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The topside sounder database – Data screening and systematic biases

Tobias Verhulst, Stanimir M. Stankov *

Royal Meteorological Institute (RMI), Ringlaan 3, B-1180 Brussels, Belgium

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Abstract

The ionospheric topside sounder measurement database developed at the US National Space Science Data Center (NSSDC) is a valuable source of information when investigating the composition and complex dynamics of the upper ionosphere. The database is increasingly used by many scientists around the world for both research and development of empirical models. However, there is always a danger of indiscriminately using the data without properly assessing the data quality and applicability for a given purpose. This paper is concerned with the issue of data screening and pre-processing of the Alouette/ISIS topside sounder database. An overview of the original database availability and formatting is given and the use of solar and geomagnetic indices is discussed. Data screening procedures, concerning detection and handling of erroneous profiles, are also presented. Special attention is drawn to the systematic biases observed in the database and the possibilities for their removal.

Keywords: Ionosphere; Topside sounding; Data screening

1. Introduction

The Alouette and ISIS satellites flew from 1962 until 1995 and carried, among other instruments, an ionosonde used to take soundings of the topside ionosphere. Part of the data obtained from these soundings has been converted to a digital format (Jackson, 1969, 1980, 1986, 1988). Each topside sounder measurement is a virtual signal depth profile as a function of plasma frequency which is then used for converting to electron density height profile. Selected datasets are now available from the National Space Science Data Center (NSSDC) and can be used for different research purposes, for which no other data of this kind is available. The space-borne radio sounding databases contain valuable data that can be used to investigate the topside ionospheric variations (Benson, 1996, 2010; Benson and Osherovich, 2004) over several solar cycles. Since the beginning of the topside sounder data restoration project (Bilitza et al., 2003), several studies have been carried out making good use of these databases (e.g. Benson and Grebowsky, 2001; Marinov et al., 2004; Webb et al., 2006a,b; Coisson et al., 2006; Kutiev and Marinov, 2007). The Alouette/ISIS topside sounder data was also used to substantially improve the topside profile specification in the International Reference Ionosphere (IRI) model (Bilitza, 1990, 2001, 2004; Bilitza et al., 2006; Bilitza and Reinisch, 2008).

However, when using this database, a special care should be taken to do an appropriate data screening/cleaning. While analysing these databases, many profiles have been encountered that contain physically impossible characteristics or are incomplete. Also, several systematic biases, stemming from the non-uniformity of the distribution of the data in both time and space, should be taken into account. This paper deals with several issues of data cleaning and bias removal that are relevant to our on-going work with topside sounder data. Even though the paper mainly concerns the issues encountered in the latter these are general concerns regarding the databases themselves and might also be useful for other research.

* Corresponding author. Tel.: +32 60 395 427; fax: +32 60 395 423.
E-mail address: S.Stankov@meteo.be (S.M. Stankov).

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2. Database overview – data availability and geophysical indices

2.1. Original data availability and formatting

The databases containing the topside sounder data are available for download from the ftp site of the National Space Science Data Center (ftp://nssdcftp.gsfc.nasa.gov). There are three datasets containing data from the Alouette-1 spacecraft and one set each for Alouette-2 and ISIS-1 and -2. In total, there are 176,662 measured profiles available. An overview of the number of data available in each database, as well as the time period covered, is given in Table 1.

NSSDC provides the topside sounder database together with a description of the data format (see Appendix). Each profile comes with a header containing the date and universal time of the measurement, geographical coordinates, magnetic inclination, *L*-value, the solar zenith angle at 100 km, sunspot and IG indices and several parameters predicted by the IRI. Also included are a spacecraft identifier and a quality index. However, the spacecraft identifiers are not used as described (see Appendix) and the exact definition of the quality index is not quite clear. In this work we do not explicitly consider the quality index. Instead, for each profile we try assessing for what research project it could possibly be used, in terms of the parts of the ionosphere that are covered by the profile. This is a consideration complementary to the intrinsic quality of the profile. To assure the quality of the research results this index should be considered in conjunction with the points discussed in the present paper.

2.2. Solar and geomagnetic indices

Since the ionospheric variability depends on the level of solar and geomagnetic activity, it is important that the most representative indices are used in the analysis. The NSSDC database does include the 12 month running mean of sunspot number and the IG index as measures of solar activity at the time of the measurements. For our study however, these indices are not as useful as the solar flux index, $F10.7$. Also, even though the magnetic inclination and the *L*-value are included, no indices for geomagnetic activity are given. Therefore, for our purposes, the NSSDC database has been supplemented with $F10.7$, K_p and D_{st} indices (for each density profile and corresponding to time of measurement) via the NOAA Space Physics Interactive Data Resource, SPIDR (http://spidr.ngdc.noaa.gov/spidr).

3. Erroneous and incomplete profiles

3.1. Physically impossible data

The topside sounder, ideally, measures the electron density down to the ionospheric F_2-layer peak density height, h_mF_2, which is in all cases above 100 km. In the database however, there are instances when the profile goes down to very low altitudes (Fig. 1). While the shape of the electron density profile looks "normal", the lowest point at which the density was apparently measured is at a height of 17 km. This would mean that the F_2 peak is at or below 17 km above the surface. This is physically not possible and using such profiles can negatively affect studies focused on vertical plasma distribution and dynamics, radio wave propagation, etc. (e.g. Webb et al., 2006a; James, 2006). Fig. 2 shows the distribution of the lowest points of the profiles for each of the four satellites. Only for Alouette-1 do some of the profiles go down below 100 km. However, that does not guarantee the validity of the lowest reaching profiles measured by the other satellites.

It is unclear what causes this type of erroneous profiles. There must have been something wrong either with the measurement itself or with the analogue-to-digital conversion. A possible explanation might be the influence of a trace from an oblique sounding on the conversion procedure. There is no obvious way to filter them out from the database. The only available ways to remove these profiles from the database is through visual inspection (not practical) or by the use of a cut-off height. Originally, a cut-off value using a fixed minimum peak-height of 100 km was used. This is still very low and might not remove all faulty profiles. However, it still assures that no eligible profiles will be removed. In the subsequent analyses it was decided that removing all faulty profiles was a higher priority than preventing the removal of correct profiles. Therefore, a cut-off height was introduced, a height relative to the F_2 peak height predicted by the IRI. These cutoffs are implemented together with the control of completeness of the profile, as discussed below.

Table 1
Overview of the different datasets and satellite orbit characteristics.

Database	Number of profiles	Period (yyddd)	Satellite orbit altitude (Km)	Inclination (°)
Alouette 1 a	15,706	62273–63082	1000	80
Alouette 1 b	43,614	62272–66089	1000	80
Alouette 1 c	26,452	62323–71350	1000	80
Alouette 2	9301	65349–72192	500–3000	80
ISIS 1	38,953	69030–80151	500–3500	88
ISIS 2	42,596	71088–79239	1400	88

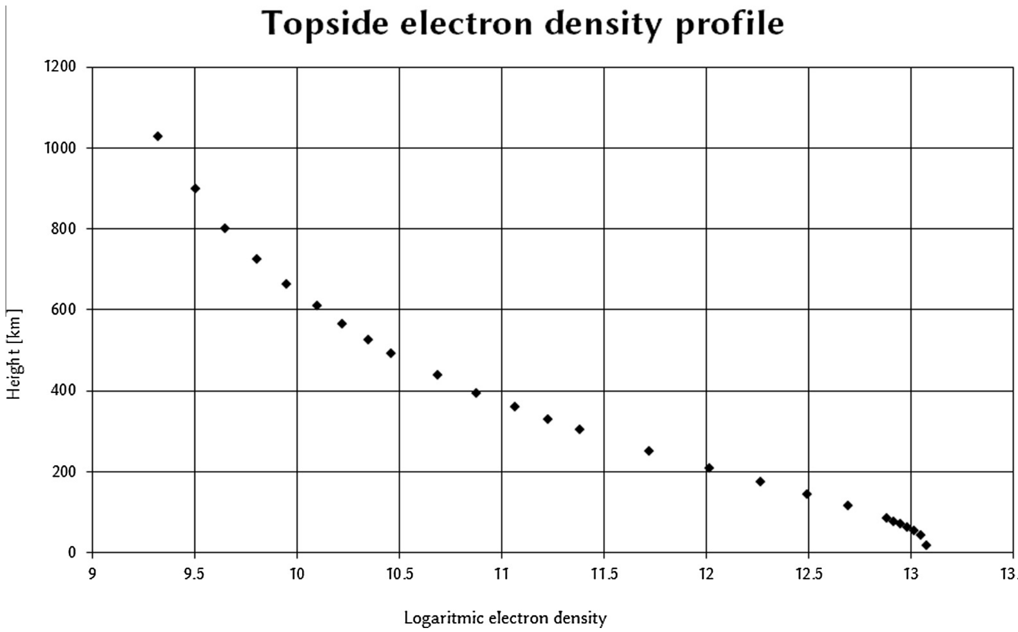

Fig. 1. Example of an impossible electron density profile. The lowest point in this profile is at a height of 17 km, which is not physically possible. Profile obtained from Alouette-1 on day 306, 1962, at 10:29:41UT, coordinates: 75.3°W, 42.86°S.

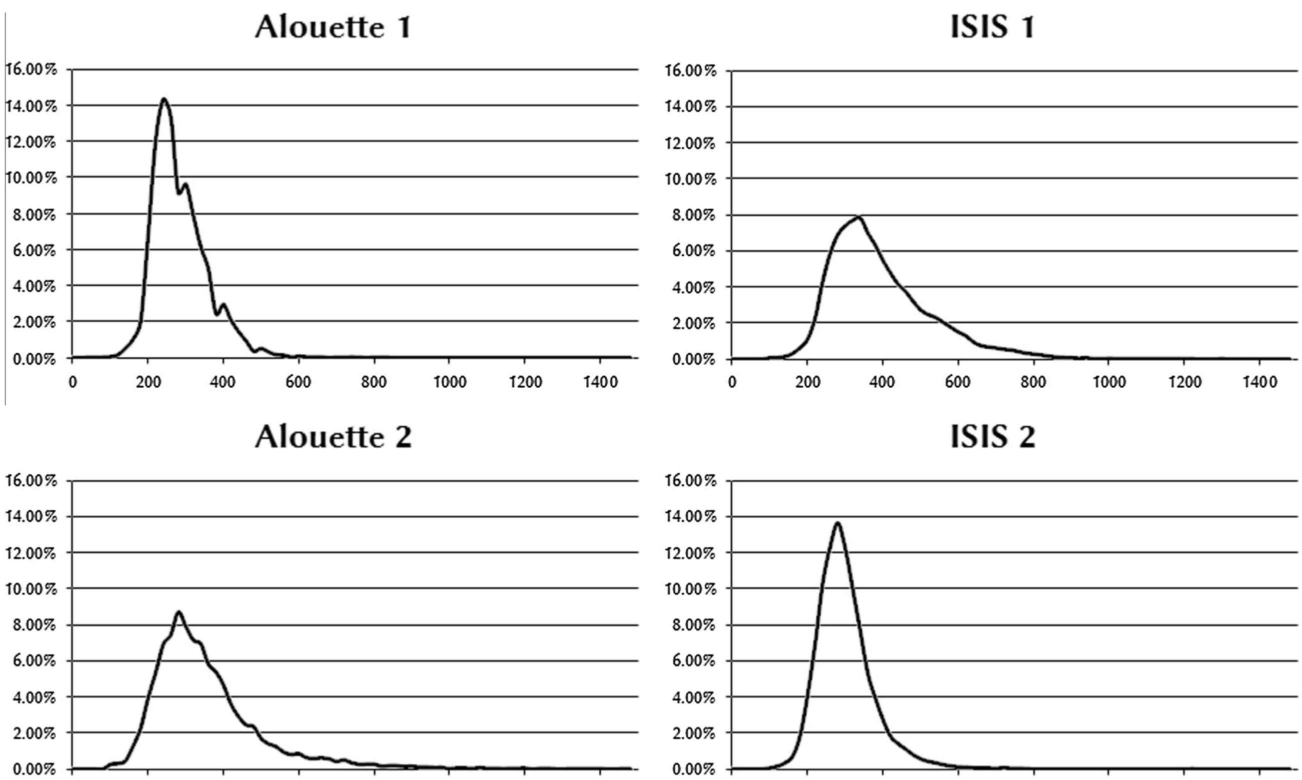

Fig. 2. Distribution of the lowest points in the profiles for each satellite. While the majority of profiles have their lowest point at the height where the F_2-peak is expected, there is a significant number of cases where this point is impossibly high or low. The horizontal axis shows the height in km, the vertical axis shows the percentage of profiles for each satellite. To make the comparison of these distributions easier, the same horizontal scale is used for each satellite, even though it reaches above the orbit of Alouette-1 (cf. Table 1).

3.2. Detection of incomplete profiles

It is important to know precisely what part of the ionosphere is covered by a density profile. It is clear that an ionosonde making downward soundings cannot cover the ionosphere below the F_2 peak. There is, however, no guarantee that the lowest measured point in a profile is indeed at the height of the F_2 peak. First of all, there is a problem with the rather limited resolution of the measurements. This causes an uncertainty of the order of tens of kilometres (the height resolution is not the same for all profiles) in the height of the F_2 peak. However, there is also the possibility that, due to some technical error during the analogue-to-digital conversion, a measured profile might have been cut short at some point above the peak height. The database for each of the satellites contains profiles where the lowest point is too high to be at the F_2 peak, even when taking into account the limited resolution of some of the profiles (Fig. 3). Therefore, it was at first decided to withhold only those profiles for which the lowest measured point, considered to be a measurement of the height of the F_2 peak, was within 50 km of the peak height predicted by the IRI, as included in the database.

However, it is possible that the actual peak height differs more than 50 km from the IRI prediction, and thus the 50 km limit is rather arbitrarily chosen. In fact, this limit is not much bigger than the height resolution of the profiles, which varies but is of the order of tens of kilometres. Climatological studies of the ionosphere, for which the cleaned database was used, are concerned primarily in periods of quiet magnetic and solar conditions and in such conditions the IRI prediction for the F_2 peak height is quite accurate. Depending on the research objectives, other methods to detect incomplete profile can be utilised. For example, the peak height from the topside sounder could be compared to the one measured by a ground-based ionosonde in proximity. Because the data selected for analogue-to-digital conversion was in many cases chosen to be in the vicinity of a ground based station this approach could be viable (Belehaki et al., 2006).

Another important issue is the top-end limit of the reconstructed electron profiles (Fig. 4). This limit is of course determined by the altitude of the satellite carrier and the question arises whether or not the highest point in the profile is above the upper transition level, *TH*, or not. This level is defined as the height where the concentration of O^+ and H^+ ions are equal and is considered to be the boundary between the ionosphere and plasmasphere. Kutiev et al. (2006) describe the following method to determine *TH*: first the height at which the gradient of the logarithmic electron density profile is the lowest is determined. Then the point above this height is searched were this gradient is 30% higher. A linear regression is done over the measurements between these two points. This is assumed to be the O^+ density profile. The height at which the electron density is twice the upward extrapolated O^+ density is the transition height.

Depending on the ionospheric characteristics that are being investigated it would be necessary to restrict the analysed dataset to only those profiles which include measurements up to (or above) *TH*. Only 32,583 profiles are retained after the described cleaning and selection. If only

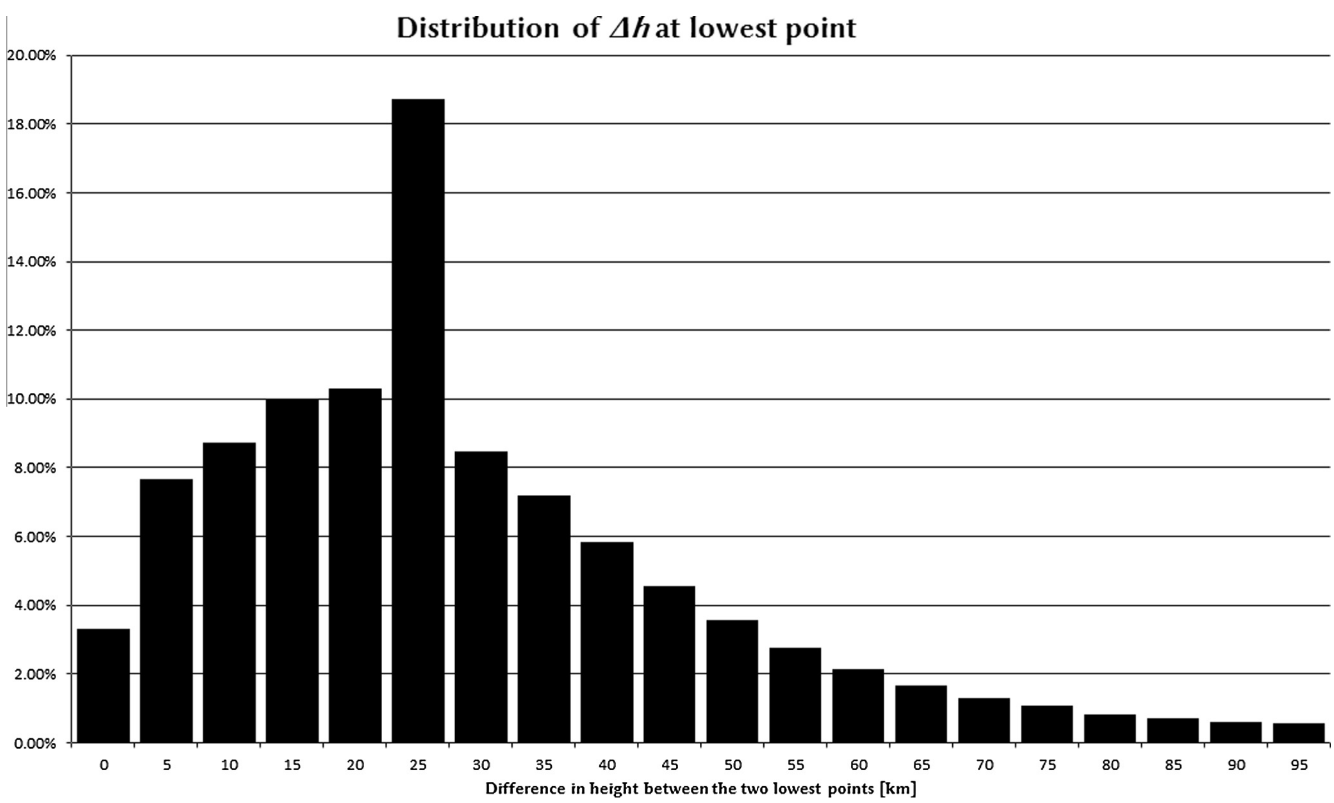

Fig. 3. Histogram of the distribution of distances between the two lowest data points in the profiles. The peak at 25 km occurs due to the Alouette-1b database in which every profile has equidistant points spaced 25 km apart. The average of this distribution is 31.1 km but because of the asymmetry of the distribution the median is only 25 km.

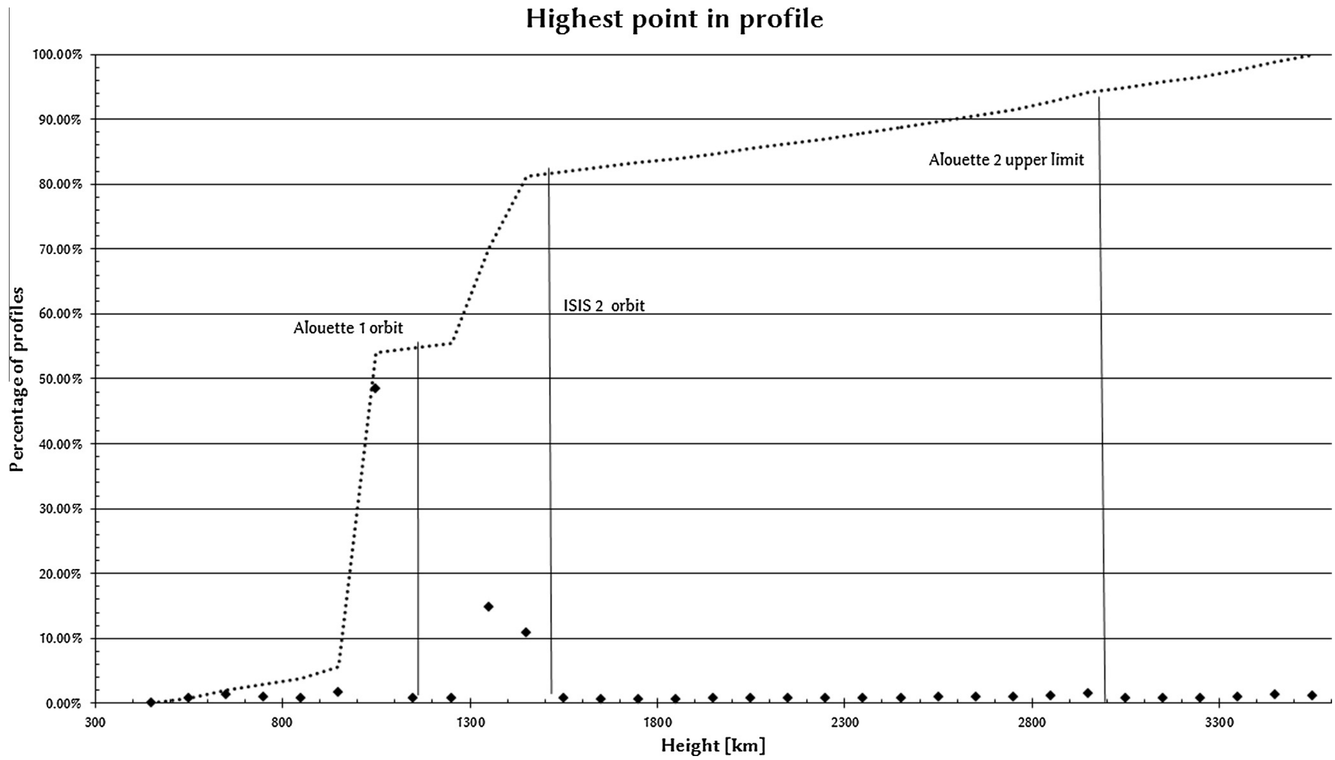

Fig. 4. The absolute and cumulative number of profiles for which the highest measured point falls within a certain height-interval. The heights of the circular orbits of Alouette-1 and ISIS-2 are clearly visible as jumps in the cumulative distribution. The upper limit of the elliptical orbit of Alouette-2 can also be seen. The upper limit of the orbit of ISIS 1 is at 3500 km, at the extreme right of the picture. The lower limits are 500 km for both Alouette-2 and ISIS-1 (cf. Table 1).

properties of the F_2 peak are studied this restriction is not needed. Larger numbers of profiles can be used in those cases.

Unfortunately, the abovementioned cleaning procedures also introduce some biases into the database. Those are discussed in the following section.

4. Systematic biases in the database

4.1. Bias caused by limited resolution

As indicated before the height resolution varies among the profiles. The distribution of the differences between the two lowest points in the profiles is shown in Fig. 2. Since the measurements are done in downward direction, the lowest measured point will, on average, be some distance above the height of the F_2 peak. The TOPIST program used for the scaling of the ionograms (Bilitza et al., 2004) used modelled values for both h_mF_2 and f_oF_2 but the final point in the ionograms rarely coincides with the modelled peak. The differences between the lowest measured points and the true peak heights are relatively small but, because they are always positive, there is a slight bias toward an overestimation of the peak height. The importance of this bias for any given study depends on the required accuracy. To alleviate this bias, it is possible to extrapolate the profile below the lowest data point (Gulyaeva et al., 2008). However, such extrapolations necessarily involve some a priori assumptions about the shape of the profile. Whether or not such an extrapolation is desirable therefore depends on the specific study the data is used for.

4.2. Bias due to height of the satellite

A second, and more important, bias is caused by the variations in the height of the satellites. It is evident from Table 1 that the satellite orbits differ in height: Alouette-1 and ISIS-2 were at 1000 and 1400 km, respectively, while Alouette-2 and ISIS-1 were on non-circular orbits. Fig. 5 shows the distribution of the maximal height at which the electron density was measured in different profiles. Clearly, the different orbits of the satellites result in a rather irregular distribution of the highest points in the profiles. Actually, more than 50% of all profiles have their highest point between 900 and 1100 km.

Due to this distribution of the upper limit point of the profiles, there is a significant bias affecting the localisation of ion transition levels. Because the profile can only cover the complete topside ionosphere if the upper transition level is below the highest measured point, there is a bias toward lower transition levels and, consequently, smaller thicknesses of the ionosphere. Because the maximal height of the profiles is known (see Fig. 2) it is possible to make an estimate for the reconstructed true distribution of *TH*. If

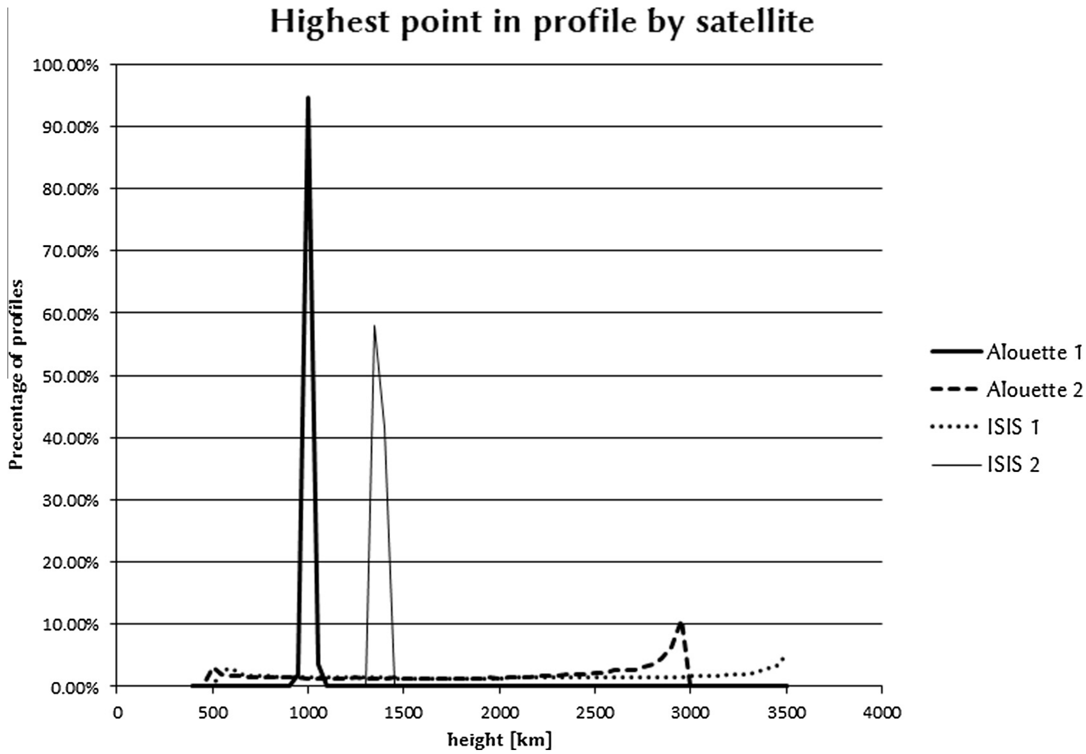

Fig. 5. Distribution of the highest measured point in the profiles by satellite. Note that the vertical axis indicates the percentage of the profiles measured by each of the satellites separately. The number of profiles measured by each satellite can be found in Table 1.

$s(z)$ is the chance that the highest point in a profile is at height z, then $\int_h^\infty s(z)dz$ is the chance that the profile extends to above z. Let $p_0(h)$ be the true chance of TH being at height h, then the chance of TH being found at that height in the data will be

$$p(h) = p_0(h) \int_h^\infty s(z)dz \quad (1)$$

Thus, from the distributions of highest points and measured TH it is possible to estimate the true distribution of the latter. There are two limitations to this that need to be taken into account: the above reasoning assumes $p_0(h)$ to be independent of $s(z)$ – since both these distributions vary with time and space this is an approximation – and it is of course impossible to reconstruct an individual TH that falls out of the range of the profile. Only the statistical distribution can be reconstructed this way.

Since there is a correlation between transition height and scale height as well as a connection between the scale height and the shape of the profile (Stankov et al., 2003; Stankov and Jakowski, 2006; Kutiev and Marinov, 2007), the biases with regard to transition height ultimately influence the shape most likely to provide the best fit of the topside electron density. On the other hand, the transition height is not the only influence on the profile shape. There are clearly other influences, albeit their origin unknown so far, which makes it difficult to separate them from the influence of the transition height and therefore, ultimately, of the data selection and cleaning procedures.

4.3. Bias due to non-uniformity of data distribution

The data selected for conversion are not distributed uniformly in latitude and longitude (a discussion of the selection criteria can be found on the website of the data restoration project; see also Huang et al., 2001). Also, not only were two of the satellites on eccentric orbits but the inclinations of the different orbits were not exactly the same either (cf. Table 1). While the non-uniformity of the geographical distribution of measurements does not directly cause biases in the data, it can do so indirectly because both the topside scale height and the transition height vary with magnetic latitude (Marinov et al., 2004; Kutiev et al., 2006; Kutiev and Marinov, 2007). Similarly, the non-uniformity of the distribution with time needs to be kept in mind because satellites on different orbits flew during different years and therefore during periods of different solar activity.

4.4. Biases introduced by data cleaning procedures

As indicated earlier, the cleaning of the database has some influence on the biases as well. Most importantly, the restriction of the database to only those profiles that cover the complete ionosphere induces an additional bias toward lower transition heights since a lower TH has a higher chance of falling within the range of the profile. As described in the previous sections, such restriction is only necessary for certain research topics. If this particular selection of the data is not needed, this bias will not affect the results. However, if this bias occurs, it can be removed, at least for each location and time separately. This can be done by substituting in Eq. (1) the distribution, $s(z)$, of the maximal heights of only those profiles retained after the cleaning procedures.

The distribution of transition heights obtained through this calculation should not be interpreted as being the true, global distribution. As discussed above, any bias in the transition height ultimately affects other measured characteristics of the ionosphere too. For example, because of the relation between TH and the scale height Ts (see Kutiev and Marinov, 2007) any bias in the transition heights will also affect the scale heights. This has to be kept in mind when interpreting the results of any analysis of the database.

A second problem with the used method for data screening is the reliance on the IRI predictions of the height of the F_2 peak. In most cases these will be good enough but if the deviations from the IRI are the subject of investigation it would be better to use a different cleaning method. In this case, comparison with peak heights measured by ground based ionosondes simultaneously with the topside sounding can be used (Belehaki et al., 2006).

5. Conclusion

While the databases with topside measurements by the Alouette and ISIS satellites provide a lot of opportunities for ionospheric research it is necessary to be very careful when using these data. Some of the included measurements are clearly wrong, so it is necessary to carefully screen the database and remove such faulty data from consideration in a particular study.

For research concerning the topside ionosphere, from the F_2 peak to the transition height, the most important bias to consider is the one caused by the variations in the height up to which the transition height can still be detected. The variations with time and place of the actual transition height do not affect the value derived from the data, but only lead to fewer data being usable in conditions with a higher TH. This, in turn, causes biases with regard to the shape of the density profile. A second bias stems from the non-uniformity of the distribution of measurements, both in time and in magnetic or geographic coordinates. This leads to some data deficiencies because results valid for some times and latitudes cannot be generalised to others where no measurements are available.

These problems do not preclude the use of this data. However, they should be kept in mind so as not to draw inappropriate conclusions from the obtained distributions of the ionospheric characteristics.

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Appendix A

Below, the format description is provided as it is distributed with the original databases (available via ftp://nssdcftp.gsfc.nasa.gov). Each record consists of a header and then the electron density profile data

```
Format Description
M              I5     number of records
HEADER:
itype          I1     spacecraft identifier
iquality       I2     quality index
date           I6     yddd year and day of year
time           I6     hhmmss hour minutes and
                      seconds
long           F6.1   longitude in degrees
lat            F6.2   latitude in degrees
dip            F6.2   magnetic inclination
                      (IGRF)
L              F5.2   L value
xhi            F6.1   solar zenith angle at 100
                      km
Rz12           I3     12-month-running mean of
                      sunspot number
IG12           I3     12-month-running mean of
                      IG index
rtec           F6.2   TEC found in data set
                      (units?)
ln(NmF2)       F7.4   IRI value for F2 peak in cm-
                      3
hmF2           F5.1   IRI value for F2 peak
                      height in km
TEC_IRI        F6.2   IRI value for TEC in TECU
n              I3     number of data points
PROFILE DATA:
n height       14I5   h/km*10
  values:
n density      10I7   ln(Ne/cm-3)*100000
  values:
```

Note: Quality index ranges from 0 (best) to 10 (worst), actually 4 to 10 for these data sets, with a most likely value of 6. Each profile is listed from top to bottom (highest to lowest altitude).

A few things need to be noticed when using this data. First, the `itype` variable is not used, as described here, to identify the satellite but rather to identify the database. The data from Alouette 1 is divided into three separate files with data from file *a* being indicated by `itype` value 1, from file *b* by 2 and from file *c* by 4. Data from Alouette

2 is indicated by 5 and from ISIS 1 and 2 respectively by 6 and 7. Also, while this is not explicitly mentioned in the data description, the `time` field contains universal time, not local time. Also, the units for `rtec` are apparently unknown and this parameter is often given as zero. However, TEC, at least for the topside part of the ionosphere, can be calculated from density measurements if needed.

In the reformatted database all data are given in a space separated format with the header, heights, and densities for every profile each taking up one line. In the original format the lines were broken at 80 columns. Also, the header is appended with the following fields:

F107	I3	F10.7 solar flux index
Dst	I3	Dst index (signed)
Kp	I2	Kp magnetic index

These new field are filled, if possible, with data from the SPIDR database. All datasets are put together in one database and the number of records is no longer stored in it.

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