was nearly completely specular for a very hot surface of 1600 K. Since the most probable mean satellite surface temperature is approximately 273 K, the diffuse model is appropriate. The expression of the drag coefficient for flat plate \( i \) of the CHAMP macro-model at incidence \( \phi^i \) to the flow is

\[
C_D = 2 \left( 1 + 2/3 \sqrt{1 + x'} \left( \frac{T^i_{\text{sat}}}{T_{\text{atmo}}} - 1 \right) \sin \phi^i \right),
\]

\[
x' = \frac{3.6u^2}{v^2},
\]

where \( T^i_{\text{sat}} \) is the temperature of plate \( i \), \( T_{\text{atmo}} \) the kinetic temperature of the ambient gas molecules, and \( u' \) the ratio of the mean mass of the incident gas atom to the mass of the surface atom of plate \( i \). The values of \( T_{\text{atmo}} \) and the mean mass of the gas are predicted by an atmospheric density model, DTM-2000 in this study. These values have an accuracy of approximately 6% for the semi-empirical density models. The effective cross-sectional area perpendicular to the velocity vector and the incidence angles \( \phi \) can be computed accurately thanks to the telemetered attitude quaternions, which allow the orientation (of each plate) of the macro-model with respect to the satellite velocity vector to be computed. The satellite mass is monitored and decreased from 521.6 to 519.6 kg over the period considered in this study (1 September 2000 – 31 May 2002), i.e. a mere 0.4%.

### 4.3. Error budget

The derivation of total density values from the STAR measurements, applying a non-gravitational model, was discussed in Sections 4.1 and 4.2. Thus, the ‘observed’ density is affected by both the measurement and the modelling error. We can furthermore divide the errors into two groups, namely those causing mainly a systematic error (offset with respect to the absolute value) and those mainly affecting the noise level.

The most important measurement error (of a few percent at present) is due to the uncertainty in the instrumental calibration parameters, while the resolution of the instrument plays a smaller role. This can be seen in Table 7, which also distinguishes between the type of error. The modelling errors are significantly larger. An offset of \( 10^{-7} \text{ m}^2/\text{s}^2 \) in the tangential bias causes an error of approximately 1% in the density. The uncertainty in the drag coefficient (Eq. (7)) potentially causes the most important systematic error since it directly affects the value of the reconstructed density at the 5–10% level (Bruinsma and Biancale, 2003). This uncertainty is due to the fact that realistic in-orbit conditions (i.e. vacuum) cannot be obtained in a laboratory. Errors in the spacecraft attitude modelling are smaller than 0.1°, and have a negligible effect on the computed effective cross-sectional area perpendicular to the velocity vector. The tangential
component of the solar radiation pressure is about two orders of magnitude smaller than the drag, so a modelling error gives a negligible contribution to the error budget. Not taking the evolution of the satellite mass into account, 2 kg over the period under consideration, would cause a maximum error of 0.4%.

The most important error source has a geophysical origin and is due to the unmodelled neutral atmosphere winds. In Eq. (6), an atmosphere that co-rotates with the Earth, i.e. no wind, was assumed. But in reality winds are encountered, mainly at high latitudes (the auroral zone) and in particular during geomagnetic storms, when they attain 600–1000 m/s. During particularly severe storms ($a_p$ larger than 154; this index is expressed in 2 nT units) they become large, up to 200 m/s even down to tropical latitudes. These wind amplitudes have been obtained from the thermosphere general circulation model (TGCM output available at the CEDAR database), which model is consistent with observed upper atmosphere winds. Simulations, in which purely zonal (easterly; E) and meridional (northerly; N) winds were added to the drag model (Eq. (6)), were done in order to quantify the effect of unmodelled wind on the densities. Due to the inclination of the CHAMP orbit, the impact of the zonal winds on the (tangential) measurement decreases with increasing latitude; a wind of 500 m/s E causes an error of 10% for a latitude of approximately 67° and decreases to zero at the pole. Its effect is maximal at the equator and there it causes an error of approximately 4% per 100 m/s wind error. On the other hand, meridional winds cause the largest errors at the poles or more generally, at high latitude. These errors are of the order of 5% per 100 m/s meridional wind amplitude, and only 2% per 100 m/s at the equator. Wind causes the noise to increase, but because strong wind mainly occurs at high latitudes it may also cause a systematic geographical error. Therefore, in Table 7 wind errors are not classified in one of the two groups. The total uncertainty in the absolute density value is at the 10–15% level for up to moderate geomagnetic activity conditions ($a_p = 15$), while the mean precision in that case is at the few percent level.

4.4. The ‘observed’ densities

When the derived densities retained are only those for which the precision is better than 5% (i.e. for $a_p$ smaller than 15), a total of 2.15 million density observations over the entire 21-month analysis interval are available. These observations have a 10 s sampling rate, except for the data in period 2 (1/1/2001–5/5/2001) where a downsampling to a 30 s rate was necessary. Fig. 3 shows, besides the bias corrections, also the temporal distribution of the processed STAR data. The data are not continuous: there are gaps at the end of 2000 and in the beginning of 2001. Out of the entire 21-month period, 415 days of density observations were derived (i.e. about 66%). This interval is adequate for the estimation of annual and shorter period variations in atmospheric density.

The altitude varied between 494 and 377 km, with an average of approximately 425 km. The solar local time coverage is homogeneously distributed from 0–24 h, with slightly less data in the 10–12 and 22–24 h local time bins (Fig. 4). The latitude coverage is complete from $-87^\circ$ to $87^\circ$, but the data distribution is not homogeneous; the inter-track spacing is widest at the equator, and smallest close to the poles. Therefore, in the model evaluations this effect is compensated for by means of decreasing the number of data with increasing (absolute) latitude. After this correction, the number of data becomes 1.22 million. Fig. 4a displays the (latitude-effect corrected) data distribution binned per 2 h solar local time, while Fig. 4b shows the data distribution when they are binned per month.

5. Model evaluations

In the following sections, the CHAMP density data will be compared to model predictions. In order to detect specific effects or model errors, the data will be analysed as a function of solar activity, of geomagnetic activity, as well as in monthly, latitude and solar local time bins.

5.1. Variations due to solar activity

The atmosphere is heated by solar extreme ultraviolet (EUV) radiation, the intensity of which is represented by a proxy indicator, or proxy, in thermosphere models. This proxy is either the solar radio flux $F_{10.7}$, or the Mg II index (Heath and Schlesinger, 1986), which is more representative of solar EUV (Thuillier and Bruinsma, 2001). The $F_{10.7}$ radio emission has been measured on a daily basis by the National Research Council of Canada since 1947 and constitutes a complete record. The Mg II index is available since 1978, but often observations are missing. In this study, a composite series was used (courtesy NOAA, R. Viereck). The missing data were padded with interpolated values, which follow the variations in $F_{10.7}$ when the data gaps are larger than 2 days. The averaged and daily values

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Error budget for the density derivation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Systematic error</td>
</tr>
<tr>
<td>STAR calibration</td>
<td>2%</td>
</tr>
<tr>
<td>STAR resolution</td>
<td>—</td>
</tr>
<tr>
<td>Drag coefficient</td>
<td>5–10%</td>
</tr>
<tr>
<td>Attitude</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Macro-model, mass</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Winds</td>
<td>Zonal (East)</td>
</tr>
<tr>
<td></td>
<td>Meridional (North)</td>
</tr>
<tr>
<td>$a_p &lt; 15$ (winds less than 150 m/s)</td>
<td>less than 7.5% at the poles, &lt; 1% at the equator</td>
</tr>
</tbody>
</table>
of both proxies are shown in Fig. 5a and b for the period covering the CHAMP density data, where Mg II has been scaled to $F_{10.7}$ units. These plots show the significantly different behaviour of both proxies. Both present the typical signature of the approximately 27-day solar rotation, but the Mg II index has smaller amplitudes and also contains the 13-day signal that is typical of EUV emissions. The mean values are significantly different also, in particular at the end of 2000 and starting about halfway of the year 2001. The approximately 1-year period from July 2001 through May 2002 presents an annual signature. The density variation induced by solar activity will therefore be difficult to separate from the seasonal variation with the present 21-month data set.

The entire density data set is compared to the DTM-2000 (constructed with Mg II scaled to $F_{10.7}$ units, and $F_{10.7}$), DTM-94 and MSIS-86 models (both constructed with $F_{10.7}$). The mean and rms of the observed-to-computed (O/C) ratios, which we will call density ratio in this study, are given in Table 8. This ratio is unity in case of an unbiased model. Because the precision of the observations is significantly higher than that of the models, the rms of the density ratios represents the capability of the model to reproduce the density variations. Table 8 shows that the means of the DTM-2000 and MSIS-86 density ratios are approximately 1.10 (both with scaled Mg II and $F_{10.7}$), while that of DTM-94 is larger. The rms of the MSIS-86 density ratios is significantly smaller than that of the DTM models. The modelling of the solar activity heating can best be verified by selecting only
data in a zonal band about the equator, so where the energy is deposited. The density ratios are next calculated and divided in mean flux bins. This has been done for DTM-2000, DTM-94 and MSIS-86 using Mg II. For an increasing flux, this revealed a density ratio that increased by approximately 8–10%, which indicates that the models underestimate the heating effect.

5.2. Variations due to geomagnetic activity

These variations cannot be studied with the density data set, because all measurements with an $a_p$ larger than 15 were eliminated. However, an example will be given to show the effect of a geomagnetic storm on the drag acceleration (the combined effect of density and wind variations). This example also serves to show why these data must not be used to derive atmospheric densities. Fig. 6a–c present the observed and modelled tangential component of the drag accelerations for approximately three orbital revolutions, each in the interval 8–9 June 2001. The three plots show the onset and evolution of a geomagnetic storm ($a_p$ increases from about 4 to 62), the effect of which is mainly seen at high northern latitude. The measurements show a maximum on the day side at approximately 65°, a minimum close to the north pole, and a maximum on the night side at approximately 80°. The passage over the north pole is highly perturbed, with a peak-to-peak amplitude of about $-3 \times 10^{-5}$ m/s² within 10° of latitude. The south pole is much less perturbed by the geomagnetic storm. Fig. 6 also demonstrates the rapidity with which the perturbations change between consecutive polar passages. The model density clearly is unable to follow reality: it is smooth and changes little from one orbit to the next.

5.3. Tidal variations

The heating rate of the atmosphere by the Sun is a function of solar local time, declination and Sun–Earth distance. The energy is mainly deposited around the sub-solar point, which is always close to the equator (within the $-23.5^\circ$ to $23.5^\circ$ latitude interval). This causes the temperature and density maxima to be centred about the sub-solar point, with several hours delay though, and thus they are functions of season. Due to the rotation of the Earth, the temperature and density maxima migrate with respect to its surface. At the altitude of CHAMP of approximately 425 km, the principal tidal effect is diurnal. Binning of the DTM-2000 and DTM-94 density ratios per 2 h solar local time showed significant modelling errors. This is evident in Fig. 7, where the MSIS-86 density ratios are also displayed. While MSIS-86 does not reveal a particular model error, the DTM-94 density ratios present a strong diurnal and semi-diurnal signature, as do the DTM-2000 density ratios, but to a lesser degree. The diurnal and semi-diurnal components are too strong in the DTM models.

5.4. Seasonal variations

The DTM-2000 density ratios, when the model is driven by either Mg II or $F_{10.7}$, do not present the same signature when they are binned per month. This is shown in Fig. 8. When the model is driven by Mg II, a clear, annual signal shows up. However, when the model is driven by $F_{10.7}$, the interpretation of the density ratios is not so obvious.
Fig. 7. The density ratios of four models binned per 2 h local time.

Both indices (the Mg II was scaled to $F_{10.7}$ units) were used in the construction of DTM-2000, but not in DTM-94 or MSIS-86. Despite this, the DTM-94 and MSIS-86 density ratios present smoother and more physical signatures (annual and semi-annual; not shown) when driven by Mg II than by $F_{10.7}$. We attribute this result to the better representativity of Mg II for atmospheric heating processes, which allows for a better separation between solar activity driven and seasonal density variations.

6. Construction and analysis of a test model

The comparisons in Section 5 of the STAR-derived densities to the DTM models in particular revealed errors in their tidal representation and latitudinal gradient. In order to evaluate the pertinence of the DTM model algorithm to reproduce these variations precisely as well as analysing them, a test model was constructed. Only the atomic oxygen and molecular nitrogen (i.e. the main constituents at CHAMP altitude) coefficients of the a priori model, DTM-2000, were re-estimated. The coefficients representing the partial density perturbation due to geomagnetic activity could not be re-estimated because the STAR densities are precise up to a maximum value for the geomagnetic index $K_p$ equal to 15 (corresponding to a value 3 for its $K_p$ equivalent) (Section 4.3).

The test model assimilated the STAR densities, but also molecular nitrogen partial densities over the period 1981–1983 from the Dynamics Explorer 2 (DE-2) mission (Carignan et al., 1981). It is called DTM-STAR in the following. The DE-2 molecular nitrogen observations, which are affected by an instrumental calibration error (Hedin, 1987), were corrected with an estimated scale factor of 0.64. The scale factor estimated in DTM-2000 is 0.68, in DTM-94 0.70 (Berger et al., 1998) and that in MSIS-86 is 0.60. Both data sets contain only observations under high, and few under moderate solar activity conditions. Therefore, DTM-STAR is a test model that can be expected to be biased under low solar activity conditions, while the seasonal variation cannot be accurately separated from the solar activity induced variation. It is however representative of the high solar activity conditions during the rather short period considered here. Taking the temporal variability of the thermosphere into account, the semi-annual variability in particular, one may consider DTM-STAR to be a tuned model.

Table 9 presents the mean and rms of the model density ratios for the assimilated data in DTM-STAR as well as the CACTUS (Villain, 1980) and a selection of the DTM database (Barlier et al., 1978) total densities. It is not surprising that the best fit to the STAR densities is with DTM-STAR, but the model also reproduces the DE-2 N$_2$ data with the highest precision, but with a 8% bias (underestimation). Of the non-assimilated data sets, the DTM data base, observations of which were selected with a moderate to high mean solar flux of 130–170 solar flux units (sfu) and in the 200–1000 km altitude range, fits well. On the other hand, the CACTUS observations, which were all taken with a mean solar flux of less than 100 sfu, show that DTM-STAR has a 10% bias under low solar activity.

The STAR density ratios of DTM-STAR binned per 2 h local time are displayed in Fig. 7. The local time modelling of DTM-STAR is more accurate than that of the other models, although a weak terdiurnal signal is present. That variation was not re-estimated in DTM-STAR, but Fig. 7 demonstrates that this is required. Fig. 9a displays the STAR density ratios binned in latitude bands of DTM-2000, DTM-94 and MSIS-86 as well as DTM-STAR. The latitudinal gradient is reproduced unbiased with DTM-STAR only. Fig. 9b shows the DE-2 molecular nitrogen ratios, similar to Fig. 9a, and these data are produced with systematic effects in all four models. DTM-STAR presents a minimum at the equator and (weak) maxima on both hemispheres, while the other models have their maxima at the equator and the ratios decrease towards the poles. These signatures are due to the modelling algorithm that uses Legendre polynomials, the coefficients of which are not accurately estimated; in
Table 9
Modelling performance, expressed as the mean and rms of the observed-to-computed ratio, with respect to the CHAMP density data set

<table>
<thead>
<tr>
<th>STAR densities</th>
<th>DE-2 N₂</th>
<th>DTM data base</th>
<th>CACTUS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
</tr>
<tr>
<td>DTM-94</td>
<td>1.19</td>
<td>0.91</td>
<td>1.03</td>
</tr>
<tr>
<td>MSIS-86</td>
<td>1.11</td>
<td>0.94</td>
<td>1.02</td>
</tr>
<tr>
<td>DTM-2000</td>
<td>1.09</td>
<td>0.99</td>
<td>1.02</td>
</tr>
<tr>
<td>DTM-STAR</td>
<td>1.00</td>
<td>1.08</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>rms</td>
<td>rms</td>
<td>rms</td>
</tr>
<tr>
<td>DTM-94</td>
<td>0.23</td>
<td>0.26</td>
<td>0.22</td>
</tr>
<tr>
<td>MSIS-86</td>
<td>0.18</td>
<td>0.27</td>
<td>0.22</td>
</tr>
<tr>
<td>DTM-2000</td>
<td>0.22</td>
<td>0.28</td>
<td>0.22</td>
</tr>
<tr>
<td>DTM-STAR</td>
<td>0.15</td>
<td>0.22</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The model calculations were done using \( F_{10.7} \) (with the DTM data base and CACTUS for all models), while the Mg II index was used with the STAR densities and DE-2 molecular nitrogen observations in case DTM-2000 and DTM-STAR.

Fig. 9. The STAR-derived (a) and the DE-2 molecular nitrogen (b) density ratios of four models binned in 20° latitude bands.

The aim of the present exercise is to look at the impact STAR-derived densities (will) have on the models. This will be done by plotting the predicted densities on latitude-local time grids for mean CHAMP conditions (altitude of 425 km, mean solar flux of 180 sfu, and a \( K_p \) of 1) of the four models. DTM-STAR is representative of the thermosphere at CHAMP altitude and below, despite the assimilation of only two data sets, as was shown in Table 8 and Figs. 7 and 9. Therefore, it is valid to compare the output of this model to that of DTM-94, DTM-2000 and MSIS-86. Fig. 10 shows the predicted density grids for day-of-year 200 (i.e. northern hemisphere summer). The structure predicted by DTM-STAR is significantly different from that of the other models, and its amplitude is higher. Its maximum does not present significant meridional structure, similar to MSIS-86, but it is at higher northern latitude, at approximately 45° compared to 10° for MSIS-86. The density maximum is predicted at approximately 14 h local time for DTM-94 and DTM-STAR, while that of MSIS-86 is at 16 h, and that of DTM-2000 varies significantly as a function of latitude. The comparisons for day-of-year 20 (not shown) give similar results, except that the DTM-STAR maximum is at higher latitude still, approximately 50° south, and also an hour later (15 h local time) with respect to the northern hemisphere summer.

Semi-empirical density models are used in orbit computation. Because of the significantly different structure and amplitude of the density predicted with DTM-STAR compared to those of the other models, orbit computations were done in order to evaluate the impact of this. A means to evaluate the accuracy of a density model consists in analysing the drag scale coefficients that were estimated in the precise orbit determination (POD) procedure. In POD, the computed drag force, which uses model-predicted densities, is on average corrected for modelling errors by means of multiplicative coefficients that can be estimated thanks to the satellite tracking observations. These drag scale coefficients provide basic information on density: if they are unity on average, the density model is unbiased, while their rms about mean represents the model’s ability to reproduce the density variations. By choosing satellites (altitudes) and epochs (solar activity) judiciously, one can obtain information mainly on a single atmospheric constituent. In the case of DTM-STAR, atomic oxygen and molecular nitrogen are the constituents that were re-estimated and that must be tested. The geodetic satellites Starlette and Stella, at approximately 800 km altitude, and GFZ-1 at 380 km, with orbital inclinations of 50°, 97° and 51°, are suitable targets and are used in this study. Their individual satellite trajectories are each time fitted to 7 days of SLR data in case of Starlette and Stella, and 4 days of SLR data in case of GFZ-1. The epochs correspond to solar minimum (1996), moderate (1999) and
Fig. 10. The density at 425 km altitude and day-of-year 200 on a latitude-local time grid for a mean flux of 180 sfu and a $K_p$ of 1 predicted with: DTM-94 (a), MSIS-86 (b), DTM-2000 (c) and DTM-STAR (d).

Table 10
The mean and rms about mean of the estimated drag scale coefficients issued from Starlette, Stella and GFZ-1 POD using different density models under low (June 1996, 70 sfu), moderate (April–June 1999, 130 sfu) and high (January–February and September–October 2001, 180 sfu) solar activity.

<table>
<thead>
<tr>
<th></th>
<th>MSIS-86</th>
<th>DTM-94</th>
<th>DTM-2000</th>
<th>DTM-STAR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>rms</td>
<td>Mean</td>
<td>rms</td>
</tr>
<tr>
<td>Starlette (10/01)</td>
<td>1.17</td>
<td>0.19</td>
<td>1.17</td>
<td>0.21</td>
</tr>
<tr>
<td>Stella (01/01)</td>
<td>1.23</td>
<td>0.17</td>
<td>1.21</td>
<td>0.15</td>
</tr>
<tr>
<td>Stella (04/99)</td>
<td>1.16</td>
<td>0.24</td>
<td>1.22</td>
<td>0.26</td>
</tr>
<tr>
<td>GFZ-1 (06/96)</td>
<td>0.93</td>
<td>0.14</td>
<td>0.87</td>
<td>0.15</td>
</tr>
</tbody>
</table>

maximum (2001) conditions. The mean and rms about mean of the estimated drag scale coefficients are presented in Table 10. The results demonstrate two points in particular: first, that DTM-STAR is the least-biased model under high solar activity and it reproduces the density variations with the highest fidelity, and second, that the Mg II index is more representative of upper atmosphere heating processes than $F_{\text{10.7}}$ is, as shown by the significantly smaller rms about mean of the drag scale coefficients of both DTM-2000 and DTM-STAR compared to those of MSIS-86 and DTM-94. The drag scale coefficients are displayed for DTM-94 and DTM-STAR in Fig. 11 for the five Starlette arcs covering 35 days in September–October 2001. Under low solar activity, DTM-STAR is biased and the results in Table 10 are
consistent with the result of the comparison to the CACTUS data in Table 9. The Stella results under moderate solar activity, which conditions lead to both atomic oxygen and helium to be the major constituents, present the highest bias of DTM-STAR. The helium modelling was not modified with respect to DTM-2000, which means that the atomic oxygen partial density is too high in DTM-STAR under moderate and probably also low solar activity.

7. Conclusions

The stability of the tangential calibration parameters of the STAR accelerometer is presently at the $10^{-7}$ m/s$^2$ level. This is more than adequate for the present study, taking into account that an error of $10^{-7}$ m/s$^2$ in the applied instrumental bias causes a 1% error in the atmospheric density values. The CHAMP orbit determination, which is necessary to tie the STAR observations to the terrestrial reference frame, is at the few decimeter level, and thus also more than adequate for density modelling. The total densities derived from the STAR observations are accurate and provide good global coverage at approximately 425 km altitude. In this study, only observations for which the geomagnetic activity index $a_p$ is less than 15 were converted into densities in view of contamination of the results by unmodelled winds otherwise. The modelling as a function of geomagnetic activity can probably be improved when observations for which the geomagnetic activity index $a_p$ exceeds 15 are converted into densities, despite their poorer accuracy. The test model constructed with STAR-derived densities and DE-2 molecular nitrogen data only predicts a significantly different density structure at CHAMP altitude than the other models do. The amplitudes as given by DTM-STAR are significantly higher also. Despite these differences, comparison of DTM-STAR to observations under moderate to high solar activity from the DTM data base showed an overestimation of only 4%.

Moreover, analysis of drag scale coefficients issued from POD showed that DTM-STAR is the least biased model under high solar activity. That analysis also confirmed that the Mg II index is more pertinent in density modelling than $F_{10.7}$ is.

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References


