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Appendix 1
1. Introduction

This report describes the results of activities performed during the Science Study “Ionospheric Current Quantification and Modelling for Improved Magnetic and Electric Field Analyses” (ESTEC Contract No. 20943/07/NL/JA). This study intends to evaluate magnetic field recovery approaches for single component current systems in the night side ionosphere. The determination of ionospheric magnetic fields is especially important for main and crustal magnetic field modellers in order to avoid spurious effects in their results. These corrections are particularly important when field gradients (differences between two satellites) are employed in field modelling efforts. The gradient approach is considered as being a dedicated analysis tool for Swarm.

The assessment of the single component current recovery is achieved by comparing the retrieved magnetic fields with results derived from the integration of current elements on the entire low and mid latitude night side. The requested test environment is provided by a physics-based ionosphere/thermosphere model.

At the beginning, section 2 introduces dominant night side ionospheric currents and their significance for main and crustal field modelling. It also includes methods for the single component current recovery and reveals their limitations. Section 3 describes the physics-based model in use, the Coupled Ionosphere-Thermosphere-Plasmasphere (CTIP) model pointing out its advantages and limitations. Section 4 describes the process of creating the modelled ionospheres and the resulting CTIP synthetic data base. The verification of the model output (the synthetic data base) against independent observations is performed in section 5. Methods of magnetic field recovery from modelled ionospheres and its applicability to the CTIP data base are discussed in section 6. Section 7 assesses the magnetic field derived from single component current recovery in comparison with the Biot-Savart method of currents calculated from the modelled data.

The GPS measurements of total electron content (TEC) on board satellites are crucial ingredients to develop ionospheric models which in turn will help to interpret ionospheric current systems. Swarm will provide TEC observations, and section 8 describes our TEC retrieval approach. It also includes the justification for the product and mentions anticipated users.

Small-scale but significant magnetic field deflections arise from ionospheric plasma irregularities in the post-sunset ionosphere (bubbles). The method of identifying bubbles in satellite magnetic field observations is given in section 9. Section 10 summarizes the important results obtained in this study.

2. Single component current recovery

2.1 Dominant ionospheric current components

Electric currents in plasma can be seen as the response to forces acting on the charged particles. The current density is proportional to the electron density, \( N_e \), and the difference in ion and electron velocity (\( v_i \), \( v_e \)).

\[
j = N_e (v_i - v_e)
\]  

(2.1)
where $e$ is the elementary charge.

The charged particles of type $p$ (ions or electrons) are moved by various forces, $F_i$.

$$
\mathbf{v}_p = \sum_i \frac{\mathbf{F}_i \times \mathbf{B}}{q_p B^2}
$$

(2.2)

where $q$ is the charge of the particle and $\mathbf{B}$ the ambient magnetic field.

In the ionosphere the main drivers, apart from the electric field, are winds, the gravity field and the plasma pressure gradient (Kelley, 1989). The gravity force exerted on the particles is $m_i \mathbf{g}$ for the ions and $m_e \mathbf{g}$ for the electrons. From this we obtain the ion velocity

$$
\mathbf{v}_i = \frac{m_i \mathbf{g} \times \mathbf{B}}{eB^2}
$$

(2.3)

Due to the small electron mass its velocity is neglectable. The pressure gradient force has the form $\nabla (n k T)$. Inserting this into Eq. (2.2.) reveals for the ion and electron velocities

$$
\mathbf{v}_i = -\frac{\nabla (N_e k T) \times \mathbf{B}}{eB^2}, \quad \mathbf{v}_e = \frac{\nabla (N_e k T) \times \mathbf{B}}{eB^2}
$$

(2.4)

The resulting velocity is independent of mass. Finally, we have to consider the drag force between plasma and neutral air. The term for the frictional force is $m_i \nu_{n,i} (\mathbf{u} - \mathbf{v}_i)$, where $\nu_{n,i}$ is the collision frequency and $\mathbf{u}$ is the neutral wind. When considering the relation between plasma velocity and electric field, $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$, we get for the ion velocity

$$
\mathbf{v}_i = m_i \nu_{n,i} \frac{\mathbf{E} + \mathbf{u} \times \mathbf{B}}{eB^2}
$$

(2.5)

The electrons are almost unaffected by the neutral particles. Their velocity is $\mathbf{v}_e = \mathbf{E} \times \mathbf{B} / B^2$.

Inserting all the velocity components from Equ. (2.3) to (2.5) into (2.1) we get the expression for the resulting current density. Here all the frictional terms have been lumped together into the conductivity term.

$$
\mathbf{j} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}) + \{N_e m_i \mathbf{g} \times \mathbf{B} - k \nabla [(T_e + T_i)N_e] \times \mathbf{B} \} \frac{1}{B^2}
$$

(2.6)

where $\mathbf{g}$ is the conductivity tensor, $\mathbf{E}$ is the electric field, $\mathbf{u}$ the thermospheric wind velocity, $N_e$, is the electron density, $m_i$ the ion mass, $g$ is the gravitational acceleration, $k$ is the Boltzmann constant, $T_e$ and $T_i$ are the electron and ion temperature and $\mathbf{B}$ is the ambient magnetic field. At night time the first term on the right side can be considered to be small at middle latitudes due to a vanishing E-layer conductivity. The first part of the second term represents the gravity driven current. The magnetic effect of this current type at CHAMP altitudes has been studied by Maus and Lühr (2006). Figure 2.1 shows the relevant parameters determining the gravity-driven current density, $j_g$, at 400 km altitude. The factor $H/B^2$ ($H$ being the horizontal component of the geomagnetic field) favours the equatorial region, but in particular, the South Atlantic anomaly. Current concentrations are expected along the bands of the equatorial ionization anomalies (EIA). The EIA exists also far beyond the terminator (dashed line). Thus the gravity-driven currents are expected to be substantial also on the night side.
Fig. 2.1: Distribution of electron density and normalised horizontal magnetic field strength at 400 km altitude. These quantities determine the intensity of gravity-driven currents, $j_g$.

The last term of Eq. (2.6) denotes the pressure gradient current. This is also independent of a formal conductivity. Its magnetic effect at CHAMP altitude has earlier been studied by Lühr et al. (2003). They report values of up to 5 nT. The currents are circulating around regions of enhanced plasma pressure in a sense that the magnetic field is reduced in regions of dense plasma. Prominent regions for this type of current are again the EIA. During local times past sunset until midnight steep density gradients form both on the F region bottom side and along the plasma trough above the dip equator. Figure 2.2 shows the electron density distribution as observed by CHAMP around 20 hours local times during late October. In some sectors the electron density varies by more than 3 orders of magnitude across the EIA. Here a strong focusing of the pressure gradient currents is expected.
Steep gradients spanning 3 orders of magnitude develop in the equatorial region (from Lühr et al., 2003). 

Thermospheric winds are another means of moving charged particles across the geomagnetic field. On the night side zonal winds are of particular importance at low latitudes. It was Rishbeth (1971) who introduced the concept of the so-called “F region dynamo”. This dynamo drives toroidal current systems on both sides of the dip-equator. The magnetic field caused by these currents is well confined within the toriodal current loops. Therefore it requires a low flying spacecraft that cuts through the current system to observe the field deflection. Magsat was the first to observe magnetic signatures of the F region dynamo (Maeda et al., 1982), but measurements were limited to the 18 LT sector. Only CHAMP provided the opportunity to sample the effect of the F region dynamo at all local times, for details see Lühr and Maus (2006). The derived current configuration is sketched in Fig. 2.3.
The zonal wind, blowing perpendicular to the geomagnetic field, causes charge separation near the equator due to the Lorentz force, which results in a downward E-field before noon and an upward E-field in the evening and on the night side. This electric field is mapped along the field lines to the ionospheric E-layer. During day time the E-layer is highly conductive and a meridional current system can form. In sunlight the dynamo acts as a current source. Opposed to that on the night side it behaves like a voltage generator obeying the simple relation

\[ \mathbf{E} = \mathbf{u} \times \mathbf{B} \]

The observed current densities in the dark sector are thus proportional to the product of the zonal wind speed and the ionospheric conductivity.

### 2.2 Methods for single component current recovery

For a proper calculation of all these currents, in principle, the global distribution of the plasma, its temperature and the forcings have to be known. In case of CHAMP only local measurements of the environmental parameters are available, therefore we had to limit ourselves to first order approximations and calculate the currents individually for each component.

For estimating the gravity-driven currents we employ the plasma density distribution given by the IRI-2001 model. Current densities are computed for all volume elements from the E-layer up to 1000 km altitude. For each magnetic latitude and altitude level we find the longitude (local time) of lowest current strength. This minimum current (hereafter termed
“bottle neck approach”) is assumed to circle the Earth divergent-free. Figure 2.4 shows the sheet current density distribution at 400 km altitude for the two solstice seasons. Between two lines 1 A/m is flowing. Underlain is the electron density distribution for 18 UT. As expected, the current density is clearly higher in the summer hemisphere. For further details see Maus and Lühr (2006).

Fig. 2.4: Current streamlines at 400 km altitude of the non-divergent part of the gravity-driven currents. A sheet current density of 1 A/m flows eastward between two contour lines (from Maus and Lühr, 2006)

By integrating over all current elements the magnetic effect at the satellite can be computed. In particular the radial field component is affected by the gravity-driven current. As seen in Figure 2.5, a downward directed field of about 5 nT is generated in the southern hemisphere and an equally strong upward in the northern. We are aware that this approach may underestimate the magnetic deflection, due to the restriction to the zonal minimum current strength.
Fig. 2.5: Magnetic deflection of the vertical component caused by gravity-driven currents. The model estimates are in reasonable agreement with the observations from 20-22 LT.

The uncertainties associated with the determination of the gravity-driven currents are mainly limited to the electron density. All the other quantities are well known, e.g. $g$, $B$, $m_i$ (dominance of $O^+$). In particular, the height distribution of the plasma density is not well constrained from in situ measurements of a single satellite. In this case a reliable ionospheric model is needed to extrapolate the vertical profile from the measurement point. A significant improvement is expected when observations at two altitudes are available, as in the case of the Swarm constellation. This will help a lot to adjust the model to the actual electron density profile. When considering a typical plasma height distribution after sunset, the local density measurements at 400 km can account approximately for 30% of the magnetic field deflection in the vertical component. The remaining 70% depend on the upward and downward extension of the profile. For this reason the correction of this type of ionospheric current is strongly dependent on a good ionospheric model.

Also in the case of pressure gradient currents only a first order approximation can be applied. Based on the assumption of a stationary momentum equation we argue that every change in plasma pressure has to be counter-balanced by an adjustment of the magnetic pressure

$$\frac{(B - b)^2}{2\mu_0} + \Delta \left[ N_e (T_i + T_e) \right] k = \text{const}$$

(2.8)

where $\mu_0$ is the susceptibility of free space and $b$ is the magnetic field required to balance the change in plasma pressure. All the other quantities have been defined in Eq. (2.7). For stationary, large scale plasma regions we may write according to Lühr et al. (2003)

$$b = \Delta N_e (T_i + T_e) \frac{k_0}{B}$$

(2.9)

Here we have neglected the quadratic term, $b^2$ because $b$ is 10000 times smaller than $B$. Since all the quantities on the right hand side are measured or known, the modification of the magnetic field can be estimated. This so-called diamagnetic effect changes primarily the field...
strength. At low latitudes it can therefore be distinguished reasonably well from the magnetic effects of other current types. Figure 2.6 shows the estimated diamagnetic effect for the same time period as shown in Figure 2.3. Deficits in magnetic field strength of up to 5\,nT are found along the EIA crests.

![Fig. 2.6: Global distribution of depletion in magnetic field strength at 400 km altitude caused by the diamagnetic effect (from Lühr et al., 2003).](image)

Eq. (2.9) places certain requirements on the accuracy of the plasma measurements. In order to obtain the needed precision for $b$ of better than 0.5 \,nT some typical error limits are listed below. For typical ionospheric conditions we find $T_e \approx 2000\,K$, $T_i \approx 1000\,K$ and $N_e\approx 10^{12} \,m^{-3}$. Considering an ambient field strength of 30,000 \,nT and inserting the constant $k = 1.38 \times 10^{-23}$ we obtain $b = 1.75 \,nT$. To achieve the quoted accuracy of $b$ the error of $T_e$ has to be less than 500\,K, of $T_i$ less than 250\,K and of $N_e$ less than $2 \times 10^{11} \,m^{-3}$. All these requirements are moderate for up to date instruments.

The currents driven by the F region dynamo can be derived directly from CHAMP magnetic field measurements. As illustrated in Figure 2.3, there are downward currents above the dip-equator in the noon sector and upward currents in the evening. From the peak-to-peak variation of the magnetic field $By$ component, when passing the equator, one can deduce the integrated, vertical current strength, $J_z$ , (Lühr and Maus, 2006)

$$J_z = \frac{1}{\mu_0} \Delta B_y$$

(2.10)

This vertical current is diverted into the northern and southern hemisphere. It flows along field lines to the E-layer. There it is conducted to the field lines which support the return.
currents. The balance between the current densities in the two hemispheres is of cause influenced by the respective conductivities in the ionosphere.

Figure 2.7 shows the local time distribution of the typical current density driven by the F region dynamo, as observed by CHAMP. Displayed are average values of the years 2001 to 2005. The current density shows clear peaks of opposite signs at noon and dusk. This is indicative for a change in zonal wind direction from westward during daytime to eastward in the evening/night. Towards midnight the current fades slowly away, probably because the ionospheric conductivity gets progressively smaller. The magnetic fields caused by these currents are confined primarily to the east/west, By, component. Peak-to-peak deflections are generally less then 10 nT.

![F-region dynamo, vertical current](image)

Fig. 2.7: Local time variation of the vertical current density driven by the F region dynamo.

The prediction of the F region dynamo currents depends at first place on the determination of thermospheric zonal wind velocity. Since thermospheric winds are known to vary only a little with altitude, single side measurements should provide suitable inputs. The height dependence of the wind will be, however, tested with the Swarm constellation. For estimating the required accuracy of the wind measurements we have a look at Fig. 2.7. At 18 LT we find a current density of 4 mA/m, which causes deflections of ±3 nT in the eastward component. Prevailing winds at this local time are about 150 m/s (Liu et al., 2006). For predicting the magnetic effect to 0.5 nT the wind velocity has to be measured with a precision of 25 m/s, which is a challenging task for an accelerometer. Another quantity of importance for the wind dynamo is the collision frequency. It depends on the neutral and plasma density, the composition and on the temperatures. Vertical profiles of these quantities have to be derived from models, but with anchor points at the Swarm satellite heights for the densities and the electron and ion temperatures. A proper characterisation of the F region dynamo driven currents is therefore considered to be most challenging.

In summary, the magnetic effects expected from the various current components are compiled in Table 2.1. Since the most variable parameter of environmental conditions is the electron density, $N_e$, we provide numbers for two extreme cases; worst case at solar maximum and
best case at solar minimum. The components, for which the deflections are listed, are mentioned in the last column. In addition, a typical wavelength for the peak signal amplitude is also given.

Table 2.1: Estimate of the magnetic deflections caused by the various current components both for solar maximum and minimum conditions.

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<th>Current drivers</th>
<th>Typical magnetic effect</th>
<th>peak wavelength</th>
<th>affected component</th>
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<tr>
<td></td>
<td>@ n=10^{11}</td>
<td>@ n=3\times10^{12}</td>
<td></td>
</tr>
<tr>
<td>gravity</td>
<td>±0.25 nT</td>
<td>±7.5 nT</td>
<td>3000 km radial</td>
</tr>
<tr>
<td>pressure gradient</td>
<td>-0.2 nT</td>
<td>-5.5 nT</td>
<td>1000 km magnitude</td>
</tr>
<tr>
<td>zonal wind</td>
<td>±0.2 nT</td>
<td>±6 nT</td>
<td>2000 km eastward</td>
</tr>
</tbody>
</table>

2.3 Shortcomings and needed improvements

So far we have treated all the various current components independently. In reality they all contribute to the total current distribution. This has to be divergent-free. In case of missing closure currents charges are piled up and a polarisation electric field is set up, which terminates the excessive current. By now we have no suitable tool to realise such a system approach.

In order to assess the quality of the magnetic field predictions derived from the calculated currents we perform comparisons between most recent magnetic field models and actual CHAMP measurements. From the obtained residuals we get at least a qualitative idea about the reliability of the derived current components.

The magnetic effect of the pressure gradient currents has been calculated according to the first order relation, Eq. (2.9). This does not take into account the current geometry. Figure 2.8 illustrates schematically the geometry of the pressure gradient currents in the vicinity of the equatorial ionization anomaly. The flux tubes of enhanced electron density are flanked by currents reducing the field strength inside the dense area. This means, the generated magnetic field, $b$, is pointing in the opposite direction of the ambient. At higher altitudes, where the ionization anomaly has its top limit, the generated magnetic field continues into the diluted plasma region because of the boundary conditions that require a steady continuation of the radial component. We thus expect a depletion of the ambient field close to the dip-equator outside of a denser plasma region.
For a test of this hypothesis we made use of CHAMP total magnetic field measurements. In a first step we removed the core, crustal, and magnetospheric fields with the help of a recent POMME-3 field model (Maus et al., 2006). In a second step the diamagnetic correction according to Eq. (2.9) is applied. The magnetic field residuals should be close to zero after this reduction. Figure 2.9 shows latitudinal profiles of quiet day averages for the hours around midnight. Within the range of ±40° latitude the curves of residual are rather flat and close to zero, as expected. In the vicinity of the equator there is a small but consistent deficit in field strength of about 1 nT. This is evident during all displayed hours. We interprete this as the external part of the diamagnetic field, as illustrated in Figure 2.8, which is not accounted for by our Eq. (2.9). With the Swarm constellation, sampling the ionosphere at two heights, it will be possible to check this hypothesis and probably correct for the deficit.

The applied diamagnetic correction approach has another limitation. In the case of a small (<100km) size of the plasma anomaly region the assumptions for Eq. (2.9) are violated. Therefore, it cannot be used for compensating the modification of the ambient magnetic field. Also current ionospheric models are not able to predict these plasma density irregularities. A dedicated approach for identifying these so-called plasma bubble events has to be developed. This will be the task of WP 3400. It will be used in the date selection scheme for main field modelling.
In the previous sections we have described how the gravity-driven currents are estimated for the correction of the CHAMP magnetic field data. For an assessment of the reliability of the derived current distribution we make again use of actual CHAMP measurements. As done before, we calculate the residual magnetic field by subtracting a field model (POMME-3) and correcting for the diamagnetic effect. In this case we focus on the vertical component, Bz, (positive downward), which reflects best the effect of gravity-driven currents. Figure 2.10 shows average latitude profiles of the derived residuals for the hour before midnight. There is clear evidence that the bipolar deflections, which can be attributed to the effect of gravity-driven currents, get significantly smaller during the hours from 20 to 24 LT. This implies a reduction of the current strength towards the later night time.

In Figure 2.5 we have presented the magnetic effect of gravity-driven currents as predicted by our model when applying the ‘bottle neck approach’. As can be seen, the modelled magnetic deflection fits reasonably well the observations from the time sector 20 to 22 LT. Since we are considering in our model only the minimum current density at all longitudes, the predicted magnetic deflection is independent of local time. This result is not consistent with the CHAMP residuals shown in Figure 2.10.

For a further investigation of the above found inconsistency between predicted and observed magnetic effect caused by gravity driven currents we made use of the high-resolution (up to SH degree 100) lithospheric field model, MF5 (Maus et al., 2007). Figure 2.11 shows a comparison between CHAMP quiet-days night time observations and the MF5 model. Clearly visible is a systematic bipolar signal of ±2 nT amplitude, which is centered on the magnetic equator. For the construction of the MF5 model the CHAMP data have been corrected for the effect of the gravity-driven currents using the bottle neck approach. Obviously, this procedure overestimates the effect by 2 nT when taking all night time hours into account. This result is surprising since the minimum current strength was applied everywhere. We may suggest that the electron density in the ionosphere on the night side is even further depleted than reflected by the IRI model. From this fact we may conclude that the accuracy of the IRI on the night side is not sufficient for predicting the effect from gravity-driven currents.
Fig. 2.10: CHAMP vertical magnetic field residuals from quiet days after subtraction of the POMME-3 model and correction for the diamagnetic effect. Averages each of the four hours, 20-24 LT, are shown.

Fig. 2.11: Residuals of the vertical component between CHAMP measurements and the MF5 lithospheric magnetic field model. A prominent bipolar signal, anti-symmetric about the magnetic equator, is visible (from Maus et al., 2007).
3. The Coupled Ionosphere-Thermosphere-Plasmasphere Model (CTIP)

3.1 Identification and Justification of input model

3.1.1 Modelling the upper atmosphere

For the current project we are looking at supplying modelled atmospheric parameters for working on the analysis of satellite data. The idea is to provide as realistically as possible what the satellite would measure at a particular location and height. The model used must therefore supply the necessary parameters, at an appropriate spatial and temporal resolution.

The parameters needed (see 3.3 and section 2) are mainly ionospheric, like electron density and ion mass. An ionospheric model might therefore be considered adequate, and there are a number of empirical or numeric ionosphere models available. However this assumes the ionosphere is unaffected by external factors such as the background neutral atmosphere chemistry and the time history of the atmosphere, which is demonstrably not true. The basic gravitational and magnetic field configurations can be provided by separate models since there is little dependence of these factors on other than position (with the exception of the minor dependence of B on the currents this project sets out to quantify). However, to properly represent the ionosphere one needs a model that relates the ionospheric components to all the external variables which can affect them. This implies that there must be some dependence on neutral parameters and any factors not built into simple ionospheric models. For this reason we recommend using a 3-d coupled numerical ionosphere-thermosphere model. It is possible to get separate empirical ionospheric and thermospheric models but these would not be mutually self-consistent.

3.1.2 Models of the upper atmosphere

The two main types of model we might use are empirical and numerical (first principles) models.

Empirical models are usually constructed by taking a large set of “real” data, taken under a variety of conditions, and fitting a set of parameters to that data. The empirical models are either of the ionosphere or of the neutral atmosphere. The ionosphere models include IRI (International Reference Ionosphere; Bilitza, 2001), and Chiu (Chiu, 1975). These are of different complexity and dimensionality, but usually consist of an expansion in relevant components and a set of coefficients for the expansion terms. Chiu is the simplest using just 50 coefficients to describe the ionospheric density in local time, latitude and sunspot number. FAIM (Fully Analytic Ionospheric Model) is an analytic version of this, with more ionospheric profiles being used to constrain the coefficients (Anderson et al., 1989). IRI divides the ionosphere into several layers and finds different functions to represent the shape of each layer. It uses 21 parameters to describe the topside, then different representations of bottomside, intermediate region, “valley” etc. It can be used to give electron density, the number densities of the major ions, electron and ion temperature from 50-2000 km altitude, though the authors say it is only reliably a mid-latitude model, and its output is primarily monthly averaged data. PIM (Parameterised Ionosphere Model; Daniell et al., 1995) is produced by combining three different empirical and theoretical models and then representing them as empirical orthonormal functions, using several million coefficients. It gives primarily height profiles of electron density from 90 to 25000 km for specified geophysical conditions and spatial coordinates. A version of it can be used with data assimilation, and one of its
component programs (GTIM) computes the constituent ion densities and ion drifts. The ionospheric models provide the geographic and height distributions of electron density, \( N_e \) – and usually also the ion densities of the different ion species (which in any given volume must sum to equal \( N_e \)). The TEC (Total Electron Content) – the column cross-sectional sum from ground to infinity – is also often available as the sum of electron densities with height, though how accurate this is will depend often on how high the model goes.

The models of the neutral atmosphere are also usually based on expansions. The most commonly used are MSIS (which stands for Mass Spectrometer and Incoherent Scatter, illustrating its main data sources – Hedin, 1983, 1987, 1991) and CIRA (COSPAR International Reference Atmosphere – which is based on an early version of CTIM, the precursor of CTIP [see section 3.3] but constrained by a database of largely satellite and rocket data – Rees (ed), 1988 and Rees et al., 1990). These models will provide neutral composition and the neutral temperature profile. The MSIS model is the most developed and has gone through a number of upgrades since the first version, as more data has been incorporated – the latest version has been taken over by the Naval Research Laboratory in the USA and is known as NRL-MSISE-00 (Picone et al., 2002).

MSIS and CIRA will not provide ionospheric parameters. In fact there is no empirical model which provides all the neutral and all the ionospheric parameters in one package. The resolutions and accuracies of these empirical models (neutral and ionospheric) is constrained by the number of coefficients they use for their expansion. The MSIS-86 model, for example, has 191 coefficients – but that obviously does not go very far if you are expanding in latitude, longitude, height, day of year, year and Kp and constituent. Some assumptions are made to reduce the coefficients needed. The “year” is a proxy for solar activity and the number of coefficients used for the height expansion is reduced by assuming a Bates profile in the thermosphere (i.e. that the species fall off from the turbopause with their individual scale heights). The resolution in reactivity to magnetic activity is restricted to a function of Kp – which is anyway not continuous, but is not perhaps the best of proxies to use in all conditions.

Besides the ionospheric and neutral atmosphere models, there is an empirical model of upper atmosphere dynamics which is closely related to MSIS - the Horizontal Wind Model (Hedin et al., 1988) which is based on Fabry-Perot Interferometers and some satellite data. This just gives average wind patterns for specified conditions but is limited in variability and resolution even more than MSIS.

The other class of models is “first principles” or numerical models. These work by calculating the state of the atmosphere from the thermodynamic and chemical influences it is under. They range from models which use an input neutral composition to calculate from the solar EUV radiation (and possibly also the neutral wind dynamics) the ionospheric composition and temperatures, such as the FLIP – Field-Line Interhemispheric Plasma (Richards, 2002) – model which includes a model of the Earth’s dipole field to calculate transport of plasma. More comprehensive in their approach, though are the self-consistent fully coupled 3-d numerical models. It is not true that these are entirely “data free” since there has to be a starting point for the physical calculations involved. They usually start with an assumed composition (at least up to the turbopause from which they are allowed to diverge by diffusion) and an assumed pressure at a reference altitude. A “start-up” model is often used at the beginning of the simulation to speed up the time to convergence to a numerically self-consistent end-point. They usually then solve the Navier-Stokes equations of energy,
momentum and composition. A number of these models exist but the best known and the longest-running developments have been with the TIME-GCM/TIE-GCM series of models from NCAR in Boulder, USA (Roble and Ridley, 1994) and the CTIM/CTIP series of developments which were a joint development of the Atmospheric Physics Laboratory at UCL, the Department of Applied Mathematics at Sheffield University and the SEC (Space Environment Center) at Boulder. There are a number of other models available worldwide which provide variations on the way the TIME-GCM and CTIP work. These include the US WACCM, CISM models, the Canadian CMAM, and German models such as Hammonia. These may cover smaller or larger height ranges than TIME-GCM and CTIP, and sometimes use different coordinate systems (e.g. spectral gridding) or assumptions but all basically use the basic physics of energy, momentum and composition conservation to calculate from first principles the state of the atmosphere under specified inputs.

We shall not attempt to compare the multitude of different models available, but use instead as our example the CTIP model, which is described here below. Other numerical models could be used for this study but this is the one with which we are obviously most familiar, and within Europe is the model with the longest history of development. We recommend the use of such a first principles model for several reasons. The most important of these is the control over resolution which it enables. We can use empirical models to define behaviour in "average conditions" but they will not respond at higher temporal or spatial resolution than their parameters allow. They may be more accurate when it comes to representing absolute values on average, but they have an averaged structure which prevents small spatial scale features being represented. As an example, MSIS is a poor representation of temperatures in the auroral zone (Griffin et al., 2004) because heating and momentum inputs are very localised (and the datasets on which MSIS was based tended to be mid- to low-latitude extrapolated to the poles). The second reason for choosing CTIP is its coupled nature – that is the ionospheric parameters are not derived independently of the neutral atmosphere composition and dynamics. The electron density even at mid-latitude where particle precipitation and large electric fields can be ignored, is thought to be primarily determined by EUV solar insolation and the local ratio of O/N₂. So the ionospheric composition cannot be assumed independent of the neutral composition. The empirical models assume that at a given magnetic and solar activity level the using conditions such as the neutral composition which contribute to the electron density, Nₑ, will always be the same. This ignores any neutral composition “history” or transport from other active regions. The first principles approach allows all combinations of time variable and historic inputs, and indeed for differing combinations of inputs to be tried to look for matches with what may at first appear to be non-conformist data. The closer we get to the auroral zones, the equatorial zones, or “active conditions” even at mid-latitude, the more the advantages of first-principle models become apparent.

3.1.3 Justification of CTIP

CTIP - the Coupled Thermosphere Ionosphere and Plasmasphere model is a 3-d numerical Global Circulation model (GCM). It is based on a thermosphere model using a Euclidean grid (latitude, longitude and pressure level for height) coupled to a Lagrangian model of the ionospheric flux tubes. It is described in Fuller-Rowell et al. (1996) and Millward et al. (1996). The technique of solution is such that at each timestep the energy, momentum and composition equations are solved numerically (and hence increments of temperature, velocity
and chemical composition calculated for that time step for each grid point of the model). The thermosphere and ionospheric flux tubes calculations are done separately, but the thermospheric composition is fed into the plasmasphere code to use as a basis for its chemistry, and at (typically) every fifteen minutes (model time) the ionospheric parameters such as ion velocity and electron density are passed to the thermospheric code for use in, for example, the solution of the momentum equation.

It is this self-consistency which is the advantage of using a coupled model for this study. The basic time step in the model is 60 seconds (30 seconds under active conditions) and this gives a control over temporal variability which is superior to empirical models. CTIP includes a global electrodynamics solver which provides a globally self-consistent solution to the conductivities and electron densities worldwide given the pattern of neutral winds.

In section 2.1 the calculations are described for the gravity and plasma pressure terms leading to local ionospheric currents. For the first of these the parameters needed for the calculation are electron density, average ion mass and the value of \( g \). CTIP uses a constant “\( g \)” value, but this is unlikely to have a significant effect on the derivation of current (a separate calculation of "\( g \)” from a suitable geophysical model could be used, see Appendix 1). The value of \( N_e \) is available from CTIP for every grid point, as is the average ion mass (using the volume mixing ratios of the different ions, although at CHAMP altitudes it would tend most of the time to be pure O⁺). Extracting the data for the CHAMP orbit, for whatever (linear) resolution is needed requires appropriate interpolation between grid points. This can be done at arbitrary spatial resolution. The model time steps on every minute and so in principle the required data is available from the model at that time resolution. However normally the data files are only written out every hour, so to match a specific time not on an hour boundary, a "trace" output would have to be included in the model code. (This is often done for studies requiring a specific time to be output, but may be slightly more complex here since the time and spatial position are both changing along the spacecraft orbit. The UCL group is looking into the best way of doing this.)

For the plasma pressure gradient term the supply of parameters is more complex. The parameters needed to derive the current now include electron density, \( N_e \), as above, but also the ion and electron temperatures - or at least the local gradient in temperature. The magnetic field is also needed.

Dealing with the magnetic field first, in CTIP currently the main B-field configuration - used to define the shape and movement of the plasma tubes – is calculated using a tilted dipole approximation to the Earth's field. This is in effect the first 3 terms of the full IGRF (International Geomagnetic Reference Field) field expansion. For many uses this is usually adequate but where the local details of magnetic field are important this can be a limitation. For example, the field in the American sector (Fig. 3.1) is not well represented around the magnetic equator and the directions of currents derived in this section would be offset and rotated from their true orientations. A new version of CTIP plasmasphere is being developed using an “Apex Coordinate system” which is based on the “full” IGRF. This version is not fully validated for all ionospheric parameters yet. Where the directional information is important in this study, if we cannot just transform the components into the right orientations using the IGRF as we extract the data from the model, then the apex field system could be used, though then there may be caveats attached about the validation.
The ion and electron temperatures from CTIP are based on the full ion and electron energy equations. Such implementation has first been done in other models like the Utah State ionosphere model (Sojka et al., 1980) but the calculated values have been difficult to validate. All the parameters which go into the energy equations are available from within CTIP and are applied in this module.

Some possible limitations of the CTIP calculations must be mentioned here. GCMs of the CTIP type are developed primarily nowadays for studies of specific or dynamic events where it is the difference between two states of the terrestrial system that we are interested in. They are not necessarily optimised for calculating absolute number densities. The parameters used to specify some of the controlling conditions can be quite simple. So, for example, it has been found that F10.7 cm flux does not produce a linear response of temperature in the thermosphere. E.g., when the model efficiency is adopted for correct thermospheric temperatures at F10.7=130, it underestimated the temperature at lower F10.7 flux, but overestimated it above 130 (Fuller-Rowell, private communication). This can be allowed for by putting in a variable efficiency – i.e. make the efficiency itself a function of F10.7 – but apart from a crude “dog-leg” function suggested by Fuller-Rowell this has not been considered worthwhile for most studies (as calculating the form of the function would require a large number of runs). The F10.7/temperature non-linearity is unlikely to be a problem for this study where $T_n$ would be a second order correction to the ionospheric parameters, but a similar comment can be made about the absolute electron density values, since they are also derived from solar insolation. We will need to look at how serious this is for these simulations – it may be possible to cope with this by a simple scaling, but if not the number of simulations may have to be increased to “bracket” the conditions for each comparison with the satellite data.

![Fig. 3.1: Difference in the field configuration between a simple offset tilted dipole approximation of the Earth’s field (left) and the full IGRF filed (right). The white points represent the flux tubes crossing the 100 km altitude surface, positioned at equal L-shell and geomagnetic latitude. These are the plasma tubes used in the current apex-coordinate version of CTIP.](image-url)
Also the available number of heights for the model is limited. CTIP uses 15 pressure levels (spaced one scale height apart) in its standard configuration, with a lower boundary at 80 km. At times of high solar activity and high Kp, the atmosphere is heated and thus expanded - and the top pressure level can be over 600 km in altitude. However, conversely when the solar activity is low and there is little geomagnetic activity the top pressure level may have a problem to reach much over 300 km in some locations. Swarm’s altitude of 400 km may thus not be achievable by the simulations with CTIP in its standard configuration. Attempts have been made to overcome this limitation in the past by adding pressure levels to the top of the model. However this is not always as easy as it sounds – as the proportions of He and Hydrogen may be then large enough to make the CTIP assumptions about the three main neutral species no longer valid. Also runs of this sort in the past have proven liable to instabilities due to the increased vertical diffusion velocities in the topside meaning some species can cross a significant proportion of a scale height in one iteration period.

One task of the project is the description of TEC retrieval from GPS observations onboard the Swarm satellites (WP-2500). This task will rely on experiences from the successful GPS experiment during the CHAMP mission; this task does not require inputs from CTIP modelling efforts.

### 3.2 Model algorithms and performance

CTIP has a number of limitations which apply to the accuracy and resolution of the modelled parameters. It has been used primarily to analyse phenomenological behaviour and as such has not been optimised to give accurate absolute values. Its usage has also been concentrated on certain parameters (like \( N_e \) and neutral temperature \( T_n \) and winds \( U_x \) \( U_y \) and \( U_z \)). Other parameters like the plasma temperatures \( T_e \) and \( T_i \), while they have been experimented within the past have generally not been developed in any systematic way.

CTIP solves the Navier Stokes equations for a (neutral) fluid on a latitude, longitude, pressure level grid, with a lower boundary set at 80km, and fixed in temperature (140K) and pressure (1 Pa). It was developed initially as a thermosphere model - ie it was aimed primarily at getting the neutral atmosphere correct, as its description as a GCM - Global "Circulation" model, implies. The ionosphere was incorporated in the mid-80s because this had an important effect on the energy and momentum inputs to the neutral atmosphere. As the reverse was also true, the model was turned into a "Coupled" model with feedback in both directions ionosphere to neutral and back again. The morphological accuracy of the model is limited by its spatial resolution and by the resolution of the empirical inputs it uses. Thus the high latitude (magnetospheric derived) ionospheric energy and momentum inputs are described by the Foster electric fields in the version we have used here, and the precipitation by a Tiros precipitation model. These are averaged empirical models with limited Kp and spatial resolution, so the model cannot do a better job in terms of resolution than they do. The model is not, in that sense, like a meteorological model, because it is not served by the hundreds of weather stations that meteorologists have. On the whole the inputs are very limited in scope and resolution.

One exception to the low resolution of available atmospheric parameters can be the electron density where extensive TEC measurements are available nowadays. However pure ionospheric models (ie those not self-consistent with neutral atmosphere parameters) have been developed which on a short time scale can describe the ionosphere to much finer
absolute accuracy than a first-principles model like CTIP. CTIP's forte is in the insight it gives into processes on the medium and long time scales result from neutral atmosphere changes.

CTIP uses a number of external inputs to provide its energy, momentum and composition drivers. We have already mentioned the Tiros and Foster high-latitude empirical models. The main energy input, however, is of course the solar insolation. The solar radiation input is a fairly detailed spectrum (1nm resolution generally) and it has a moderately comprehensive ionisation and dissociation cross-section database, so that the rates of ionisation and dissociation from solar insolation are probably accurate to 10% or better. The heating this produces is less well constrained since the amount of the ionisation, dissociation and energisation energy that goes into heating is not well known. However, synoptic studies indicate that the heat input is probably accurate to 10-20% under most circumstances. All these figures refer to the neutral atmosphere. The ionospheric ionisation rates should be accurate to the same level, but recombination and redistribution processes are more complex and a number of validation factors are needed to get the absolute values right. Most of the work with the model has been looking at variability, and the work needed to continually maintain the absolute value accuracy has not been a priority. Hence the variability of ionisation has been generally reckoned to be representative of the "real" ionosphere, but absolute magnitudes can be prone to offsets of several tens of percent. If the model were to be used for more in-depth comparative studies, the version to be used could easily be made more accurate in absolute terms by refining the internal efficiencies and constants in a validation exercise. (Nevertheless, because of the nature of the first-principles calculations, we would never expect the model to be "locally" accurate at the time resolution of the model as the controlling inputs are not accurately known.)

One constraining influence on the ionisation distribution is the earth's magnetic field. The version of the model used for this study uses a tilted dipole approximation to the field, which as we have seen has limitations. This can be improved slightly by using the tilted offset dipole which is an option in the model, but to get realistic morphology on a "local" basis one would need to use a detailed IGRF field configuration. This is not possible with the electrodynamics solver currently in the UCL version of the model, though a version using the APEX coordinate field system and a revised solver is under development by our collaborators in Boulder.

The plasma parameters other than electron and ion densities has also not been a priority in the past since the electron and ion temperatures do not play a major role in setting the neutral temperature or modifying the gas flow. Currents, while calculated in the model, have also not been an important output for most studies. The result of this is that $T_e$ and $T_i$, where they are available, have been calculated using simple routines that do little more than give a regional average. To calculate them to more accuracy for this study, we solved the ion and electron energy equations - and while this option is available with one of the builds of the model that we have, the routines involved have never been validated enough to make them stable enough for the sort of calculations needed for the Swarm study. Applying the full energy equation module caused the model to crash occasionally, and few hours are missing in the provided data base.

The currents calculated in previous studies have concentrated on the stronger auroral features, so prior to this study more esoteric effects like the gravity current and the pressure gradient
current were not included. The electrodynamics solver did do a global solution of the 2-d electric field distribution set up to counter the space charge generated by neutral winds blowing the ionisation across magnetic field lines, but this was also limited to the grosser features, and should be altered to give global consistency if the smaller current effects are introduced. The other element of the electrodynamics solver that could be modified would be to make it divergence-free. At the moment the solution is only for a 2-d surface, and it is assumed that the currents are closed off by field-aligned currents which are not themselves calculated. We believe we have a method for doing this but have not attempted to implement it in the course of this study.

Other features which need to be taken into account to improve the absolute values and resolutions in the model include refining the lower boundary input to the model. It already includes tides as an input (though it is rare that one has details of the tides in the real atmosphere at this level) but to properly include effects such as gravity waves and planetary waves would require a model like CMAT2, the successor to CTIP, which has a much lower bottom boundary.

4. Forward modelling

4.1 Model setup and simulation of representative ionospheres

CTIP is a first-principles model. It calculates the electron density distribution by taking the solar insolation at a given F10.7 cm flux and the neutral density distribution with height and estimating the balance of ionisation vs. recombination. The neutral temperature is calculated by assuming a fraction of the ionisation, dissociation and excitation energy goes into thermal energy. The winds are calculated by considering the pressure gradients, ion drag and other forces acting upon the neutral air cells. The energy and momentum inputs are represented via parameters in the input file: solar insolation via F10.7 cm flux value, magnetic coupling to the solar wind via the Tiros Activity index (which translates into Kp or Ap), and coupling to the lower atmosphere via tidal amplitudes and phases. Thus, to simulate the conditions appertaining to the CHAMP periods identified for this study, the relevant indices were used for those days. The tides (initially) were ignored - that is, set to zero amplitude at the 80 km lower boundary - since there are no current estimates of what they were on those days.

Fig 5.1 is a Table of the ‘CHAMP days’ used in this study. We are primarily looking at a comparison with the satellite on days 334 (2001), 190 (2003) and 149 (2006). F10.7 flux value is given in the table. The Ap values were converted to Tiros index.

An initial atmosphere is needed as a starting point. To make this as accurate as possible, a ‘run-up’ to the specific CHAMP days was used. Thus, starting several days beforehand (typically 8 days, depending on the run) an initial ‘steady-state’ condition was set up by running the same day over and over until the output stopped changing between runs. (We start from a previous simulation that had conditions near to those being modelled, then run at the Tiros/F10.7 for the day in question, using the output of each run as the input for the next until there is little discernible difference between the outputs from consecutive runs.) Once a ‘steady-state’ run has been set up for the start day, the model is run forward in time to the specified ‘CHAMP day’ using the appropriate Tiros/F10.7 inputs, each day's output being used as the starting point for the next day. Thus, for day 334 (01) - refer to Fig 5.1 - we started by setting up a steady-state run on day 329, then running forward to day 337.
The currents are not a standard output from the model, but all the parameters needed to calculate the main currents are. Thus we have electric fields and conductivities as outputs. At mid-latitudes, the electric fields are a combination of $u \times B$ fields due to the neutral winds and balancing fields set up by space charge in the atmosphere, which is calculated by the electrodynamics solver in the model. The electrodynamics solver is a 2-d solution to the global balance of neutral wind dynamo and conductivity. As such it is not divergence-free - it assumes 3-d balance is maintained by field-aligned currents which it does not itself calculate. The model generally also does not calculate the smaller currents such as the $g \times B$ current and the current due to the plasma pressure gradient. A further limitation on what can be provided for the CHAMP comparison study is that the model thermosphere is limited to 15 pressure levels above the 80km (1 Pa) level, which means it may not reach as far as CHAMP altitudes. The electron densities can be supplied from the plasma tube data, however, as these give $N_e$, $T_e$ and $T_i$ through the full length of the closed plasma tubes.

Considering all the above limitations, it was decided while the CHAMP runs were being carried out, that a reformattting and reassignment of data would take place when the data was supplied to GFZ. It had originally been decided that the model output would be supplied to GFZ on the ‘standard’ CTIP pressure level grid, but since GFZ preferred data to 1000km altitude and a height-based grid, the extra work to make this conversion was agreed on. The plasma data would come from the plasma tube output rather than the thermospheric grid output so that the full height range could be covered completely. This lead to a further problem as it was found that the plasma tube output was only dumped at the end of a run, and not every hour throughout the run as is the case with the thermospheric output. Thus to give 24 hours of data on the ‘CHAMP days’ the model had to be re-run 24 times for progressively longer periods (1 hour, then 2, then 3 etc) starting at 12UT. (Note that strictly we do not then have the data all from the same day as it really covers 12UT one day to 11UT the next: details like this can be sorted out in any future ‘production’ runs.)

The $g \times B$ and plasma pressure currents have been added to the currents calculated from the CTIP run. The currents from the run have been calculated using the $E_x$, $E_y$ values from the electrodynamics solver and assuming the magnetic field lines are equipotentials to give the height distribution. The conductivities have been calculated from the electron densities which have also been supplied in a separate file. The electron densities come entirely from the plasma tube code at the latitudes where the tubes exist (equatorward of 50 degrees) and from the thermosphere code poleward of this (extrapolating to 1000km assuming exponential fall-off with height). $T_e$ and $T_i$ are given like the $N_e$ values from the plasma tube data where it exists. The neutral winds (used for calculating the $u \times B$ part of the electric field) are taken from the thermospheric code and assumed to be uniform with height up to 1000 km. $T_n$ is taken from the thermospheric code, assuming isothermality above this. Note that all these calculations (including $g \times B$ and the plasma pressure current) are carried out outside the model after the standard CTIP run has been completed.

We have considered calculating the field-aligned currents necessary to close off the current system (ie make it divergence free) but although we know how to do this in principle its realisation is a major task. The results about the CHAMP-model comparison retrieved from this study will help a lot in defining right directions.
4.2 The synthetic data base

The standard output from CTIP consists of a set of files in a standard ‘thermospheric’ format which comes from the neutral atmosphere part of the code, plus some extra files with different formats.

The ‘standard’ output includes the parameters: \( N_e, T_n \), height of pressure level, mean molecular mass, ion velocity (3 components), neutral velocity (three components), \( T_e, T_i, E_x, E_y \), fractional number densities of atomic oxygen, and molecular oxygen and nitrogen, Hall and Pedersen conductivities, and Joule heating. There are also number densities for the ions \( O^+, NO^- \) and \( O2^- \). Which of these files are produced during a run is determined by switches (one per file) in the driver file.

These are all in individual files, written in ASCII characters, with a format of 20° longitudes (across) by 15 levels (down), repeated 91 times, and this whole pattern then repeated typically 24 times, once per hour the model runs. The 15 are the 15 pressure levels in the model, the 91 the number of latitudes (starting with 1= south pole and going up to 91 = north pole). The time output is controllable within the driver file to be any time spacing one wants (down to the 1 minute resolution of the model) but is usually set to give output every hour.

The data set normally consists of 24 hourly dumps starting at 13UT (end of the first hour's run) and finishing at 12 UT the next day. (If it is run with fixed F10.7 and Kp these will be the same over the two half days, which is not strictly what they are meant for. For these tests though, this is unlikely to be much of a problem as we are only approximating the true conditions.) The time, at which it starts, and the spacing of the output can be varied in the driver file.

Besides the ‘standard’ output there are a few other important output files. The *prs file is a binary file containing the basic thermospheric parameters and is the minimum input needed for one run to be used as an input for another. All of the information here is also contained in the ASCII files so it is not necessary to know the format. The *plas file contains all the information from the plasmasphere - number densities and plasma properties at a variable spacing along each of the flux tubes. Note that the plasma tubes only cover mid- and low-latitudes. The high-latitude ionosphere – that is, poleward of \( \pm 50^\circ \) - is represented in the model by a separate routine (high-lat-ions.f) which has its own data arrays. We have not attempted to extract this data since this study is only concerned with the lower latitude regions. The flux tubes in high-lat-ions.f are similar to the plas flux tubes, but are open flux tubes going out to 10,000km altitude.

The data that exists in the ‘standard database’ is one set of files for each of the days in Table 5.1, as well as the Arecibo day. These are called CHAMP2 to CHAMP7 for days 186-191 2003, CHAMP8 to CHAMP20 for days 139-151 2006, CHAMP21 to CHAMP29 for days 329-337 2001, and CHAMP30 to CHAMP37 for the days 172-179 2006. The ‘CHAMP days’ for the comparisons are thus CHAMP26, CHAMP6 and CHAMP18, and the Arecibo day is a combination of the last 13 hours of CHAMP35 and the first 11 hours CHAMP36. The data sets consist of sets of files as described above, one per parameter. Thus CHAMP6Ne is the electron density data from run CHAMP6, CHAMP26VionX the X component of the ion velocity for CHAMP26 run etc.
A ‘special’ format of output was produced for this study. We shall call this the GFZ format. This is really the result of reformatting the data in the ‘standard’ format described above onto a different grid. In the GFZ format we have the same ‘outer’ structure as the standard data - that is 24 hours of output. The ‘inner’ structure is different however. The file format is a flat plain text (ASCII) file, output directly from a (40,91,20) Fortran array to disk without processing. The indices are (height, (co-)latitude, longitude). The height values are a 40 element array, with the values list below in km:

80  85  90  95 100 105 110 115 120 125 130 135 140 145
150 160 170 180 190 200 210 220 230 240
250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000

That is, 14 levels with spacing 5 km starting at 80 km, followed by 10 levels with 10 km spacing starting at 150 km, followed by 16 levels with 50 km spacing stating at 250 km. The spheroid assumed by CTIP is a sphere of radius 6370 km, which the current calculation has followed. The latitude array has the same 91 elements as the ‘standard’ output, with a spacing of 2° and an initial value of -90° north (geographic south pole). The longitude array has the ‘standard’ 20 elements, with a spacing of 18°, and an initial value of 0° east (Greenwich meridian). Within the data files, stored as ASCII data in a flat file, the height index varies fastest, then the latitude index, and the longitude index the slowest.

Three different interpolations are performed to get the data from the model grids to the study’s grid of longitude, latitude, height. These are:

- Model pressure grid to output height grid
- Geographic coordinates to plasmaspheric coordinates
- Plasmaspheric coordinates to geographic coordinates

The vertical grid the model works on is a pressure level grid, spaced every one scale height. The horizontal grid is an evenly spaced grid in latitude and longitude. This same horizontal grid is used for the output grid, but the vertical coordinate here is height. The plasmaspheric coordinate system is magnetic longitude, field line apex height, and an along-field line coordinate.

The interpolation between the model grid and the height based grid is a cubic polynomial interpolation in physical height. For data above the top of the thermosphere model, the data is extrapolated, either as a constant (velocity, assuming large viscosity) or an exponential drop-off in height (conductivity) using the scale height at the top of the thermosphere.

The interpolation from the height grid to the plasmaspheric grid is a tri-linear interpolation in geographic coordinates. The position of the required plasmaspheric point is bracketed by the geographic points, and linearly interpolated in each dimension.

The interpolation from the plasmaspheric grid to thermospheric grid is also a tri-linear interpolation. The four closest field lines to the target point are selected, and the two points closest to the target point in height are selected. This is to allow for the fact that the height scale in the atmosphere is much smaller than the horizontal scale, allowing better sampling than using pure plasmaspheric coordinates would allow.
These are the files which are available through this study. The naming convention follows the numbering system used for the ‘standard’ files but with different endings. Thus the current files for, e.g., the CHAMP6 run are called CHAMP6.x.Jtotx, CHAMP6.x.Jtoty and CHAMP6.x.Jtotz and for the other parameters it is CHAMP6.x.Ne, CHAMP6.x.Te, CHAMP6.Ti, CHAMP6.x.Tn. The entry ‘x’ denotes the hour of the day after 12UT. So ‘1’ stands for 13UT of day 190, ‘11’ for 23UT of day 190, ‘12’ for 00UT of day 191, …, and ‘24’ for 11UT of day 191 in 2003.

The provided data base is continuous in principle, but outputs for few hours could not be modelled because the reactivated full energy implementation (see chapter 3) has not been stable in all model runs. Therefore, 04UT and 12UT of day 191 in 2003 (CHAMP day 2), 04UT and 09UT of day 150 in 2006 (CHAMP day 3), and 06UT – 12UT and 17 UT of day 178 in 2006 (Arecibo day) are missing.

The *plas file

The *plas file is intended to allow the plasmasphere to restart from the end of a previous run. As such it contains data for only one time value. The general format is that of an unformatted Fortran binary file, meaning that the exact format varies depending on machine precision and endian-ness. The file consists of 5 Fortran records. The most used values are given where appropriate.

Record 1: 4 INTEGER scalars

INTEGER npts = 201
   The number of points along each flux tube.

INTEGER nlp = 70
   The number of flux tubes at each magnetic longitude.

INTEGER nmp = 20
   The number of magnetic longitudes.

INTEGER mgtype = 2
   An integer denoting the approximation to the magnetic field: 1-axial dipole, 2-centred tilted dipole, 3-offset tilted dipole.

Record 2: 2 REAL*8 arrays

REAL*8 in(nmp, nlp)
   The index of the northernmost active point in each flux tube.

REAL*8 is(nmp, nlp)
   The index of the southernmost active point.

Record 3: 3 REAL*8 arrays
REAL*8 re(nmp, nlp)

The radius of the apex of each flux tube, in units of metres.

REAL*8 q(npts, nmp, nlp)

The q coordinate of each point. Along with the apex radius of the flux tube this can be used to calculate the magnetic latitude and radius of each point.

REAL*8 blon(nmp, nlp)

The magnetic longitude of each flux tube

Record 4: 3 REAL*8 arrays
REAL*8 ni(npts, nmp, nlp, 2)

The number density of 1) O\(^+\) and 2) H\(^+\) ions at each point on the plasmasphere grid.

REAL*8 vi(npts, nmp, nlp, 2)

Plasma drift velocities at each point on the grid.

REAL*8 ne(npts, nmp, nlp)

Electron number density at each point on the grid

Record 5: 2 REAL*8 arrays
REAL*8 ti(npts, nmp, nlp, 2)

Ion temperatures for 1) O\(^+\) and 2) H\(^+\) ions at each point on the grid.

REAL*8 te(npts, nmp, nlp)

Electron temperatures at each point on the grid.

For more information, especially on the coordinate system, see Millward et al., 1996.

5. Model verification

5.1 Selection of validation period

It is important to investigate the reliability of a model when using the model predictions as a simulated ionospheric environment. For our study a suitable method of validation is to compare the model outputs to satellite observations, as provided by the CHAMP mission. In particular, we compare electron density and temperature measurements of the Planar Langmuir Probe (PLP) onboard CHAMP with CTIP model predictions. Another possibility is to compare predicted electron density and electron temperatures with readings of the Incoherent Scatter Radar (ISR) at Arecibo.

For building a simulated satellite data base, the study team agreed on three specific dates during the CHAMP mission which have been found appropriate for comparison of model outputs with observations. The primary aim of the study is to model ionospheric currents on the night side and during times of low magnetic activity. These are the conditions used in data
selection procedures for main and crustal magnetic field modelling. Therefore we are most interested in the model validity under these conditions. In this respect the dates as represented in Fig. 5.1 were chosen in agreement with the following criteria:

1. The local time of the CHAMP orbit has to be between 18LT and 05LT which correspond to night times in low-latitude regions.

2. The dates have to lie in a magnetically quiet period. At least 4 days, including the day of observation, have to reveal a daily mean Ap < 15. The long term period of preceding low magnetic activity was chosen to exclude long lasting effects of thermosphere to geomagnetic disturbances.

3. The selected days should be from the beginning, the centre and the late part of the CHAMP mission. With such a temporal distribution we are able to provide validations at three atmospheric altitudes and at three different levels of solar activity since the CHAMP orbit has decayed in phase with the solar cycle decline.

The percentage of days when there were 3 or more quiet days beforehand is 42% for solar cycle 20, and 52% for solar cycle 21. This means a considerable number of days with the assumed conditions can also be expected for the upcoming solar cycle.

The limitation in number and character of days may reduce the validation of the model results to specific conditions. However, by the appropriate choice of dates, as explained above, we covered the relevant range of the different criteria.
Fig. 5.1: Table of days surrounding the agreed dates for model validation with CHAMP data. The selected days are marked with a left arrow.

<table>
<thead>
<tr>
<th>Date</th>
<th>DoY</th>
<th>mean Ap</th>
<th>F10.7</th>
<th>CHAMP LT</th>
</tr>
</thead>
<tbody>
<tr>
<td>25/11/01</td>
<td>329</td>
<td>8</td>
<td>166</td>
<td>~4:30</td>
</tr>
<tr>
<td>26/11/01</td>
<td>330</td>
<td>4</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>27/11/01</td>
<td>331</td>
<td>2</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>28/11/01</td>
<td>332</td>
<td>2</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>29/11/01</td>
<td>333</td>
<td>3</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td>30/11/01</td>
<td>334</td>
<td>2</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>01/12/01</td>
<td>335</td>
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<td></td>
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<tr>
<td>02/12/01</td>
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<td>03/12/01</td>
<td>337</td>
<td>8</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>05/07/03</td>
<td>186</td>
<td>18</td>
<td>147</td>
<td>~23:00</td>
</tr>
<tr>
<td>06/07/03</td>
<td>187</td>
<td>9</td>
<td>134</td>
<td></td>
</tr>
<tr>
<td>07/07/03</td>
<td>188</td>
<td>11</td>
<td>138</td>
<td></td>
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<td>08/07/03</td>
<td>189</td>
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<td></td>
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<td>190</td>
<td>4</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>10/07/03</td>
<td>191</td>
<td>7</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td>19/05/06</td>
<td>139</td>
<td>6</td>
<td>77</td>
<td>~22:00</td>
</tr>
<tr>
<td>20/05/06</td>
<td>140</td>
<td>5</td>
<td>78</td>
<td></td>
</tr>
<tr>
<td>21/05/06</td>
<td>141</td>
<td>6</td>
<td>80</td>
<td></td>
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<td>22/05/06</td>
<td>142</td>
<td>8</td>
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<td></td>
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<td>144</td>
<td>3</td>
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<td>87</td>
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<td>29/05/06</td>
<td>149</td>
<td>3</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>30/05/06</td>
<td>150</td>
<td>8</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>31/05/06</td>
<td>151</td>
<td>5</td>
<td>81</td>
<td></td>
</tr>
</tbody>
</table>

Furthermore, three sample periods within the scheduled Swarm mission (mirrored back by one solar cycle) have been identified. One of it (25/11/2001) is overlapping with a CHAMP example. Figure 5.2 lists the dates which were chosen for Swarm according to the same criteria as the ones for the CHAMP comparison.

The CHAMP data base available for comparison with CTIP model predictions consists of a nearly continuous time series of in situ electron density and temperature reading from the Planar Langmuir Probe. The time resolution is 15 seconds.
The vertical distribution of ionospheric parameters in the CTIP model is compared with the ground-based Incoherent Scatter Radar (ISR) in Arecibo, Puerto Rico, located at -66.75° geographic longitude and 18.34° geographic latitude (~30° geomagnetic latitude). From this facility, vertical profiles of electron density and electron temperatures are available from measurement campaigns of usually 3–5 days within the period September 2000 to June 2006. Unfortunately, Arecibo measurements do not exist for the CHAMP days agreed in Table 5.1. Hence, we identified one suitable day for comparison with CTIP being 27 June 2006 with full 24-hour data coverage from Arecibo and from the CTIP model. This day is assigned to low solar flux and low magnetic activity with F10.7=80, Ap=4. Incoherent scatter radars are established instruments and are believed to provide very reliable measurements.

In this section, the output of the CTIP model is compared with empirical data. These comparisons are very useful for getting better insight in the CTIP synthetic data base. However, since a comparison is performed between a physical-based model and a purely empirical data base obtained over 4 days, it is not meaningful to present a statistical analysis or error estimation. Here, it is especially interesting to verify whether CTIP is able to

Fig.5.2: Table of days surrounding the agreed dates for modelling synthetic Swarm data base for magnetic field recovery

<table>
<thead>
<tr>
<th>Date</th>
<th>DoY</th>
<th>mean Ap</th>
<th>F10.7</th>
<th>Swarm1 LT</th>
<th>Swarm3 LT</th>
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<tr>
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<td>7</td>
<td>120</td>
<td>~19:45</td>
<td>~20:30</td>
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<tr>
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<td>6</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>12/10/98</td>
<td>285</td>
<td>5</td>
<td>113</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13/10/98</td>
<td>286</td>
<td>5</td>
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<td></td>
<td></td>
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<td>289</td>
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</tr>
<tr>
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<td>291</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>13/03/00</td>
<td>73</td>
<td>4</td>
<td>186</td>
<td>~21:15</td>
<td>~1:15</td>
</tr>
<tr>
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<td>4</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>25/11/01</td>
<td>329</td>
<td>8</td>
<td>166</td>
<td>~1:00</td>
<td>~21:30</td>
</tr>
<tr>
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<td>330</td>
<td>4</td>
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<td>331</td>
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<td>332</td>
<td>2</td>
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<td></td>
</tr>
<tr>
<td>29/11/01</td>
<td>333</td>
<td>3</td>
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<td></td>
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</tr>
<tr>
<td>30/11/01</td>
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</tr>
<tr>
<td>01/12/01</td>
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</tr>
<tr>
<td>02/12/01</td>
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</tr>
<tr>
<td>03/12/01</td>
<td>337</td>
<td>8</td>
<td>228</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CHAMP:~4:30
reproduce physical mechanisms, hence parameter distributions. Exact amplitude predictions cannot be expected from an physical-based model in the considered time range, due to the large ionospheric day-to-day variability. Therefore, our analysis emphasises on important ionospheric key points, as the Equatorial Ionisation Anomaly, the ionospheric height or typical ionospheric gradients.

5.2 Validity of CHAMP electron density and electron temperature

When comparing model outputs with independent data it is a crucial prerequisite to get first an idea about the validity of the independent data themselves. Therefore, we will shortly report on comparison studies of the CHAMP PLP observations with other, well established ionosonde and radar observations.

The CHAMP PLP electron density readings have been validated by a comparison with plasma frequency measurements of the Jicamarca digisonde (McNamara et al., 2007). For CHAMP orbit heights below the F2 peak they report an average discrepancy between the PLP and ionosonde records of only 4%, with a standard deviation of 8.8%. At heights above the F2 peak a mean difference of 2.6% (standard deviation 13.3%) is given. Such discrepancies lie within the uncertainty of the ionosonde measurements and the applied electron density retrieval technique.

The CHAMP PLP electron temperatures are determined by a more sophisticated retrieval than the electron density. Its estimation depends on the slope of the electron current over one sweep of PLP records, which is not always easy to retrieve. Hence, validation studies have not been performed extensively so far. However, Schlegel et al., 2008 compared PLP electron temperatures with Arecibo radar observations. In their report they found the PLP electron temperature about 10% higher than Arecibo measurements during daytime and 20% lower during night time. They also identified that the PLP gives more accurate electron temperatures after day 50 in year 2002.

5.3 Building CTIP predictions along the CHAMP orbits and for Arecibo radar data

For an appropriate validation between CHAMP measurements and CTIP predictions, the model values along the CHAMP orbit have to be retrieved. Therefore, we first divide the CHAMP database in equatorial segments between ±40° geocentric latitude and for night side local times between 18LT and 06LT. The UT when the satellite crosses the equator is identified and rounded to the full hour. This number determines the time of the CTIP model output in use for predicting this specific orbital segment. The modelled value for each observational point of the orbital segment is obtained through 3D linear interpolation from the CTIP model output grid.

This procedure is performed for the electron density parameter between 13 UT of the day in question and 12 UT of the following day applied on all three days as agreed in Table 5.1. A data base for electron temperature is also established but only for the two days in 2003 and 2006 since CHAMP PLP electron temperature measurements are recommended for use only after day 50 in year 2002.
The Arecibo ISR facility provides vertical profiles of electron density and electron temperature every minute. In this report we extract the ISR profiles for each full hour between 00 UT and 23 UT of 27 June 2006. The corresponding vertical CTIP profiles are constructed from the grid points using 3D linear interpolation in the same way as described for the CHAMP orbit synthetic data base.

5.4 Comparison with CHAMP electron densities

This section describes the results of the comparison of CTIP model output with CHAMP electron densities. Each orbital segment of electron density in question was modelled by CTIP. Fig. 5.3 shows two examples from 2001, when CHAMP was at about 4:40 LT. The left panel gives the CHAMP and the CTIP profiles, the right column shows the horizontal distribution of CTIP electron density at the time epoch used for simulating the satellite data and at the height level nearest to the CHAMP altitude. The white vertical line indicates the location of the CHAMP orbit. Figs. 5.4 and 5.5 repeat two examples for 2003 (~23:15LT), and 2006 (~22:15LT), respectively.

An important feature of the low latitude ionosphere is the Equatorial Ionisation Anomaly (EIA). It is characterised by an electron density trough at the magnetic dip-equator, and a dual band of enhanced electron density at about 15° north and south of the trough. The formation of the EIA is a result of the diurnal variation of the zonal electric field, which primarily points eastward during the day. With the horizontal geomagnetic field at equatorial latitudes, the plasma is lifted up by vertical $E \times B$ drift. Once transported to higher altitudes, the plasma diffuses downward along the geomagnetic field lines into both hemispheres due to gravitational and pressure gradient forces. The EIA builds up in the morning hours and persists until after sunset. This characteristic is shown in all plots in the right columns of Figs. 5.3-5.5. The EIA is a suitable feature to compare between model and observations.

The CTIP results in the profile plots in Figs. 5.3-5.5 show the EIA at satellite altitudes. In most of the cases, the CTIP EIA is more intense than what is observed by CHAMP, or CHAMP did not see an anomaly feature at all. Probably, the equatorial eastward electric field in the CTIP runs is so high, that it produces a stronger night side EIA than is observed in the data. The post-sunset ionosphere is regularly occupied by equatorial bubbles (see also section 9). This phenomenon manifests itself as localised equatorial plasma depletions, quite prominent in the CHAMP profile in the lower panel of Figure 5.4. Evidently, such small-scale structures due to plasma instabilities cannot be reproduced by global models like CTIP. However, being aware of such limitations of the model, there are also days and regions which provide good fit between the model and CHAMP. Such an example is given in the lower panel of Figure 5.5, where the location and the strength of the EIA are similar in model and observational data.

The intensity of the EIA can be expressed by the Crest-to-Trough Ratio (CTR) which is described by

$$CTR = \frac{Ne_{north} + Ne_{south}}{2 \times Ne_{trough}},$$

where $Ne_{north}$ and $Ne_{south}$ are the electron density values at the northern and southern EIA crests and $Ne_{trough}$ is the electron density value of the EIA trough. If the EIA is not properly developed at satellite altitudes, CTR is set to 1. For example, the CTR for the
CHAMP profile in the upper left graph of Fig. 5.4 is 1.9 and for the CTIP profile the CTR is 30.5.

The width of the EIA can be described by the latitudinal separation of the two crest peaks. The higher this value, the wider the crests are apart and to greater heights the plasma is lifted. If the EIA is not developed at satellite altitudes, the latitudinal separation is 0. Again, the latitudinal separation of the CHAMP EIA in the lower left graph of Fig. 5.4 is 16.5°, and of the CTIP crests it is 31.1°. This corresponds to an equatorial peak height of the plasma of ∼500 km for CHAMP and of ∼900 km for CTIP. For an overall impression, Table 5.1 lists the mean CTR and latitudinal separations for each 24-hours period selected in 2001, 2003, and 2006. In the years 2001 and 2003, the CTR estimated by CTIP is about double the one observed by CHAMP. In 2006 the CTIP CTR is 3.5 times bigger. Also the latitudinal separation between the two crests is clearly larger for CTIP than for CHAMP in all years. As already discussed above in this section, the strength of the night side EIA is overestimated in the model. This can be due to very large zonal electric fields.

Table 5.1: Mean CTR and mean latitudinal separation between the two crests as derived from CHAMP and from CTIP separately for the three 24-hours analysis periods.

<table>
<thead>
<tr>
<th>Year / LT</th>
<th>Mean CTR</th>
<th>Mean latitudinal separation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CHAMP</td>
<td>CTIP</td>
</tr>
<tr>
<td>2001 / 04:45</td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>2003 / 23:15</td>
<td>8.3</td>
<td>16.1</td>
</tr>
<tr>
<td>2006 / 22:15</td>
<td>1.8</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Another aspect is the location of the EIA trough. Following the electrodynamics of the ionosphere, the EIA trough lies ideally above the dip-equator. As already lined out in section 3, the CTIP model runs with a dipole representation of the magnetic field. The dipole magnetic equator deviates in some places (e.g., above Africa) drastically from the IGRF magnetic equator. An ensemble of the trough locations from all orbits in question is given in Fig. 5.6. The location of the CHAMP trough shows a higher variability than those derived from CTIP. This is not surprising since the empirical data base also includes a day-to-day variability which may arise from thermospheric winds. But the CHAMP troughs are all well distributed around the magnetic dip-equator. The locations of the troughs as derived from CTIP are similar but deviate significantly in the Atlantic/African region where they follow the dipole equator. Such a difference is due to the model definition of the magnetic field as a dipole, but the location of the dip equator is different, e.g., in the Atlantic region.
Fig. 5.3: Comparison between CHAMP PLP electron density measurements and correspondingly predicted CTIP value for two examples from the 24-hours analysis period at 30.11.2001 and 01.12.2001. (left) Latitudinal profiles of electron densities along the equatorial segments. The title of each panel lists UT, local time, longitude of CHAMP equatorial cross and the CHAMP altitude at the geographic equator. (right) Horizontal distribution of CTIP electron density at the epoch used for simulating the satellite data and at the height level nearest to the CHAMP altitude, both are given in the title. The white line represents the CHAMP orbit. Electron density units are given in $10^{12}$ m$^{-3}$.
Fig. 5.4: As for figure 5.3, but for two examples from the 24-hours analysis period at 09.07.2003 and 10.07.2003.
Fig. 5.5: As for figure 5.3, but for two examples from the 24-hours analysis period at 29.05.2006 and 30.05.2006.
Fig. 5.6: Global distribution of the location of the EIA trough as derived from CHAMP and from CTIP. The black line indicates the location of the magnetic dip-equator.

5.5 Comparison with CHAMP electron temperatures

This section describes the results of the comparison of CTIP model outputs with CHAMP electron temperatures. Fig. 5.7 shows the PLP measurements along the CHAMP orbit and the corresponding CTIP predictions for an example in 2003 and an example in 2006. (As mentioned, we did not compare the data in 2001 since the use of the PLP electron temperatures is recommended only after day 50 in 2002.) The right column shows the horizontal distribution of CTIP electron temperatures at the epoch used for simulating the satellite data and at the height level nearest to the CHAMP altitude.

In these two examples the CHAMP electron density profile shows electron temperatures of around 1000K on the winter hemisphere and of around 700K in the summer hemisphere. The CTIP temperatures matches well with the higher level in the 2003 case and with the lower level in the 2006 case. The latitudinal variation with higher temperatures in the winter than in the summer hemisphere is not represented by the model. The agreement in different temperature ranges in these two years is probably due to the overestimated dependency of the solar flux variation of the electron temperature in the model. The solar flux level in the 2003 case is F10.7~130 and it is F10.7~80 in the 2006 case. With respect to these limitations, the CTIP electron temperatures are more reliable for the winter hemisphere for moderate solar flux and agree better in the summer hemisphere during low solar flux years.

Small scale features as monitored by CHAMP cannot be provided by the model. This is due to the global representation of the electron temperature.
Fig. 5.7: Comparison between CHAMP PLP electron temperature measurements and correspondingly predicted CTIP value for one example from the 24-hours analysis period at 09.07.2003 and 10.07.2003 (upper row) and for another example from the 24 hours analyses period at 29.05.2006 and 30.05.2006. For details see Fig. 5.3.

As a summary of the two 24-hours analysis periods in 2003 and 2006, Figure 5.8 shows all compared data points in a scatter diagram. The majority of CTIP electron temperatures in the 2003 case are around 1000K while the variability of the CHAMP observations ranges between 600K and 1200K. The same is true for the day in 2006, where the majority of the modelled data points are located around 700K.

The two observational periods stand for two different solar flux levels (F10.7~130 in 2003 and F10.7~80 in 2006). While the mean temperatures of the CHAMP observations decreased by about 100K (from 900K to 800K), the CTIP average temperature level decreased by about 300K (from 1000K to 700K) from the 2003 to the 2006 example. Obviously, the CTIP model electron temperatures are more sensitive to solar flux variations than is observed with CHAMP during the analysis periods. Such behaviour was already observed for the individual examples in Figure 5.7.
Fig. 5.8: Scatter plot of all compared data points during the 24 hours analysis period at 09.07.2003 and 10.07.2003 (left) and during the 24-hours analysis period at 29.05.2006 and 30.05.2006. The correlation coefficient, as well as the standard deviation of the difference between CHAMP and CTIP, are given in the plots.

5.6 Comparison with Arecibo radar electron densities

This section describes the results of comparisons between vertical electron density profiles from the Arecibo radar and corresponding estimations of the CTIP model. Arecibo observations are available every minute. The values from each full hour of 27 June 2006 are used to compare with CTIP outputs. The Arecibo profiles are available at -66.75° geographic longitude and 18.34° geographic latitude (~30° geomagnetic latitude), and are described by 15 fixed altitude levels between 150km and 690km.

Figure 5.10 shows the electron density profiles measured by the Arecibo radar facility and the corresponding CTIP predictions. Uncertainty estimates for the Arecibo measurement are also provided. They show that the radar observations of electron density are very reliable for almost every sample. Due to numerical instabilities, when running the CTIP model with the full energy equation module, some hours of CTIP data are missing (06UT-12UT and 17UT). In such cases, the Arecibo profiles are still shown, in order to provide the continuity of the temporal evolution. The radar and the model profiles show the typical ionospheric structure of mid-latitudes which is dominated by an electron density peak around between 300km and 400km (F2-layer). A very good agreement between model and data is found for the morning hours after local sunrise.

A very convenient way of evaluating electron density in ionospheric physics is the observations of the F2-layer peak electron density (also called NmF2) and of the F2-layer peak height (also called hmF2). Figure 5.11 shows the time evolution of the ionospheric peak electron density and the ionospheric height as derived from plots in Figure 5.10. This time series reveals that Arecibo shows low electron densities during local night time and high electron densities during local afternoon hours. Both, model and data NmF2 agree well just after local sunset (19.6LT) and during morning hours (8.6LT – 11.6LT), but CTIP largely underestimates it during local afternoon (13.6LT – 17.6LT). Apparently, on that particular day a strong Ionisation Anomaly developed, which reached Arecibo latitudes, but which could not be reproduced by the model. During the night time, when current predictions for Swarm are most important, an overestimation of CTIP is observed. This confirms results from the comparison between CTIP and CHAMP observations at these latitudes in section 5.4. The
The ionospheric height predicted by the CTIP model is in the same range as is observed by the radar. From this point of view we can consider the model to provide reliable estimates.

One main reason for the differences between radar data and model predictions is that the radar represents local electron density profiles, and the model values are retrieved from 18° longitudinal, climatological averages which can heavily differ from observations of a particular day. Although the ionospheric variability in the observations and in the model is similar in amplitude, the maximum electron density is recorded by Arecibo at ~18LT but predicted by the model only at ~23LT.

Fig. 5.10: Electron density profiles as derived from the CTIP model and as observed by the Arecibo radar for each full UT hour on 27 June 2006. Green bars indicate the estimated uncertainties of the Arecibo measurements.
Fig. 5.10: Continued.
Fig. 5.10: Continued.
Fig. 5.10: Continued.
Fig. 5.11: Peak electron density and height of the ionospheric peak as derived from the CTIP model and as observed by the Arecibo radar at each full UT hours on 27 June 2006. The vertical dashed line indicates local midnight.

5.7 Comparison with Arecibo radar electron temperatures

This section describes the results of comparison between vertical electron temperature profiles derived from Arecibo radar observations and corresponding estimations of the CTIP model. Also here, for times with missing CTIP data, only the Arecibo profiles are shown for reasons of temporal completeness.

Figure 5.12 shows the electron temperature profiles measured by the Arecibo radar facility and the corresponding CTIP predictions. Uncertainty estimates for the Arecibo measurements are also provided. They show that the radar observations of electron temperature are most reliable in regions with highest electron density, which is the F region between 200km and 500km. At night in the F region, the Arecibo profiles show electron temperatures of about 700K, and almost no vertical gradient appears. At sunrise (05LT–06LT) the electron temperature rises very quickly to nearly 3000 K before a local cooling is observed in the F region at about 350 km altitude after 11LT. This altitude-restricted cooling produces strong vertical gradients in the electron temperature profiles at afternoon hours.

In CTIP the electron temperature profiles are in very good agreement with the data for the night side observations after ~19LT with only very little vertical gradient. Unfortunately, the second half of the night is missing from CTIP but we may assume that both representations remain similar since good agreement is also visible during local morning at 8.6LT. In the subsequent sequence a large overestimation by the CTIP values is recognised during day time hours, especially in the F region. On the day of comparison the local F region cooling occurs
in CTIP only very late, at 17.6LT. From this time on, the model approaches again radar values.

The improved agreement between model and data during the night is a merit of the application of the full energy equation module in the CTIP model for this study. Before, when only simple electron temperature implementations have been used, the night side F region was heavily overestimated (see Task 3 Report).

Fig. 5.12: Electron temperature profiles as derived from the CTIP model and as observed by the Arecibo radar for each full UT hour on 27 June 2006. Green bars indicate the estimated uncertainties of the Arecibo measurements.
Fig. 5.12: Continued.
Fig. 5.12: Continued.
The aim of this study is the evaluation of magnetic field signatures due to ionospheric currents on board the Swarm satellites. It is therefore interesting to compare the CTIP predictions directly in heights of the Swarm satellites. Figure 5.13 shows the temporal evolution of the electron temperature at 400 km altitude which is the expected mean orbital altitude of the two lower satellites, and at 550 km which is close to the expected orbital altitude of the upper Swarm satellite. As already discussed, CTIP values agree well with the radar observations during the night, and they are similar in the morning (8.6LT). Due to the missing CTIP prediction around local sunrise, we cannot verify how good the strong increase at local sunrise is reproduced by the model. CTIP overestimates the electron temperature during day time at both satellite altitudes, which is due to the non-represented F region cooling in the model. However, especially on the night side where current estimates are most important for the magnetic field measurements, CTIP provides good estimates of electron temperature.
**Comparison with Arecibo radar ion temperatures**

This section describes the results of comparison between vertical ion temperature profiles derived from Arecibo radar observations and corresponding estimations of the CTIP model.

Figure 5.14 shows the ion temperature profiles measured by the Arecibo radar facility and the corresponding CTIP predictions. Uncertainty estimates for the Arecibo measurements are also provided. The ion temperatures can most reliably be measured at the lower levels where the neutral gas density is high. The ion temperatures show night time values of about 500K along the entire profile with only little vertical gradient. Just before sunrise, e.g., at 10UT (5.6LT), the ion temperatures in the upper ionosphere increase until they reach about 2000K in the late afternoon. During day time a significant positive upward vertical gradient is observed. After 21UT (16.6LT) the ion temperature of the upper ionosphere cools down until it reaches again the night time values.

In CTIP, the ion temperatures profiles are similar to the Arecibo observations during local night. They agree well in amplitude as well as in the characteristic low vertical gradient. As well as for the radar data, the CTIP ion temperature show an enhanced vertical gradient during the day but which is largely overestimated, and ion temperatures above 3000K are predicted in the local afternoon F region. Due to the missing CTIP results in the second half of the night, we cannot say how long the good agreement between model and data holds.
Figure 5.15 shows the temporal evolution of the ion temperature at 400km and at 550km which are typical for the orbital heights of the Swarm constellation. As discussed above, the temperatures between model and data are in good agreement on the night side with only a slight overestimation at 550km altitude. This is a merit of the application of the full energy equation module for this study. Before, simple temperature approaches resulted in largely overestimated values (see Task-3 Report). However, during the day, the overestimated vertical gradient in temperature creates a too high temperature especially at the altitude of the upper Swarm satellite.

Fig. 5.14: Ion temperature profiles as derived from the CTIP model and as observed by the Arecibo radar for each full UT hour on 27 June 2006. Green bars indicate the estimated uncertainties of the Arecibo measurements.
Fig. 5.14: Continued.
Fig. 5.14: Continued.
5.14: Continued.
5.9 Intercomparison between radar, satellite and model values

The intercomparison between two independent observations and the model even strengthens the results about the model validity. During the Arecibo day, 27 June 2006, the satellite passed four times in the vicinity of the radar. We chose each satellite pass with a longitudinal separation to the radar beam of less than 18° which correspond to the longitudinal grid size of the model. Table 5.2 denotes the time of such coincidence, as well as the longitudinal separation. From each of these passes we selected a range of CHAMP observations in between ±3° of the radar latitude and calculated the mean of these (about six) measurements. This value is then compared to the radar observation at 380 km altitude. The CHAMP altitude was at about 370 km. Since Arecibo observations are available every 30 seconds, the two data sets are compared for equal times. Then, we identified the corresponding model value by 3D interpolation at the radar location and from the model time step nearest to the CHAMP observations. The model times are given in Table 5.2. Due to few missing model outputs, no CTIP prediction is available for case B. For the fourth data point, the model time 23:00UT was chosen since 00:00 UT of 28 June 2006 is not available in the study’s model data base.
Table 5.2: Times of Arecibo radar and CHAMP measurements, local time at the Arecibo radar longitudinal separation between radar and CHAMP, and time of the CTIP model for the four comparison points A, B, C, and D shown in Figure 5.16.

<table>
<thead>
<tr>
<th></th>
<th>Arecibo radar and CHAMP time</th>
<th>Arecibo Local Time</th>
<th>Longitudinal distance between Arecibo radar and CHAMP</th>
<th>CTIP model time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>01:02UT</td>
<td>20:38LT</td>
<td>-14.9°</td>
<td>01:00UT</td>
</tr>
<tr>
<td>B</td>
<td>11:08UT</td>
<td>06:44LT</td>
<td>14.9°</td>
<td>—</td>
</tr>
<tr>
<td>C</td>
<td>12:39UT</td>
<td>08:15LT</td>
<td>-8.1°</td>
<td>13:00UT</td>
</tr>
<tr>
<td>D</td>
<td>23:59UT</td>
<td>19:37LT</td>
<td>-0.2°</td>
<td>23:00UT</td>
</tr>
</tbody>
</table>

Figure 5.16 shows the intercomparison for the electron density and the electron temperature between Arecibo radar and CHAMP observations and between Arecibo radar data and CTIP predictions. Points A and D lie in the post-sunset sector and points B and C just after sunrise. The left panel showing electron density reveals a very good agreement between CHAMP and the radar. The large difference between points A and D reflects the day-to-day variability of the electron density distribution. Also CTIP follows the gross trend of the radar, but it always overestimates the plasma density and it cannot follow the daily variation between points A and D.

The right panel of Figure 5.16 shows the intercomparison for electron temperature. It reveals known features, such as that the temperature is high in the morning (B, C), but lower in the evening (A, D). Points A and D agree very well for both comparisons. As already pointed out in section 5.7, CTIP gives a good estimate in the post-sunset ionosphere. Obviously, the large day-to-day variability, as it was reflected in the electron density data, is not as pronounced in the electron temperatures for these two points. In all three points the CTIP electron temperature predictions are close to radar observations. Even in the morning sector, where large longitudinal gradients occur, the model provides a reliable estimate at the Arecibo location. CHAMP shows a deviation of about 20% from the radar observations around the time of the morning temperature overshoot. These differences are consistent with the longitudinal separation between satellite and radar. For Point B CHAMP passes at a later local time (higher temperature) and for Point C at an earlier local time than Arecibo (lower temperature). This fits also findings from statistical comparison between radar and satellite presented by Schlegel et al., 2008 and mentioned in Section 5.2.

The points investigated in Figure 5.16 have different distances between the radar and the satellite. Although CHAMP observations for points A and D are far and near to the radar, respectively, they give both good results. The CTIP value was interpolated exactly to the radar point, however, very different results were achieved, e.g., in electron density. Obviously, the distance between two independent observations alone do not seem to play a major role for their agreement, but more important is the local time dependent longitudinal gradient (e.g., the morning temperature overshoot). This comparison also shows that the model alone cannot serve as a reliable reference for observational data on a day-to-day basis. For such purpose, data assimilation seems inevitable.
5.10 Summary and Conclusion

CTIP predictions for electron density, ion and electron temperature along the CHAMP orbit were compared with real CHAMP observations and with vertical profiles derived from the Arecibo radar located at ~30° magnetic latitude.

It was shown that CTIP is able to reproduce properly typical features of the equatorial ionosphere as the Equatorial Ionisation Anomaly. However, it was found that the EIA is overestimated by CTIP for the three days. Obviously, CTIP applies too high zonal electric fields at the equator. This results in the overestimation of the electron density at magnetic mid-latitudes (<30°) during night time, as was shown in comparison with Arecibo radar observations. The location of the CTIP Ionisation Anomaly trough followed generally that of the CHAMP observations, but it deviates importantly in longitude sectors where the dipole magnetic equator is displaced significantly from the magnetic dip-equator.

The CTIP electron temperature on the night side at mid latitudes was found to predict well the higher temperatures in the winter hemisphere during moderate solar activity, but it agrees better with the lower temperatures in the summer hemisphere during low solar activity. The respective other hemisphere is overestimated or underestimated by the model. Following our results, the predicted sensitivity of the electron temperature to the level of solar EUV radiation is larger than observed by CHAMP.

The CTIP electron temperature vertical profiles agree well with the Arecibo radar observations in amplitude and shape during the night, when almost no vertical gradient is found. During daytime the vertical gradient is largely overestimated by the model, and therefore the electron temperatures are too high at both Swarm satellite altitudes.

Similar results where retrieved when we compared CTIP predictions of ion temperature with vertical profiles of the Arecibo radar. Night time values from model and data correspond rather well. On the day side, a too large altitude gradient in the model gives too high ion temperatures in the F region.
The most interesting feature of this study is the reliability of the model during the night time hours when magnetic field data are selected for modelling purposes. The electron density was found to be overestimated during the night, but the electron and ion temperatures are in good agreement especially for these local times. The modelling success for the two latter quantities is due to the implementation of the full energy equation module in CTIP for this study. Applying the simple representation of temperature, as was used before, gave large deviations between model and observations, especially in the night side sector.

These comparisons are very useful for getting better insight in the CTIP synthetic data base. However, two aspects should be kept in mind which may limit possible conclusions drawn from this study. First, CTIP is a physical model based on first principles. Here, we compare the model output with a purely empirical data base. Although, the physical mechanisms may be right in the model, the absolute values might differ from CHAMP and Arecibo observations. Second, we believe that we covered a variety of different conditions, as different magnetic activity and solar flux levels, by choosing the four days in question. But CHAMP and Arecibo observations are also influenced by typical day-to-day variability of the ionosphere. Four days cannot provide climatological means, e.g., a statistically significant picture.

In the context of this study, the electron density and the plasma temperatures are the important parameters for controlling the pressure gradient and gravity-driven currents. If one of the quantities is estimated higher than observed the calculated currents densities will be overestimated.

6. Magnetic field recovery from modelled data

One outcome of the physical-numerical model of the self-consistent simulation of the near-Earth plasma environment called CTIP, which is described in the previous section, shall be the electric current distribution within the modelled volume between 80 km height above Earth and up to the outer bounds of the model. The modelled currents have to close consistently within the volume of CTIP modelling or in mathematical terms it is considered to be divergence-free (\( \text{div} \mathbf{j} = 0 \)). In nature this condition is automatically fulfilled, as any accumulation of moving charge carriers somewhere in a particular region will quickly (with characteristic times of fractions of a second) lead to a built-up of strong electric fields that drives compensating electric currents of any possible kind. Further, large-scale currents in the ionosphere induce currents in subsurface layers that oppose the original magnetic effect.

Keeping this in mind, we are interested in deducing the variations of the geomagnetic field that are caused by the modelled currents. One method of retrieving the magnetic fields is by a poloidal-toroidal method (Engels and Olsen, 1998) which requires a strictly divergence-free current system. Section 6.1 will concern discussions about the poloidal-toroidal method. Section 6.1.1 introduces this method and section 6.1.2 will evaluate the applicability of this method to the CTIP output, e.g. in terms of current divergence.

Another possibility of deriving the magnetic fields from the modelled data base is by integrating the current elements (e.g. by the Biot-Savart method) which have been retrieved from the CTIP plasma parameters. This method and results from the application to the CTIP data base is discussed in section 6.2.
6.1 Applicability of the poloidal-toroidal method

6.1.1 Retrieval method

The poloidal-toroidal method was developed by Nils Olsen for similar tasks in a previous study (Vennerstrom et al., 2005) and is described in the paper by Engels and Olsen (1998). It represents a general method of computing the geomagnetic field effect caused by a previously determined three-dimensional current distribution. The basic idea of this method is to take advantage of the fact that solenoidal vector fields like the divergence-free current \( \mathbf{j} \) and magnetic field \( \mathbf{B} \) can be represented in separate terms for the poloidal and toroidal parts (Stern, 1976, Backus, 1986) that are expressed by two independent series of spherical harmonics for \( \mathbf{B}_{pol} \) and \( \mathbf{B}_{tor} \) or \( j_{pol} \) and \( j_{tor} \), respectively.

\[
\mathbf{B} = \mathbf{B}_{tor} + \mathbf{B}_{pol} = \text{curl} \mathbf{r} \Phi + \text{curl} \text{curl} \mathbf{r} \Psi
\]
\[
\mu_0 \mathbf{j} = \mu_0 j_{pol} + \mu_0 j_{tor} = \text{curl} \mathbf{B} = \text{curl} \text{curl} \mathbf{r} \Phi + \text{curl} \text{curl} \text{curl} \mathbf{r} \Psi = \text{curl} \text{curl} \mathbf{r} \Phi + \text{curl} \mathbf{r} Q \tag{6.1}
\]

The physical background for the used approach, given by equations 6.1, is taken from the Swarm Science Study, Final Report, 2005. The toroidal and poloidal field components are represented by the scalars \( \Phi \) and \( \Psi \), respectively, or the scalar field \( Q \), which is connected to \( \Psi \) by the relation:

\[
\text{curl}(\mathbf{r} [Q + \Delta \Psi]) = 0 \tag{6.2}
\]

The toroidal geomagnetic field \( \mathbf{B}_{tor} = \text{curl} \mathbf{r} \Phi \) is directly related to the poloidal current density \( \mu_0 j_{pol} = \text{curl} \mathbf{r} \Phi \). However, in order to obtain the poloidal magnetic field \( \mathbf{B}_{pol} = \text{curl} \text{curl} \mathbf{r} \Psi \) from a given toroidal current density \( \mu_0 j_{tor} = \text{curl} \mathbf{r} Q \), the Poisson equation \( \Delta \Psi = -Q \) has to be solved. Due to the spherical harmonic expansion and the fact that \( r^2 \Delta (P_n^m e^{im\lambda}) = -n(n+1) P_n^m e^{im\lambda} \), the three-dimensional Poisson equation reduces to an ordinary differential equation in \( r \), which can be solved with a Green's function. Any further details of the method and its numerical realization can be found in the original paper by Engels and Olsen (1998) and in Vennerstrom et al. (2005, pages 33-36).

6.1.2 Applicability to current distribution from CTIP outputs

Electric current simulation results from the CTIP model, as described in the previous section, were delivered by UCL for testing the applicability of the algorithm for calculating the generated magnetic field. The current data files comprise the CTIP standard output of the 3D current distribution (\( J_{basx}, J_{basy}, J_{basz}, \) the “basic current” components) and, additionally, the contributions from pressure gradient and gravity force currents, which were calculated subsequently from other CTIP standard output parameters described in the following section. The latter currents were included as the sum of all current contributions in data arrays called “total current” (\( J_{totx}, J_{toty}, J_{totz} \)).
The 3D current distributions were given on a global spherical grid at 40 non-equidistant height levels above the Earth surface between 80 km and 1000 km. The current density components ($J_x$, $J_y$, $J_z$) at each grid point are pointing southward, eastward, and upward, respectively, in a local orthogonal system. These components could also be understood as the current density components ($J_\theta$, $J_\varphi$, $J_r$) in spherical coordinates with $\theta$ as the meridional, $\varphi$ as the azimuthal, and $r$ as the radial outward component. Because of the large range from 80 km to 1000 km that includes the satellites orbit paths in any case, the currents had to be deduced from the plasmaspheric part of the CTIP model, using an interpolation scheme. It resulted in a good coverage at low- and mid-latitudes. There is a high latitude outer border with zero current densities beyond and a small gap region close to the magnetic equator at lower heights (< ~200 km). Figure 6.1 shows as an example the global x-component (southward) “total” current distribution at a given height level near CHAMP’s orbital altitudes (400 km).

Fig. 6.2 shows two meridional cuts of the “total” current vector for the same epoch as shown in the upper row of Fig. 5.4 of the validation section for direct comparison with CHAMP measurements of electron density along the satellite orbit. Here, we show the model current density vector in the x-z-plane (geographic latitude and altitude) with the third component in azimuthal direction, the eastward pointing $J_{toty}$-component, as colour-coded background with the colour scale on the right-hand side. Large eastward directed currents are found in the F region at the location of the Ionization Anomaly crests. These high amplitudes are located, where the gravity-driven currents are expected. Only low currents are observed in the night side E-region, which is reasonable due to the depleted conductivity there.
Figure 6.1: Global distribution of x-component of the “total” current from CTIP outputs at 400 km altitude for epoch 20UT at 09 July 2003.
First of all, we were interested in testing the divergence-free (div $j = 0$) condition. Using spherical coordinates, the divergence of the current vector can be calculated as:

$$\text{div } j = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 J_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} J_\phi + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\sin \theta J_\theta)$$  (6.3)

Two different numerical methods for estimating the current divergence have been used. They are both approximate methods because the current density is given at discrete grid points only, and we have assumed linear variations of the continuous current density between the pixel elements of the grid for the algorithm to deduce the divergence of the 3D current density vector array.

The first method considers so-called voxels, i.e. the smallest volume element of the grid, each of which is formed by eight closest neighbour grid points at the corners of a rectangular space element. Strictly speaking it is a curvilinear spatial element with edges in meridional ($x$), azimuthal ($y$), and radial ($z$) direction (see Fig. 6.3a) and the divergence is estimated at the barycentre of this voxel. One has to calculate the balance currents flowing into and out of this spatial element of a certain volume and through its given surface area. The current density is available at the corners 1-8 only, so that the balance is calculated from the current density differences of diagonally opposite pairs of the voxel’s corners, i.e., 1-7, 2-8, 3-4, and 4-6 (see Fig. 6.3a).

The second method relies on the direct numerical solution of equation (6.3) within the 3D grid of the spherical coordinate system. Using one central pixel and its 6 nearest neighbour pixel elements in each spatial direction (see Fig. 6.3b), it is possible to estimate the current vector divergence. The spatial derivatives are solved in radial ($r$), azimuthal ($\phi$), and meridional ($\theta$) direction and the resultant scalar divergence is then valid at the centre point of this spatial element. The divergence is therefore estimated at the same 3D grid point, at which the discrete current density is given.
The ratio of the current divergence to its magnitude, \( \text{div} j / |j| \), as an estimate of the div-term significance, can hence be calculated without any further interpolation. This can be considered as an advantage of this method in comparison with the method above. The latter method has been applied in this study. Fig. 6.4 shows the results of the estimation of the model current’s divergence for the current density distributions shown in Fig. 6.2.

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**Fig. 6.3:** Schematic illustration of the two methods used for divergence estimation.
The divergence of the currents can be compared to the magnitude of the current. In the 20UT plot of Figure 6.4 the maximum amplitude of the current divergence is $1.56 \times 10^{-12} \text{A/m}^3$. The maximum current strength as derived from Figure 6.2 is $8.40 \times 10^{-8} \text{A/m}^2$. The characteristic scale length of the current divergence ($\Delta x = |\mathbf{j}| / \text{div } \mathbf{j}$) is $5.4 \times 10^4 \text{m}$ which is $\sim 50 \text{km}$. This is equal to the distance between two model grid points, therefore the divergence cannot be considered insignificant.

**6.2 The Biot-Savart method**

A classical method for computing the magnetic fields is based on Biot-Savart’s law:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{j}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'. \quad (6.4)$$

where $\mathbf{r}$ is the radius vector pointing from the origin to the observation point, e.g., the S/C location, and $\mathbf{r}'$ is the radius vector to the current elements, $\mathbf{j}$ given at each grid point. $V'$ is the considered current volume. Solving the Biot-Savart integral does not explicitly require closed and divergence-free global current systems but delivers also reliable results, when the regional currents, e.g., only on the night side, are considered for integration. This makes this method especially suitable for application on the CTIP data base.

**6.2.1 Application to the CTIP data base**

The most important current components in the low and mid latitude night side ionosphere are the pressure gradient-driven and the gravity-driven currents. These currents can be calculated from equation 2.6 of this document. The pressure gradient-driven current is described by the term $\{-k\nabla[(T_{\parallel} + T_{\perp})N_e] \times \mathbf{B}\} / B^2$ and the gravity-driven current by the term...
\{N_e \mathbf{m} \mathbf{g} \times \mathbf{B} \}/B^2 \}. The quantities of electron density, \( N_e \), electron temperature, \( T_e \), and ion temperature, \( T_i \), are provided by the CTIP model. For consistency with the CTIP model, the magnetic field is derived from a centric tilted dipole field. The gravitational acceleration, \( \mathbf{g} \), is retrieved from the formula in Yoder (1995) (see Appendix 1).

Figure 6.5 shows the pressure gradient-driven currents as derived from the CTIP plasma parameters. The left panel shows the current in the longitude/latitude plane at an altitude of 400 km. It is obvious from this plot that the current is related to the plasma gradient of the Equatorial Ionisation Anomaly (EIA). It further enhances around sunset, when the EIA is also enhanced, and this effect lasts until about midnight. The right panel in Figure 6.5 shows the current distribution in a latitude/height cross section along the meridian closest to the CHAMP orbit at that time. This figure illustrates that eastward (e.g., positive zonal) currents flow when the plasma density gradient is upward below the F2-peak and they flow westward when the plasma density gradient is downward above the F2-peak. (See also the schematic drawing in Figure 2.8) The satellite passes just between the two current maxima, where we will expect largest effects on the magnetic field variations. It also shows that these current elements have almost no component in the meridional and/or vertical direction.

Figure 6.5: Pressure gradient-driven currents, \( J_p \), as derived from the analysis of the CTIP plasma parameters at 09 July 2003, 20UT. (left) Longitudinal/latitudinal distribution of the zonal component at 400 km altitude level and (right) latitudinal/height distribution along the meridian closest to the CHAMP orbit. In this plot, the colours describe the zonal component of the currents (positive east) and the white lines describe the meridional and/or vertical component of the current. The magenta line indicates the passage of the CHAMP satellite.

Figure 6.6 shows the gravity-driven current as derived from the CTIP plasma parameters. The left panel shows the zonal current component in the longitude/latitude plane at an altitude of 400 km. It is obvious from the plot that also this current is related to the enhanced plasma density of the EIA. The current is especially strong during day, when the plasma density is
height, but it is as well significant in the low latitude F region after sunset. The right panel shows the latitude/height distribution of the gravity-driven full current vector along the meridian closest to the CHAMP orbit. At satellite altitude (~400km) largest current amplitudes are expected. Also this figure shows that these current elements have almost no component in the meridional and/or vertical direction.

Figure 6.6: Gravity-driven currents as derived from the analysis of the CTIP plasma parameters at 09 July 2003, 20UT. (left) Longitudinal/latitudinal distribution of the zonal component at 400 km altitude level and (right) latitudinal/height distribution along the meridian closest to the CHAMP orbit. Here the colour code stands for the zonal component while the small solid lines indicate the components in the meridional plan. The magenta line shows the CHAMP orbit.

Figures 6.7 and 6.8 show the numerical solutions of equation (6.4), the Biot-Savart law, for the pressure gradient-driven and the gravity-driven night time current systems, respectively. These are time series of the magnetic variations, $\delta B$, which the S/C would observe along its path on a near-polar, circular orbit at F2 layer heights. The orbit of the CHAMP S/C is indicated by the magenta line in Figs. 6.5 and 6.6.

The calculations performed are based on the CTIP simulation results that were given on the longitude-latitude-altitude grid. The estimated current densities are assumed to be constant within each voxel, i.e. the volume element around each grid point. The integration according to equation (6.4) was executed within a circle of 5000 km range around the actual S/C location, corresponding to about one sixth of the Earth’s surface. To realize the calculations, various transformations between the spherical coordinates of the original grid to an orthogonal geocentric, geographic system and back had to be performed.

CHAMP passes at about 400 km altitude through the pressure gradient-driven current structures approximately in the meridional plane that is shown in Fig. 6.5. The resulting $\delta B$ variations are presented in the left panel of Figure 6.7. Here the three components in spherical
coordinates, i.e., the small radial outward component (green), the dominating southward component (red) and the eastward component (blue) are shown. The right panel of Figure 6.7 shows the projection of this field variation onto the background field giving the modification of the total field, \( \Delta B = \delta B \cdot \frac{B_{\text{dipole}}}{|B_{\text{dipole}}|} \). As expected, the magnetic field due to plasma pressure opposes the main geomagnetic field in regions of the large density. There is a “double-hump” structure, symmetric about the geomagnetic equator, which is somewhat shifted in the geographic system toward north in this longitudinal region. The differences in amplitude are due to the non-symmetric plasma density distributions in the crest regions of the two hemispheres.

![Figure 6.7: Distribution of magnetic field along the orbit at 400 km altitude as derived from Biot-Savart integration of the pressure gradient-driven current elements represented in the three spherical components (left), as well as the effect on the ambient magnetic field strength (right).](image)

Figure 6.8 shows the same \( \delta B \) vector plot for the gravity-driven current structures, which were presented in Figure 6.6. Here, the radial and southward field components are dominating. They show non-symmetric peaks north and south of the geomagnetic equator.

The magnetic field as derived from Biot-Savart is slightly different when a different gridding of the currents is chosen. The applied step width for the current integration, when using the Biot-Savart method, is a very crucial parameter. We tested various step widths of current integration, beginning with the CTIP model grid spacing (18° in longitude and 2° in latitude) but had to go down to 1° by 1° resolution in order to obtain reliable results, which were used for Figures 6.7 and 6.10. Generally, the estimated \( \delta B \) magnitudes are largely overestimated by the Biot-Savart integration when the grid spacing is too large and they converge finally when coming close to the 1°-resolution. This need for high spatial resolution makes the Biot-Savart integration very demanding in computation time.
7. Assessment of magnetic field estimates

Section 2 identified single component magnetic field recovery methods for the pressure gradient and the gravity-driven currents. In this section we make use of the plasma environment and the current distribution simulated by the CTIP model for assessing the reliability of the approaches introduced in Section 2. The magnetic field effect of the modelled currents is obtained by Biot-Savart integration of the current elements on the entire mid and low latitude night side.

7.1 Assessment of magnetic fields due to pressure gradient-driven currents

The simple approach for estimating the magnetic effect of the pressure gradient currents, as described in Sect. 2, makes use only of local plasma parameters such as density, electron and ion temperatures. From these quantities a reduction in field strength is predicted. Here we made use of the simulated plasma parameters and calculated the local depletion in ambient field strength. Figure 6.9 shows the obtained magnetic field deflection in the left panel at CHAMP orbital altitude and the right contains a meridional cut along the orbit. From this figure we can deduce that the magnetic perturbations are strongest at CHAMP altitude shortly before midnight. As expected, the magnetic field deviations follow well the shape of the Ionisation Anomaly.

For the same data set the magnetic field effect along the orbit was deduced from the simulated current distribution (s. Sect. 6.2.1). The results are presented in Figure 6.10. In the left panel
perturbations of the magnetic field magnitude retrieved from the currents are presented as a solid line and the dashed line represents the predicted field depletion estimated from the local plasma parameters. Both curves have the same shape and amplitude with peak magnetic field reductions at both sides of the dip equator. Such a distribution corresponds very well with observations from the CHAMP satellite as presented early in Figure 2.6. The right panel illustrates the angle between the disturbance field vector and the ambient magnetic field. In regions of significant deflections the angle is close to 180°. This confirms that the derived disturbance vector is close to anti-parallel to the background field, as expected from our simple pressure balance approach in Sect. 2.

The range of magnetic field signatures over a solar cycle was evaluated in Table 2.1. Depending on the amplitude of electron density these signatures can have amplitudes between some few 0.1nT and a few nT. With an EIA electron density peak of about $1.5 \times 10^{12}$ m$^{-3}$, as predicted by the CTIP model for the 20UT case and near the CHAMP orbit (see Figure 5.4, upper panel), the resulting magnetic field deflection of about 2.5 nT is very reasonable with respect to the expectations in Table 2.1, where 5.5 nT for an electron density of $3 \times 10^{12}$ m$^{-3}$ is given.

Figure 6.9: Magnetic field effect (magnitude) due to pressure gradient-driven currents as derived from equation 2.9 based on the CTIP plasma parameters along the CHAMP orbit at 09 July 2003, 12UT. (left) Longitudinal/latitudinal distribution at 400 km altitude and (right) latitudinal/height distribution along the meridian close to the CHAMP orbit.
Figure 6.10: Magnetic field effect along the CHAMP orbit due to pressure gradient currents as derived from Biot-Savart integration (black line) and as derived from the single component approach (green dashed line). The right panel shows the angle between the disturbance magnetic field vector and the ambient field.

With respect to the forthcoming Swarm mission we repeated the calculations for both the single component approach (according to the diamagnetic effect) and the Biot-Savart method for a typical orbit of the higher Swarm spacecraft, uplifted by 130 km in height with respect to the CHAMP orbit used for Figures 6.5 – 6.10. This Swarm satellite traverses the near-equatorial nightside current regions in the upper F region - typically above the upper, westward directed, current centres.

Fig. 6.11 shows the Biot-Savart integration of pressure gradient-driven currents similar to Figure 6.7 but now for this higher altitude orbit. The southward component is still dominating but with a smaller amplitude. The radial magnetic field disturbance becomes more important at this altitude and is now comparable in magnitude to the eastward component. The “double hump” structure of the disturbances is still present along this higher S/C orbit.

The projection of the disturbance magnetic field on the ambient geomagnetic field is shown as black line in Fig. 6.12, left panel, while the right panel illustrates the angle between the two field vectors analogously to Fig. 6.10 for the CHAMP orbit. The Biot-Savart algorithm employs the same 1° by 1° resolution in latitude and longitude as before. The result shows again a fairly good correspondence with the single component approach (green dashed line, left panel) as well as a nearly anti-parallel direction of the disturbance field to the ambient field in the central part where the currents are strongest. Here again the pressure gradient-driven currents primarily reduce the geomagnetic field.
Figure 6.11: Same as in Fig. 6.7, left panel, but now for a Swarm orbit at about 530 km height.

Figure 6.12: Same as in Fig. 6.10, but now for a Swarm orbit at about 530 km height.
7.2 Assessment of magnetic field due to gravity-driven currents

The shape of the magnetic field deflections due to gravity-driven currents, as derived from Biot-Savart integration of currents calculated from the CTIP electron density distribution, was shown in Figure 6.8. Especially the radial component is affected by this current type. Modelled and observed magnetic fields derived from the single component approach are provided in Figures 2.5 and 2.10 of section 2. The shape of the radial magnetic field component with a large gradient from outward at the northern edge to inward at the southern edge of the Ionisation Anomaly peaks correspond well in both cases. Figure 2.10 shows the observed magnetic field deflection averaged over several CHAMP years at a local time of 23 UT (yellow curve), very similar to the local time of our example in Figure 6.8. Due to the average nature of the curve in Figure 2.10, the gradients appear smoother than in our simulated example. The peak-to-peak amplitude is in the range 2 - 3 nT in the observations (Figure 2.10), approximately the same as in our modelling example (Fig. 6.8). Also the latitudes of the radial component peaks agree reasonably well between simulation and observation. Table 2.1 predicts for an Ionisation Anomaly electron density of $1.5 \times 10^{12}$ m$^{-3}$ a magnetic deflection of about $\pm 3$ nT. This is twice as much as derived by CTIP simulation.

In case of the gravity-driven currents special effort is required to keep them divergence-free. Since we could not maintain this condition, it is no surprise that differences in the size of the magnetic effect emerge between simulation and observation.

8. Description of TEC retrieval

8.1 GPS observables

Each of the Swarm satellites carries a GPS receiver with a zenith looking GPS antenna on the topside of the spacecraft. This enables measurements of the GPS signals every 10 second. The trans-ionospheric ray path of radio waves is modified by the presence of free electrons. Therefore, GPS observables contain information on the integrated electron density, $N_e$, named TEC [TECUnits = $10^{16}$ m$^{-2}$], along the ray path, $s$, between the GPS satellite (T) and the receiver (R)

$$TEC = \int_T^R N_e ds.$$  \hspace{1cm} (8.1)

The GPS satellites transmit signals on two carriers at frequencies $f_1 = 1.575$GHz and $f_2 = 1.227$GHz. A GPS TEC measurement is derived when the phase observations or the code observations carried by the two GPS frequencies are differenced:

$$L_1 - L_2 = 40.3 \frac{m^3}{s^2} \frac{f_1^3 - f_2^3}{f_1^2 f_2^2} TEC + \lambda_1 \cdot N_1 - \lambda_2 \cdot N_2 + \Delta \varepsilon_L$$  \hspace{1cm} (8.2)

$$P_2 - P_1 = 40.3 \frac{m^3}{s^2} \frac{f_1^3 - f_2^3}{f_1^2 f_2^2} TEC - dcb_T - dcb_R + \Delta \varepsilon_P$$  \hspace{1cm} (8.3)
where \( L_1 \) and \( L_2 \) are the carrier phase observations, \( P_1 \) and \( P_2 \) are phase observations of the P code modulated on the carriers, \( \lambda_{1,2} \) are the wavelengths of the two carriers, \( N_{1,2} \) are integer numbers of phase ambiguity. The terms \( \lambda_1 \cdot N_1 - \lambda_2 \cdot N_2 \) are called cycle slip ambiguity. \( dcb_T \) and \( dcb_R \) are the transmitter and receiver differential code biases and \( \Delta \varepsilon_{L,P} \) are noise terms.

![Figure 8.1: CHAMP occultation with GPS satellite PRN 4 on April 28, 2001. The black curve shows TEC derived from P-code phase measurements and the grey curve shows TEC derived from carrier phase measurements. (Figure adopted from Stolle (2004))](image)

As is visible from equations 8.2 and 8.3 the phase difference \( L_1 - L_2 \) is affected by cycle slip ambiguities. The P-code difference is ambiguity free, but it contains receiver and transmitter differential code biases. Figure 8.1 shows an example of GPS TEC time series received onboard CHAMP (occultation antenna). This figure illustrates well the different behaviours and error sources of the two TEC observables. The TEC series derived from P-code observations is more affected by noise than the carrier phase derived TEC series. After approximately half of the recording time, the TEC series derived from carrier phase observations suffer a cycle slip after a loss of lock (missing data). Such data gaps may occur, e.g., when the GPS signal crosses small scale ionospheric irregularities.

8.2 Correction of carrier phase measurements

This section describes a procedure which allows for correcting the low noise carrier phase TEC observations for ambiguities.

Blewitt (1990) developed an algorithm to detect cycle slips, to correct for them, and to delete possible outliers in a time series of a GPS satellite track. Therefore, he introduced a model for non-differenced range data:
\[ L_1 \equiv -\frac{c\Phi_1}{f_1} = \xi - I \frac{f_2^2}{f_1^2 - f_2^2} + \lambda_1 N_1 \]
\[ L_2 \equiv -\frac{c\Phi_2}{f_2} = \xi - I \frac{f_1^2}{f_1^2 - f_2^2} + \lambda_2 N_2 \]  
(8.4)

where \( c \) is the speed of light, \( \Phi_{1,2} \) are the actually recorded phases of the carriers, \( \xi \) represents all non-dispersive terms which are eliminated by differencing the observations (geometric distance, clock errors and neutral air propagation error), and \( I \) is \( P_2 - P_1 \). The number of cycle slips in the carrier phase measurements is an integer value and is named \( \Delta N_i \):

\[ (\Delta N_1, \Delta N_2) = (N_1^*, N_2^* - N_1) \]  
(8.5)

where \( N_1^* \) and \( N_2^* \) are the new values of phase ambiguity after the cycle slip occurred.

### 8.2.1 Cycle slip detection

Linear combinations of the dual frequency measurements are applied showing useful characteristics for the procedure. Cycle slips are better detectable when dealing with long rather than with short wavelengths. For this reason the wide-lane phase combination is performed (Misra and Enge, 2001):

\[ \Phi_\delta = (\Phi_1 - \Phi_2) \]  
(8.6)

With the corresponding wide-lane “wavelength”:

\[ \lambda_\delta = \frac{c}{(f_1 - f_2)} \approx 0.862 \text{ m}. \]  
(8.7)

The wide-lane ambiguity \( N_\delta \) is the difference of the carrier phase ambiguity at both frequencies:

\[ N_\delta = N_1 - N_2 = \frac{L_\delta - P_\delta}{\lambda_\delta} \]  
(8.8)

where

\[ L_\delta = -\Phi_\delta \lambda_\delta = \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2} \]
\[ P_\delta = \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2} \]  
(8.9)

\( N_\delta \) can be understood as the number of wavelengths between the carrier phase and the simultaneously recorded P-code phase (see Fig. 8.1). The aim is to detect jumps in \( N_\delta \) that
exceed a critical value and are therefore defined as cycle slips. Herein, the definition of the threshold value is crucial. Too low values bear the danger of misinterpreting noise as data jumps. A too high threshold would ignore small slips.

During the data analysis so-called phase connected arcs are built. A phase connected arc consists of a series of data points recorded during a GPS satellite track without detected cycle slips (e.g., Fig. 8.1 shows 2 connected arcs.). The detection criterion for a cycle slip is given by the standard deviation of the $N_{\delta}$s from one arc, and $N_{\delta i}$ is related to the datum of index $i$ within the arc. To determine connected arcs the arc related mean $\langle N_{\delta} \rangle$ is iteratively calculated with an increasing number of $i$ successive measurements, as well as its standard deviation $\sigma^2$:

$$\langle N_{\delta} \rangle_{i+1} = \langle N_{\delta} \rangle_i + \frac{N_{\delta i+1} - \langle N_{\delta} \rangle_i}{i+1}$$

$$\sigma^2_{i+1} = \sigma^2_i + \frac{(N_{\delta i+1} - \langle N_{\delta} \rangle_i)^2 - \sigma^2_i}{i+1}$$

The cycle slip criterion is fulfilled when the two ambiguities $N_{\delta i+1}$ and $N_{\delta i+2}$ differ by more than a critical value from the actual mean value of the arc $\langle N_{\delta} \rangle_i$. Then, a new arc begins to build. The applied critical value has to be evaluated from experiences with the data. Heise, 2002 found a threshold value of $4\sigma_i$ as appropriate for CHAMP GPS zenith antenna observations. For CHAMP occultation data a threshold value of $2\sigma_i$ was identified (Stolle, 2004). If only $N_{\delta i+1}$ but not $N_{\delta i+2}$ exceeds the critical value, $N_{\delta i+1}$ is defined as an outlier. In this case $N_{\delta i+1}$ is deleted and replaced by linear interpolation. At each beginning of a new arc the root mean square is initialised with $\sigma_0 = 0.5$, as was recommended by Blewitt (1990).

8.2.2 Cycle slip correction

After the cycle slip detection the series of arcs are analysed whether they are connectable. Here, the ionospheric combination $L_1$ is relevant:

$$L_1 = L_1 + L_2 = I + \lambda_1 N_1 - \lambda_2 N_2 = I + \lambda_1 (N_1 - N_2) + (\lambda_1 - \lambda_2) N_2 = I + \lambda_1 N_\delta + (\lambda_1 - \lambda_2) N_2$$

To test the continuity over the data gaps the trend after the last samples of one $L_1$-arc is approximated, and is extrapolated to the first few points of the following one. In case of CHAMP occultation data, arcs with more than 20 samples are approximated and extrapolated with a cubic polynomial and arcs with more than 8 but less than 20 samples with a quadratic polynomial. The records are extrapolated upwards to the first four (for cubic polynomials) or to three (for quadratic polynomials) time steps, $\Delta t$, of the following arc, respectively. Arcs with less than 9 samples are discarded, because the risk of interpreting noise as curve trends increases with decreasing number of samples. The differences $\Delta(t)$ of the temporal overlapping data points are calculated:

$$\Delta(t) = L_1(t) - L_1^{extrapolated}(t)$$

The two arcs are considered connectable if the root mean square of $\Delta(t)$
\[ \sigma_{\text{extrapolated}} = \sqrt{\frac{1}{t-1} \sum_{i=1}^{t} (\Delta(t)-\langle \Delta(t) \rangle)^2} \]  

\( (8.14) \)

is below 0.25.

A second condition for piecewise connection is given when reasonable arc shifting integer values \( \Delta N_i \) can be derived. First of all, \( \Delta N_\delta \) is determined by the difference of the \( \langle N_\delta \rangle \) with smallest \( \sigma_i/(i-1)^{0.5} \) of the arcs at both sides of the cycle slip. Using equations 8.12 and 8.13 \( \Delta N_2 \) is determined by:

\[
\Delta N_2 = \frac{\Delta(t=1) - \lambda_1 \Delta N_\delta}{\lambda_1 - \lambda_2}.
\]  

\( (8.15) \)

Since the cycle jumps can only be integers, \( \Delta N_\delta \) is rounded down or up if the first decimal after the dot of \( \Delta N_\delta \) is lower than 4 or higher than 6, respectively. Otherwise, the connection is rejected due to rounding uncertainties.

Determining \( \Delta N_1 = \Delta N_2 + \Delta N_\delta \) is straight forward. When two arcs are finally recognised as connectable, the original ranges of the second arc are corrected through:

\[
L_1^* = L_1 - \lambda_1 \Delta L_1, \quad L_2^* = L_2 - \lambda_2 \Delta L_2
\]  

\( (8.16) \)

and the new, longer connected arc is analysed for its connection to the following one until the end of the satellite track is reached.

The cycle slip correction procedure for the CHAMP GPS zenith antenna observation is mathematical identical, but other criteria, e.g., concerning the arc length have been deduced from experiences with the data (Heise, 2002).

8.2.3 Carrier phase to P-code range levelling

After the piecewise cycle slip correction, the last step to eliminate the carrier phase offset, the carrier phase measurements are levelled to the unambiguous code range measurements. Therefore, the difference between the mean values of \( L_1 \) and \( P_1 = P_2 - P_1 \) is calculated:

\[
SF = \langle P_1 \rangle - \langle L_1 \rangle.
\]  

\( (8.17) \)

Each arc is then related to a shifting factor \( SF \) which is added to all \( L_i \) of the respective arc. The ionospheric combination in the carrier phase data is no longer ambiguous:

\[
L_{i, SF} = L_i - SF
\]  

\( (8.18) \)
Figure 8.2: Typical example of a time series of differential carrier phase and P-code phase observations from the zenith looking antenna onboard CHAMP after the application of cycle slip correction and phase levelling (Figure adopted from Heise, (2002)). The black curve shows TEC observations derived from P-code phases and the red curve shows TEC observations derived from the carrier phase. The yellow curve gives the elevation of the zenith antenna. The x-axis denotes the time from the start of the tracking in min.

Figure 8.2 shows the time series of $L_{1 SF}$ and the P-code phase differences for a typical example record onboard CHAMP. The low noise carrier phase curve is shifted into the noisier code differences. This figure also demonstrates well the dependence of the code noise level on antenna elevation angle. The noise level increases with decreasing elevation angles (see also section 6.4).

8.3 Differential Code biases

The low noise, unambiguous, and cycle-slip-free carrier phase-derived TEC time series still include instrumental differential code biases (see equation 8.3). Code biases are range errors which are due to technical issues existing independently in each GPS transmitter and receiver. It is commonly assumed that the $dcb’s$ are stable over a couple of days and exhibit only small drifts over a couple of weeks.

8.3.1 GPS satellite differential code biases

The IGS (International GNSS Service) provides daily values of differential code biases for each GPS satellite. These biases are included in the so-called IONEX files and are given in nanoseconds. Multiplied by the speed of light, the IGS bias values replace the $dcb_s$ in
equation 8.3. The IONEX files are available at ftp://igs.ensg.ign.fr/pub/igs/iono/ with a latency of 2-3 days.

8.3.2 Differential code biases of GPS space receivers

The calibration of GPS receivers in low Earth orbit is an underdetermined problem, and no definitive solution has been presented so far. However, based on the evaluation of appropriate assumptions, two ways of satellite receiver bias estimation processes were published for zenith antenna observations (Heise et al, 2004; Syndergaard et al., 2005; Syndergaard, 2007).

Heise et al. (2004) presented the following model-assisted retrieval technique for receiver differential code biases from CHAMP and SAC-C zenith antenna GPS observations:

The relation between relative TEC values (cycle slip free and P-code levelled) and the absolute bias free TEC is described by:

$$RT_{rel} = DCB_T + DCB_R + TECTEC$$  \hspace{1cm} (8.19)

where

$$DCB = dcb \cdot \left(40.3 \frac{m^3}{s^2} \frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right)^{-1}$$  \hspace{1cm} (8.20)

is given in TECU. The $DCB_T$ are directly available from IGS (see section 8.3.1). Assuming an average agreement between the real ionisation state and an ionospheric model on selected radio links with expected small TEC values (e.g., high latitude night time measurements at high elevation angles), the receiver $DCB_R$ can be assessed by:

$$DCB_R \approx \frac{1}{n} \sum_{i=1}^{n} (TEC_{mod}(i) - TEC_{rel}(i) - DCB_T)$$  \hspace{1cm} (8.21)

where $TEC_{mod}$ denotes the modelled TEC according to the selected $TEC_{rel}$ path. This approach assumes a stationary receiver $DCB_R$ at least over a temporal range of one day. Since $DCB_R$ is mainly influenced by the hardware temperature, this assumption seems to be valid if the satellite internal temperature is stable, like on CHAMP. To calculate the modelled TEC they used the PIM model (Daniell et al., 1995) which includes also the Gallagher model of the plasmasphere (Gallagher and Craven, 1988). The practical application of equation 8.21 is depending on the required mean agreement between the model and the real ionosphere along the selected radio links. In order to reduce the model dependence of the receiver $DCB$ estimation they prefer an approach which does not demand an average agreement between model and real ionosphere but simply assumes that all absolute TEC measurements exceed a certain minimum value ($TEC_{min}$) which is estimated by the model according to the observation ray paths. By this assumption the receiver $DCB$ can be derived in an iterative process which gradually increases a knowingly underestimated initial receiver $DCB$. This initial receiver $DCB$ can be derived from equation (8.21) if $TEC_{mod}(i)$ is replaced with $TEC_{min}$. For the iterative increment the median value of all positive differences $TEC_{min} - TEC_i$ is used where $TEC_i$ denotes absolute TEC after the $i^{th}$ iteration step according to equation (8.19). To reduce the influence of possible inaccuracies or outliers in $TEC_{rel}$ the iteration is stopped when positive differences $TEC_{min} - TEC_i$ occur for less than three different transmitter receiver combinations. The receiver $DCB$ is calculated as sliding averages over 5 days.
Using this method, Heise et al. (2004) derived a CHAMP GPS (orbit altitude ~400 km) receiver bias of -19.8 TECU (1TECU = $10^{16}$ electrons/m²) with a RMS of 0.9 TECU and a SAC-C (orbit altitude ~700 km) GPS receiver bias of -7.0 TECU with a RMS of 0.5 TECU for the year 2002 (see Fig. 6.3).

The instrumental phase delay calibration for these two satellites can be considered as representative for two Swarm satellites at different orbital altitudes. Therefore, we expect a better performance of the bias retrieval for the upper satellite, Swarm C, than for the lower pair, Swarm A and B, since the GPS rays cross less plasma and the dependence on the model is reduced.

Syndergaard et al. (2005) and Syndergaard (2007) proposed an algorithm where the daily weighted average of paired observations describes adequately well the receiver bias of GPS zenith antennas in space. This process is based on the assumption that $\text{TEC}_A M(\theta_A) = \text{TEC}_B M(\theta_B)$, where $\theta_A$ and $\theta_B$ are the elevation angles of the line-of-sight to two GPS satellites (A,B) in view at the same time, and $M(\theta_A, \theta_B)$ is a function mapping the line-of-sight TEC observations into the vertical, perpendicular to the tangent of the satellite orbit. Syndergaard et al. (2005) used the mapping function $M(\theta_A, \theta_B) = \sin \theta_A \theta_B$. They found for CHAMP GPS observations that the assumption $\text{TEC}_A M(\theta_A) = \text{TEC}_B M(\theta_B)$ is only valid when both $\theta_A$ and $\theta_B$ are larger than 45° and when the estimated vertical TEC above the satellite is less than 3 TECU. For the evaluation of receiver DCBs for the satellites of the FORMOSAT3/COSMIC mission (http://www.cosmic.ucar.edu/), Syndergaard (2007) replaced the mapping function $M(\theta_A, \theta_B)$ by a more sophisticated formulation (Föltsche and Kirchengast, 2002). They found that dropping the condition of high elevation angle (e.g., > 45°) did not harm the
FORMOSAT3/COSMIC receiver bias stability. It should be mentioned that the 6 FORMOSAT3/COSMIC satellites are flying at higher altitude (500 – 800 km) than CHAMP. The average receiver bias over a day is retrieved by:

\[
DCB_R = \frac{\sum (\sin \theta_A - \sin \theta_B) (TEC^*_A \sin \theta_A - TEC^*_B \sin \theta_B)}{\sum (\sin \theta_A - \sin \theta_B)^2}
\] (8.22)

where the summations are made over all paired observations selected upon the above mentioned conditions. The \( TEC^*_A,B \) are the TEC values based on L1 – L2 phase data, levelled to P-code measurements (equation 6.18) and also includes known GPS satellite transmitter biases. After the completion of a day we thus may apply \( TEC = TEC^* + DCB_R \).

Syndergaard et al. (2005) retrieved a \( DCB \) for the CHAMP zenith antenna GPS receiver of about -19 TECU in October 2003. This value is very similar to CHAMP \( DCB \)'s found by Heise et al., 2004 using the model assisted approach. The correspondence of the two independent results supports the consistency of each of the methods applied for \( DCB \) retrieval on space receivers. Syndergaard (2007) presented calculations for the 12 FORMOSAT3/COSMIC receiver biases (6 satellites, 2 antennas each) over a 15 days period in 2007 with stable values between -5 TECU and -45 TECU. They provided an internal uncertainty estimate of ~ 0.6 TECU and a day-to-day variability of less than 1 TECU. The receiver \( DCB \) estimates derived by Syndergaard (2007) are end products of the FORMOSAT3/COSMIC mission.

Table 8.1 summarizes the characteristics of the \( dcb \) retrieval methods developed by Heise et al., 2004 and Syndergaard et al. (2005); Syndergaard (2007). To obtain an exact evaluation, both methods have to be applied and validated with the same data set. This would require the implementation and testing of both algorithms by the same group. This is connected to a major effort and requires a dedicated study. The above described rough comparison implies, however, similar accuracy (or uncertainty) for both approaches. The Heise et al., 2004 assumption of an average agreement between observations and an empirical ionospheric model may appear physically sounder than the required equality between vertically mapped rays. However, the rather simple computational implementation together with very reasonable \( DCB_R \) results obtained by Syndergaard et al. (2005), Syndergaard (2007) seem currently to be most suitable for high-quality near-real time data processing. Due to the rapid development in this field, it is anticipated to implement the most reliable \( DCB \) retrieval technique available at the launch of Swarm.
Table 8.1: Comparison between two different methods for differential code bias estimations of GPS receivers in space.

<table>
<thead>
<tr>
<th>Basic assumption</th>
<th>Heise et al. (2004)</th>
<th>Syndergaard et al. (2005), Syndergaard (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reasonable agreement between modelled and realistic ionosphere</td>
<td>Vertically mapped simultaneous TEC observations derived from different GPS signals are identical</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>&lt; 1 TECU</td>
<td>&lt; 1 TECU</td>
</tr>
<tr>
<td></td>
<td>depending on solar cycle, satellite height, magnetic activity and internal temperature stability of the satellite</td>
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</tbody>
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<table>
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<tr>
<th>Processing modules</th>
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<tr>
<td>Creation of P-code levelled, cycle slip free TEC</td>
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<tr>
<td>Data selection (latitude, local time, link elevation angle)</td>
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<tr>
<td>Use of ionospheric model</td>
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<tr>
<td>Ray tracing along line-of-sight links to obtain modelled TEC</td>
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<tr>
<td>Vertical mapping of line-of-sight TEC</td>
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<tr>
<td>Retrieve daily weighted mean of receiver $dcb$</td>
</tr>
</tbody>
</table>

| Processing demand | several modules with partly expensive computational demands (ionospheric modelling, ray tracing) | minor, near real time capability |

Due to the special Swarm constellation, e.g., the side-by-side flying satellite pair, the bias retrieval can be shortened compared to a full retrieval for each single satellite. In this context and for magnetically quiet days it is reasonable to assume that the two lower satellites observe the same TEC when receiving a signal from the same GPS satellite simultaneously. If calibrated TEC is available for one of the satellites ($TEC_A$), the difference to the uncalibrated, but P-code levelled TEC of the other satellite ($TEC_B^*$) is equal to its instrumental code bias ($DCB_B$):

$$DCB_B = TEC_B^* - TEC_A.$$

(8.23)

It is further recommended that averaged TEC values from low electron density regions, e.g., polar night time regions, are considered for this retrieval. This will avoid occasionally outliers and provide stable daily biases. At the beginning of the Swarm mission, when all three satellites fly in the same local time, this simplification may also be considered between one lower and one upper satellite. Taking advantage of this constellation may reduce the three identical full approach bias retrievals up to only one execution.
8.4 Sensitivity of TEC observables

A very suitable experiment for estimating the sensitivity of GSP TEC observations is the CHAMP mission since Swarm will also carry two-frequency GPS receivers.

The terms influencing the quality of the TEC retrieval most importantly are:

1) Number and severity of cycle slips and outliers
2) Signal-to-noise ratio (SNR) of the carrier and P-code phase measurements
3) Differential Code Bias estimation and stability (receiver and satellite)

In the following the different error terms are described in more detail.

1) Montenbruck and Kroes (2003) analyzed the in-flight performance of the GPS receiver onboard CHAMP. They found carrier phase outliers to affect roughly 1% of the total number of observations. Such outliers are confined to range errors of less than 1 m (~9.5 TECU) and can be attributed to cycle slips in the L1 and L2 measurements. The outlier observations are mostly observed during low elevation angles of the GPS antenna. So, less than 0.1% of affected measurements are found when only elevation angles > 10° are considered. After a successful application of the cycle slip detection and correction (section 6.2.1 and 6.2.2), we expect an almost complete solution for cycle slips and outliers.

2) In GPS terminology, the range error introduced by SNR is called multipath effect. Montenbruck and Kroes (2003) found multipath errors of the carrier phase observations up to 2.5 mm (~0.03 TECU). The P-code phase multipath is much more important. It ranges from 5 cm (~0.5 TECU) at high elevation angles of the GPS antenna to 1 m (~9.5 TECU) for elevation angles of ~10°. Most severe multipath effects are confined to the backward looking low elevation angles and are most pronounced close to the satellite horizon (compare with Fig. 6.3). The multipath errors in the back-looking mode vary predominantly with elevation and change only slightly with azimuth. Multipath reflections are caused by the satellite surface and when interferences with the occultation antenna occur. The latter error source can be excluded for the Swarm mission.

After an appropriate levelling of the TEC time series derived from carrier phase observations to the codes phase TEC observation (section 6.2.3), we expect a maximum SNR induced error of < 0.1 TECU for high elevation angles and ~ 1 TECU for low elevation angles. These assumptions are based on the sum of the expected maximum carrier phase multipath (~0.03 TECU) and 10% of the expected code phase multipath at the different elevation angles, which may influence the accuracy of levelling described in section 6.2.3.

3) The differential code biases for the GPS satellite transmitters are available from the IGS. They provide an RMS value along with the bias estimates of typically below 0.1 ns (~0.3 TECU). The differential code biases for the CHAMP zenith looking antenna have been evaluated in section 6.2.4 with errors below 1 TECU. In summary, an error of ~ 1 TECU can be expected from erroneous bias estimates.

Typical values of CHAMP TEC observations at the zenith looking antenna range between few TECU to about 60 TECU. Compared to these total electron observations the above
mentioned error sources amounts to \( \sim 1.5\% \) in high electron density regions sounded with high elevation angles of the antenna to \( \sim 30\% \) in low electron density regions sounded with low elevation angles of the antenna. It should be noted, the uncertainty analysis presented here is based on experiences within the CHAMP mission. The actual implementation on Swarm may cause differences from our estimates.

8.5 Recommendation as Level 2 product

8.5.1 Product definition

The study team recommends providing bias calibrated, cycle slip free and code phase levelled TEC (see equation 8.18) as a standard Level 2 product. The product will include three independent time series of TEC; one related to each of the three Swarm satellites. The temporal representation will be time series with 10 s resolution, as determined by the sampling rate of the GPS receivers. The TEC Level 2 product shall be provided in units of TECU.

The differential code biases are recommended also to be provided as an additional quantity besides TEC. Then, the end user can easily decide whether he/she trusts the absolute TEC. It is not recommended to provide the user with absolute TEC without information on the receiver’s DCB since DCB retrievals for space receivers are not sufficiently established yet, and many user still prefer the application of cycle slip free but biased TEC for their scientific studies (e.g., Schunk et al., 2004). On the other hand, to provide TEC including an DCB estimate is an opportunity for the Swarm mission since specific users (ionospheric and magnetic field community) are especially interested in absolute TEC appreciating the provision of a DCB estimate with an accuracy of < 1 TECU. The receiver differential code biases shall be provided as 3 independent daily averages in units of TECU one for each of the three Swarm satellites.

8.5.2 Justification of TEC as Level 2 product and anticipated users

TEC is a very valuable data source for many aspects of ionospheric and space weather applications. The sounding of the ionosphere and plasmasphere by the globally distributed multi-satellite links enhances especially ionospheric imaging (Mitchell and Spencer, 2003) and data assimilation results (Schunk et al., 2004) that are used to monitor ionospheric processes in near-real time. The accuracy of such applications is mainly determined by the data availability and distribution rather than by the assimilation technique itself (McNamara et al., 2008). At this point Swarm products will credibly enhance the data situation. An important advantage of Swarm is the side-by-side flying formation of the two lower satellites. Simultaneous observations of TEC will provide information on small scale TEC gradients which were not achievable on global scale until recently. For example, this constellation can be used to detect very precisely edges of high electron density plasma patches. Such plasma patches are subject of intensive research since they seriously affect GPS scintillation activity. The international interest in global TEC observations from a swarm of satellites is also mirrored by the great interest in the FORMOSAT3/ COSMIC mission.
9. **Definition and development of a bubble index**

9.1 **Ionospheric plasma bubbles and its effect on magnetic observations**

The low latitude ionosphere is susceptible to instabilities during the hours after sunset. The absence of sunlight leads to a much faster recombination at lower than at higher altitudes. This causes a steep upward directed plasma recombination gradient existing between the depleted bottom side ionosphere and higher density in the F region. Such density gradients together with the prominent eastward electric field are known to be unstable to the growth of the Rayleigh-Taylor (R-T) instability (Kelley, 1989). The R-T instability is responsible for the initiation and evolution of equatorial plasma bubbles. Plasma bubbles are depleted flux tubes generated at the bottom side F region near the magnetic equator, then rising upward and hence, expanding north and south of the equator. Figure 9.1 shows a schematic example of such a rising flux tube.

![Figure 9.1: Schematic view of a bubble depleted flux tube and a typical orbital segment of a polar orbiting satellite (here CHAMP).](image)

The sharp plasma density gradients between the ambient ionosphere and the depleted plasma bubble produce a plasma pressure gradient driven current (see Equation (2.6))

\[
j = k \nabla \left[ n \left( T_i + T_e \right) \right] \times \frac{B}{B^2}
\] (9.1)

creating systematically positive excursions of the total magnetic field inside the bubble flux tube. As is demonstrated in Figure 9.1, low-Earth orbiting satellites, such as CHAMP or the *Swarm* satellites will directly fly through the bubble, whenever the depleted flux tube reaches at least the altitude of the spacecraft.

Figure 9.2 gives an example of bubble signatures in the magnetic field as detected during the CHAMP mission. It is clearly seen that positive deflection of the magnetic field strength are associated with plasma depletions, here, at about ±10° magnetic latitude. Since the deflections are always positive, they cannot be treated as random noise, or Gaussian-like distributed and will systematically bias the satellite magnetic field measurements. In order to avoid spurious effects in geomagnetic field models contaminated samples should be omitted from the...
analysis. By omitting bubble-contaminated CHAMP orbits, Maus et al., 2006 increased the accuracy of the POMME model.

Figure 9.2: Time series of the residual total magnetic field (1Hz – upper panel) and the electron density (1/15 Hz – lower panel) along a CHAMP equatorial orbit at 03 February 2002.

The CHAMP mission was used to detect plasma bubble events over the multi-years time period and to compile the first global climatology of the magnetic signatures of this phenomenon (Stolle et al., 2006, 2008). Figure 9.3 shows the longitudinal/local time distribution of the plasma bubble occurrence for years 2001-2004 for three different seasons, December solstice (Nov., Dec., Jan., Febr.), Equinox (March, April, Sept., Oct.), and June solstice months (May, June, July, Aug.). This diagram indicates that bubble signatures increases rapidly after sunset, are most important around 21 LT, but may last until post-midnight hours in some regions. It further demonstrates the strong seasonal/longitudinal dependence of the bubble distribution. E.g., during December solstice months, occurrence rates up to almost 100% have been detected in the Brazilian/South-Atlantic region (~45°E longitude), but this region is void of magnetic signatures in June solstice. During equinox, a more uniform distribution of the bubble occurrence is found over all longitudes.
Plasma bubbles at satellite altitudes show a strong linear dependence on the solar flux level. Their occurrence rate enhances dramatically during high solar flux periods. Therefore, it is especially important to provide a bubble identification process for the Swarm mission which will be launched during the peak of the upcoming solar cycle. Also, the Swarm constellation with the side-by-side flying satellites is very suitable to exploit gradient information of the solid Earth magnetic field. But this requires measurements cleaned from small scale external sources, such as bubbles. E.g., if one satellite flies inside, and the other satellite outside the bubble, a magnetic field difference of up to 5nT can be attributed just to the ionospheric phenomenon.

9.2 Plasma bubble index retrieval

The plasma bubble retrieval for the Swarm satellites can gain a lot from the CHAMP heritage. In principle, the plasma bubble retrieval will stay a single-satellite process since it is most suitable for magnetic field modellers to know about the data quality of the different satellites independently. The CHAMP retrieval actually identifies orbits that are affected by bubble signatures at any place in the low-latitude region of the orbit. The Swarm retrieval will be improved in the way that it aims to attribute a bubble index to each 1Hz magnetic field measurement, rather than only to the orbit containing a bubble observation. This will allow

Figure 9.3: Local time – longitudinal distribution of bubble occurrence rate as derived from CHAMP magnetic signatures for years 2001 – 2004. (Figure from Stolle et al., 2008.)
the user to clearly locate the bubble signature, and uncontaminated parts of the orbit are still available. The simultaneous detection of bubbles at near-by flying satellites, as provided by the *Swarm* fleet, will bring important new information in the field of bubble research as will be outlined in section 9.4.

9.2.1 Residual magnetic field

For the investigation of magnetic signatures due to plasma bubbles all other contributions of the geomagnetic field have to be subtracted from the measurements. To do so we need an actual magnetic field model which includes the main magnetic field, the lithospheric magnetisation, and the effect of large-scale magnetospheric currents, including its induction in the sub-surface layers. In the following only the time series of residual fields will be of interest. In case of CHAMP, the POMME model series are used for this purpose (Maus et al., 2006).

9.2.2 Orbit selection and filtering process

It is well known that plasma bubbles occur only on the night side and at low latitudes. Therefore, we select orbital segments which extend between ±45°latitude (geocentric) and their crossing with the geographic equator must happen between 18LT and 06LT. One such an orbital segment is completed by the satellite in about 1400 s.

From CHAMP experiences it was found suitable that each equatorial orbit segment is high-pass filtered with a cut-off period of 30 s. This corresponds to an along-track spatial scale of ~230 km. Subsequently, the filtered signal is rectified. Figure 4 shows an example of CHAMP time series. The upper panel presents the unfiltered residual magnetic field, the mid panel the filtered data sequence, and the lower panel shows the rectified filtered signal. For a successful signal characterisation, two limits need to be set. In the CHAMP analyses, the upper limit (UL) is 0.25nT and a lower limit (LL) is 0.1 nT as indicated in Figure 9.4. It is possible that the upper limit can even be decreased for the high quality *Swarm* magnetic field observations. During the last mission period of CHAMP, a quite successful plasma bubble detection with an upper limit of 0.15 has been tested.
Figure 9.4: Time series of residual total magnetic field (upper panel), the filtered (middle panel), and the rectified time series (lower panel). The horizontal dashed lines indicate the lower limit (LL) and the upper limit (UL), used for plasma bubble detection. (Figure from Stolle et al., 2006.)

9.2.3 Characterisation of signal structure

The individual orbital segments first go through two integrity checks. First, it is checked whether too many data gaps occur in the time series. One long data gap of, e.g., 100 seconds probably does not affect the filtering process. Several 100 second gaps distributed along the orbital segment may seriously harm the results. Stolle et al. 2006 found that a number of 13 gaps or more disturb the filtering process. Second, missing torquer corrections produce a signal in the magnetic field which has similar frequencies than that of the plasma irregularities (Balasis et al., 2005), but it is extending over the entire orbital segment. This is unlikely in the case of plasma bubbles. In the case of CHAMP, missing torquer correction is assumed if 25% of all orbital data is above UL. If either too many data gaps, or missing torquer correction were identified, the entire orbital segment is not analysable.

If the orbital segment passed the integrity check, it is tested whether there are data points above UL. If none exists, all data points of this segment are flagged positively indicating that no bubble signature was detected.

In the CHAMP data base bubble signatures were evaluated by eye for multi-peaked features and not isolated peaks. Therefore, each amplitude above UL needs to be accompanied by further amplitudes above UL within a window of 40 s centred at the detection time. This corresponds to a latitudinal section of ~3°. Furthermore, the high amplitude event needs to be surrounded by low signals (< LL). Therefore, if a first signal amplitude above UL is detected, it is checked whether the following 20s show at least another amplitude above UL, and whether the amplitudes are separated by low amplitudes below LL. If these conditions are confirmed, the satellite is considered to have entered a bubble. Swarm will provide the great
opportunity to verify this assumption in the 1Hz electron density data: entering a bubble must be accompanied by a sudden depletion in plasma density. All following data points are flagged until a high amplitude above UL is reached which marks the end of the bubble signature. This is when it shows the bubble signatures only in its previous data, but not in following data, and when a significant plasma enhancement can be observed in the electron density.

If signal power above UL at the edges of a bubble cannot be attributed to a sudden change in plasma density as well, then the data point has to be flagged as not analysable and the detection process continues. One possibility of such power signals without signatures in the electron density are pulsations, which are compressional waves of the magnetosphere and occur preferably during high magnetic activity.

The possibility to verify the bubble detection with high resolution plasma density observation has not been possible routinely for CHAMP, and hence could not been tested. Figure 9.5 shows the time series of the total magnetic field and the DIDM electron density. The DIDM was harmed during the launch of the satellite, and it could not be calibrated afterwards. But sudden small scale variations are detectable, even if the amplitudes are questionable. However, Figure 9.5 shows exemplarily that the magnetic field deflections are exactly synchronous with the plasma density variations.

Since signal power in high-pass filtered data may also originate from data gaps, each identified amplitude has to be checked whether it is associated with a data gap. If yes, it is checked whether the analysed point sticks out from the neighbouring unfiltered data. If it does not stick out, then the power comes solely from the data gap and the data point can be flagged.
like the previous data points. If it sticks out we cannot reliably tell the nature of this magnetic field variation since information on the surroundings are missing (data gap). Then, the data point has to be flagged as not analysable.

Another artificial data error was detected in the CHAMP data base. Occasionally, individual outliers stick out by about 6nT to 10nT from the quite environment (Balasis et al., 2005, Stolle et al., 2006). Hence, if a high power signal is associated with a data jump of 6nT or more in the unfiltered data, the data point has to be flagged as not analysable.

9.2.4 Current limitations and expected improvements for Swarm

The bubble detection method applied to the CHAMP data base (Stolle et al., 2006) was evaluated as very successful with a bubble signature detection certainty of about 90% even when no additional visual check is provided. However, the reliability dramatically decreases at times of high magnetic activity, e.g., for Kp \( \geq 3 \). Then, natural phenomena like pulsations disturb the magnetic field and cannot always be distinguished from bubbles by the automated detection process.

For Swarm, simultaneous 1Hz high resolution electron density observations provide the unique possibility to compare the power signals in the magnetic field with appropriate variation in the electron density. By that it may be possible to extend the validity of the bubble signature detection toward higher magnetic activity levels.

9.3 Plasma bubble product description

The bubble index is the assignment of a flag to each data point. Three flags are proposed:

0: unaffected from plasma bubbles
1: affected by plasma bubble signatures
-1: not analysable/ not analysed

The bubble index is uniquely described by a table containing one line for each measurement with the GPS second, the geocentric coordinates (lon, lat, alt), and the bubble flag. However, the data format definition should be open for adaptations during the remaining preparation phase of the Swarm mission.

Since only data between 18LT and 06LT and between \( \pm 45^\circ \) latitude (geocentric) are analysed, all day side data, and all data with geocentric latitudes higher than \( \pm 45^\circ \) will be flagged with -1.

Individual files will be created for each of the three Swarm satellite to allow independent analysis. Such an ASCII data file with the above mentioned format will have the size of \(~ 4MB/day\).

9.4 Explorer mission aspects for bubble research

The understanding or even the prediction of plasma bubble is an important issue in recent research; in observation, as well in modelling studies (Su et al., 2008, Stolle et al., 2008, Huba et al., 2008). Plasma bubbles are especially serious in maintaining continuous operation of satellite based navigation systems, such as the Global Positioning System (GPS) or the
future Galileo because the associated sharp electron density gradients cause signal scintillations (Basu et al., 2002).

The multi-spacecraft mission with the special constellation of side-by-side flying satellites and (at least at the beginning of the mission) a satellite flying just above the others provides a unprecedented possibility to investigate the size of bubbles from in situ measurements. Bubbles have a longitudinal width of about 100-200km, and they are of magnetic field aligned nature (Otsuka, 2004). It has frequently been observed that sharp gradients exist at their borders. In a Swarm constellation, e.g., one satellite flies through the bubble, but another one (either above or the side-by-side flying) is located in the ambient ionosphere, will allow unique observations about the different ionospheric environments inside and outside the phenomenon, and will help to advance the understanding of associated transition processes.

With the full instrumentation available on Swarm, the understanding of the magnetic signatures will be dramatically enhanced. As pointed out in equation 2.6, the plasma pressure gradient driven current depends on the electron density gradient, and on the gradient of the electron and ion temperature. When estimating the magnetic signature depending on the associated electron density gradient, the electron and ion temperature was assumed to be unchanged until now. This can be approximately true for the ion temperature which is closely related to the neutral background. But important variations in the electron temperature are expected (Park et al., 2005). With Swarm, the 2Hz resolution CEFI temperature and electric field data will for the first time provide high resolution information about these quantities together with electron density and the magnetic field.

10. Summary
This study has focused on ionospheric electric currents flowing on the night side at low and mid latitudes. Their magnetic field signatures cannot be neglected by main and crustal magnetic field modellers. These are in particular small- and larger-scale pressure gradient and gravity-driven currents. As part of the CHAMP modelling efforts dedicated correction methods for the different current components have been developed. These methods do not consider the interaction between the different current systems therefore their validity had to be tested. This study aims to simulate all the ionospheric currents at middle latitudes consistently in a single run. As the test bed for such an evaluation we selected the physics-based Coupled Thermosphere-Ionosphere-Plasmasphere (CTIP) model. The CTIP model was found to be suitable for such a study since it provides all the ionospheric parameters which are needed to calculate the currents, including the large-scale pressure gradient and gravity-driven currents. As an initial step the simulated ionospheric characteristics where validated against observations. Three days of model outputs were compared to CHAMP electron density and temperature measurements, and one day to Arecibo radar observations of electron density and electron and ion temperatures. The CTIP electron density was found to agree with typical ionospheric features, such as the Equatorial Ionisation Anomaly (EIA). A mismatch in latitude of the equatorial features occurs at longitudes where the dipole magnetic equator is displaced from the actual dip-equator location, since CTIP uses a dipole approximation for the ambient magnetic field. Derived electron and ion temperatures have been found to agree well at night time or just after sunset with Arecibo radar profiles, while they overestimate the temperature significantly at F region altitudes during the day.
An important outcome of this study is a synthetic data set representing for various activity levels global ionospheric conditions. This data set was used for benchmark tests of the different approaches for estimating the magnetic fields caused by ionospheric currents. The classical procedure, calculating currents from the ionospheric parameters and then retrieving the related magnetic fields by the Biot-Savart integration, provides the expected distribution of the B-field components. We have take advantage of the synthetic data set to compute the generated magnetic field from the simulated currents and in addition made use of the plasma parameters to estimate the magnetic effects according to the approach used for CHAMP. The obtained distribution and amplitude of magnetic deflection agree very well between the two methods in case of the pressure gradient currents. In that case the differences are smaller than 0.5 nT, a requirement we had set in the beginning of this study. We regard it as very positive result of this study implying that the diamagnetic effect correction proposed by Lühr et al. (2003) can also be used for Swarm data interpretation. This analysis for the magnetic effect of the pressure gradient-driven is recommended as a Level 2 product. Due to its uncomplicated computation, it is even suitable as a software tool.

No such consistent results could be obtained for the gravity-driven currents. Here the simulated current strengths seem to be too low by about a factor of 2 compared to expectation. We regard this as being a consequence of diverging currents. CTIP in its present form is not able to maintain the gravity-driven currents divergence-free. This pending problem has to be further investigated in order to obtain also a viable correction scheme for the magnetic field caused by these currents.

Some small-scale magnetic field disturbances are due to the occurrence of plasma bubbles. This report presented a method of bubble identification in satellite magnetic field data which takes advantage of important heritage from CHAMP. The improvements for Swarm are in the way how affected data are found. Here not only contaminated orbits but every affected data point is flagged individually with a bubble identifier. An algorithm for applying this approach to the Swarm data was elaborated. For the first time, the Swarm mission will provide electric field data, plasma temperatures and density together with high-resolution magnetic field measurements at a beneficial rate of at least 1Hz.

TEC observations are important ingredients for developing and improving ionospheric models and forecasts of different kinds. This report describes the classical TEC retrieval algorithm tailored to Swarm application in detail, and it suggests two alternative methods for correcting the satellite antenna differential code bias (Heise et al., 2004; Syndergaard, 2007). From published results these two methods have been evaluated against each other and it was found that both methods give very similar results and low uncertainties of about 1 TECU. Based on the lower computation time the method by Syndergaard (2007) is proposed for implementation in the Swarm processing.

The two quantities, plasma bubble index and topside TEC are recommended to be generated routinely as Level 2 products or even regarded as suitable candidates for near-real time processing.
11. Reference Documents


Hedin, A. E., N. W. Spencer, and T. L. Killeen, Empirical Global Model of Upper


Schlegel, K., Rother, M., Lühr, H., and Vo, H., Validation of CHAMP electron density and electron temperature data with corresponding data from the Arecibo incoherent scatter facility, EISCAT-CAWSES Workshop, Freiburg, Germany, March 2008.


Syndergaard, S., W. S. Schreiner, Ch. Rocken, and D.C. Hunt, Coming soon: near real time ionospheric data products from COSMIC, NOAA SEC Space Weather Week, Broomfield, CO, April 5-8, 2005.


Appendix 1

FROM: HERMANN LÜHR
TO: ROGER HAAGMANS, ALAN AYLWARD
COPY TO: TIM SPAIN, CLAUDIA STOLLE, PATRICIA RITTER
SUBJECT: EARTH GRAVITATIONAL ACCELERATION

In response to Action Item AL_006 we have identified a suitable formula for the gravitational acceleration, \( g \), to be used in this ionospheric current study.

Assumption: hydrostatic ellipsoid of a rotating body.
Acceleration experienced by a particle in a rotating atmosphere.

\[
g(r, \beta) = \frac{GM}{r^2} \left[ 1 + \frac{3}{2} J_2 \left( \frac{a}{r} \right)^2 \left( 1 - 3 \sin^2 \beta \right) \right] - \omega^2 r \cos^2 \beta
\]

where \( r \) is the radial distance and \( \beta \) the geocentric latitude.

In the WGS84 frame the quantities are defined as \( GM = 3.986004418 \times 10^{14} \text{ m/s}^2 \), \( J_2 = 1.0826266213133 \times 10^{-3} \), \( \omega_0 = 7.292115 \times 10^{-5} \text{ s}^{-1} \), \( a = 6378137 \text{ m} \).

For the application in the ionospheric current study and due to the limitation to the \( J_2 \) term it is justified to truncate the numerical values to five digits.

\[
g(r, \beta) = \frac{3.9860 \times 10^{14}}{r^2} \left[ 1 + \left( 6.6062 \times 10^{-3} - 1.9819 \times 10^{-5} \sin^2 \beta \right) \right] - 7.2921 \times 10^{-5} r \cos^2 \beta
\]

Examples at Earth surface: \( r_{\text{equator}} = 6378.137 \text{ km} \), \( r_{\text{pole}} = 6356.752 \text{ km} \)

\( g = 9.7804 \text{ m/s}^2 \) at equator
\( g = 9.8322 \text{ m/s}^2 \) at poles

Reference: