On the possible use of radio occultation middle latitude electron density profiles to retrieve thermospheric parameters

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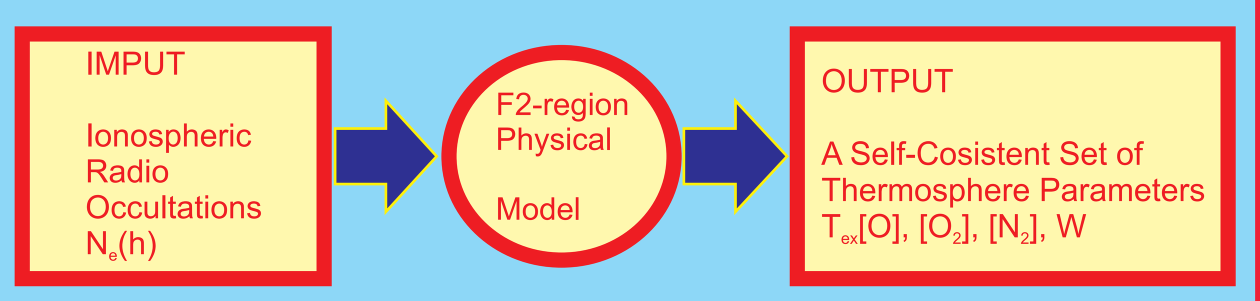
The method to retrieve thermospheric parameters from Ionospheric Radio Occultation (IRO)

The mid-latitude daytime F2-region electron density profile, Ne(h) is known to be formed under the action of:
a) photo-ionization of neutral [O], $[O_2]$, $[N_2]$ species by solar EUV with λ < 1050 Å,
b) transfer of O^+ ions by diffusion, thermospheric winds and electric fields, and
c) plasma recombination in the chain of ion-molecular reactions.
Therefore by solving the inverse problem of aeronomy it is possible to extract the main aeronomic parameters responsible for the formation of the observed Ne(h) distribution.



Aims of the paper

In summary, the aims of the paper are formulated as follows.
1) To apply the method to IRO Ne(h) observations using simultaneous CHAMP neutral gas density measurements for testing the results.
2) To assess the results taking into account the limitations of the IRO method.
3) To evaluate whether the developed method can be used in practice to retrieve thermospheric parameters (neutral composition and temperature) from routine IRO electron density profiles.

Data Presentation

INPUT DATA

For the purpose of this analysis we use Ionospheric Radio Occultation (IRO) data from CHAMP and COSMIC satellites. CHAMP satellite had a near polar orbit ($I = 87°$, $h = 450$ in the beginning of the mission). FORMOSAT-3/COSMIC mission (C/F3) consists of six microsatellites that were launched on 15 April 2006 and reached their mission orbit of 800 km in December 2007, with a separation angle between neighboring orbital planes of 30° longitude. Their orbital configuration gives global coverage of approximately 2,000 soundings per day, distributed nearly uniformly in local solar time.

CHAMP neutral gas density observations

Retrieved neutral gas density was compared to CHAMP/STAR observations.
For our comparison two issues are important: (i) what is the uncertainty in the observed absolute density and (ii) how large is the contribution of He to the total neutral density at the heights of the comparison.
For CHAMP observations "the total uncertainty in the absolute density value is at the 10-15% level for up to moderate geomagnetic activity conditions (ap=15). This is valid for the majority of our analyzed cases.
The observed neutral densities in the vicinity of the RO tangent points (the difference in longitude and latitude < 5°) were reduced to the location and UT of RO tangent points using the MSISE-00 thermospheric model and the following expression:

$$\rho_{tp} = \rho_{CHAMP}\frac{MSIS_{tp}}{MSIS_{CHAMP}}$$

The height for the reduction is selected to be close (the difference < 5 km) to the height of CHAMP neutral gas density observations to minimize possible errors due to the MSISE-00 imperfectness.
Although the retrieved ρ values were corrected for the He contribution using the model ratio $\rho_{tot}/\rho_{tot\text{-}He}$ at the height of a comparison, this does not affect appreciably our comparison with the observations

Testing of the method's performance

The method was tested both for solar minimum (2007-2008) and solar maximum (2002) conditions.
Only CHAMP RO and neutral gas density observations are available for solar maximum while COSMIC RO and CHAMP neutral gas density measurements were used under solar minimum conditions. Based on the method's results, the analyzed RO observations can be divided in three groups: 'good', 'fair', and 'bad'.
We calculated the $R=\rho_{cal}/\rho_{obs}$ ratio and estimated the average R_{ave} and the standard deviation SD.
Good cases are within the $R_{ave} - SD \le R \le R_{ave} + SD$ interval
Fair cases are outside the $R_{ave} - SD \le R \le R_{ave} + SD$ interval
Bad cases are those for which no solution can be found.

Solar Minimum

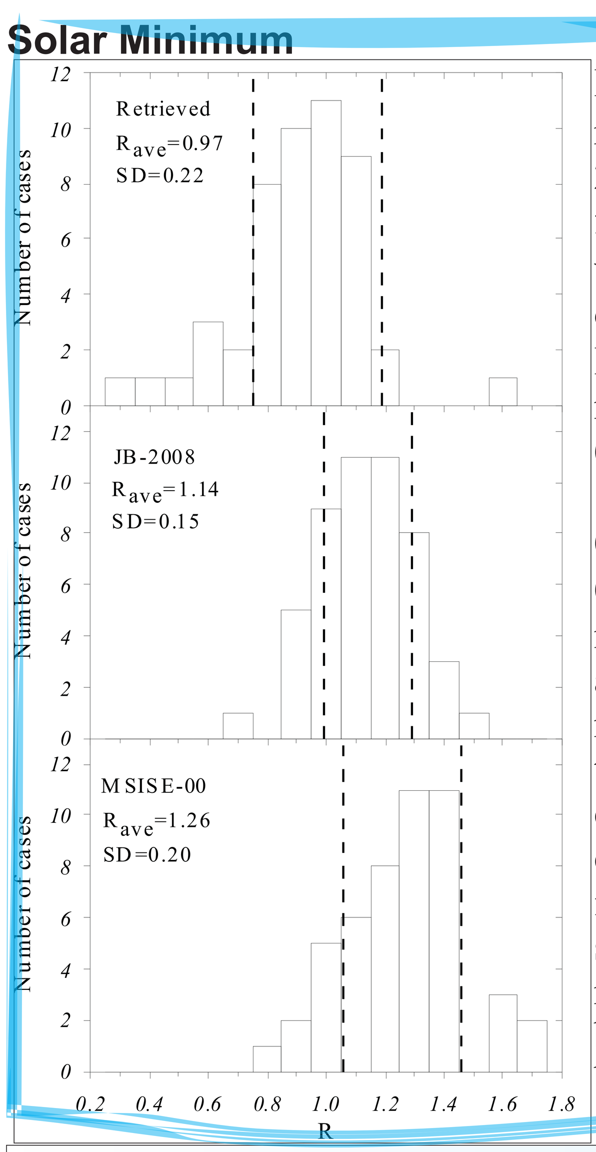


Figure 1. Distributions of $R=\rho_{cal}/\rho_{obs}$ ratio for the retrieved ("good"+"fair" cases) as well as for JB-2008 and MSISE00 model neutral gas densities for solar minimum conditions. Average R_{ave} as well SD values are given. The area between dashed lines corresponds to R_{ave}±SD.
In this case("good" + "fair" cases) the proposed method gives MRD = 15.9% and the bias = -0.20x10^{-15} g cm^{-3}; JB-2008 model gives MRD = 17.0% and the bias = 0.41x10^{-15} g cm^{-3}; MSISE-00 model gives MRD = 28.0% and the bias= 0.80x10^{-15} g cm^{-3}. It is seen that MRD of our method is the least and is still close to the announced absolute inaccuracy of CHAMP neutral gas density observations. The least bias tells us that the retrieved values are more centered with respect to the observations compared to the empirical models. This result is important from practical point of view: if a solution exists then we may expect that the retrieved neutral gas densities on average should be close to the real values, the results being better than the empirical models provide.

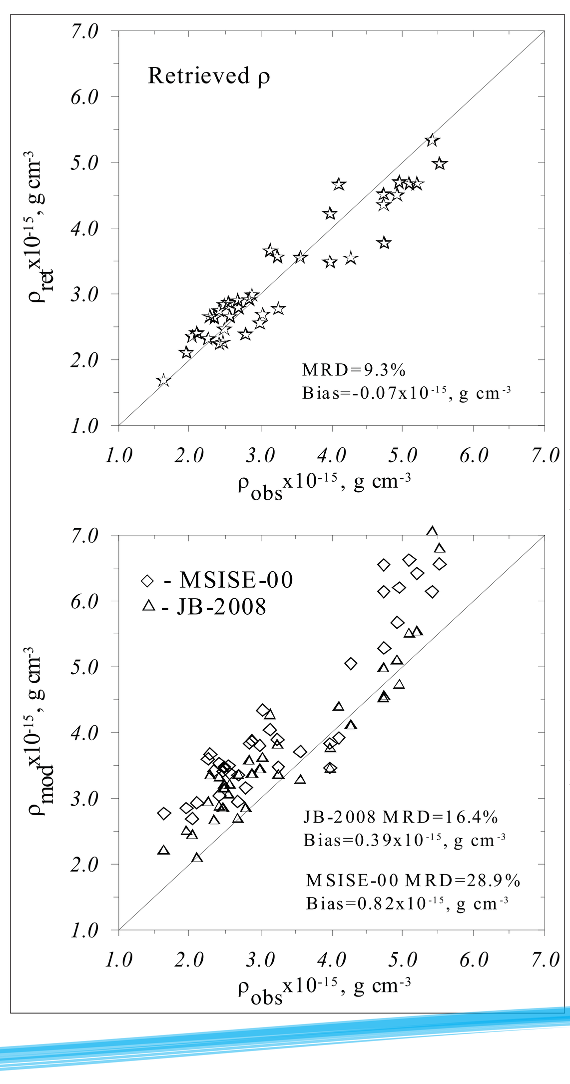


Figure 2. Retrieved and model neutral gas densities versus the observed values for "good" cases. Note that the retrieved densities are more centered with respect to the observed ones while model values are biased overestimating the observations. MRD and bias are given for a comparison.

Considering only the "good" cases the proposed method gives MRD = 9.3% and the bias = -0.07x10^{-15} g cm^{-3}; JB-2008 model gives MRD = 16.4% and the bias = 0.39x10^{-15} g cm^{-3}; MSISE-00 model gives MRD = 28.9% and the bias= 0.82x10^{-15} g cm^{-3}. This testing demonstrates that the proposed method can give good results with better accuracy than modern empirical models provide.

Solar Maximum

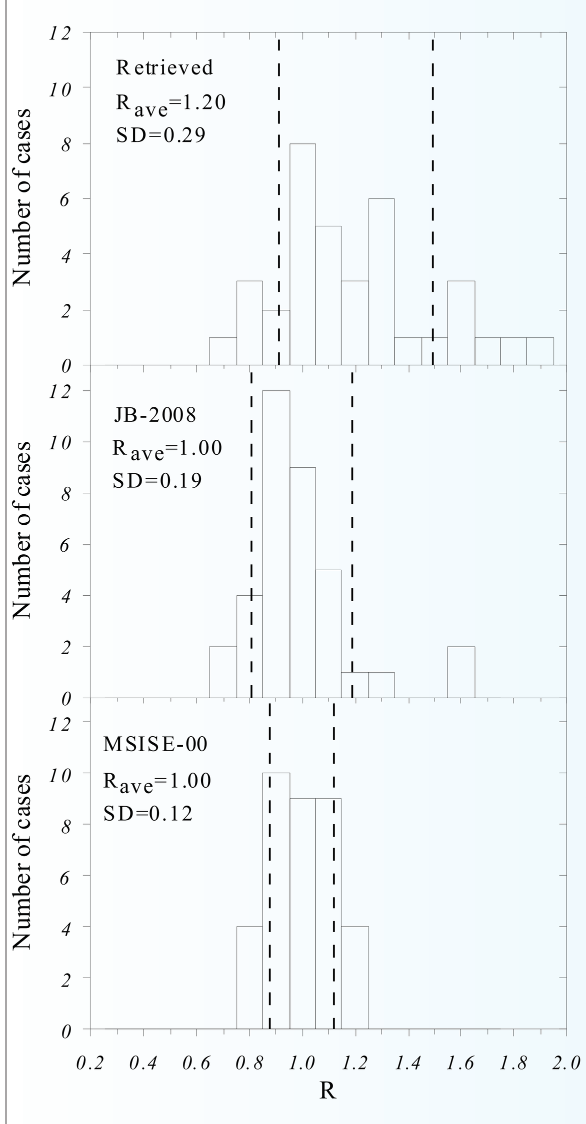


Figure 3 Same as Fig. 1 but for solar maximum conditions.

Solar maximum (2002) both IRO and ρ data are presented by CHAMP observations.
CHAMP IRO observations are available only below 400-410 km and the upper boundary condition is taken at 400 km height. This is too close to the F2-layer peak which may occur at (320-330) km and this may affect the fitting process resulting in incorrect solutions. In general all the solutions found for solar maximum are not successful enough. This may be related to the accuracy of the IRO EDP and following comparisons confirm this.
Again let us consider mean relative deviations (MRD) and bias for "good" case to quantify the comparison with observations. The proposed method gives bias=0.72 g cm^{-3} and MRD=15.5%; JB-2008 model gives bias=0.27 g cm^{-3} and MRD=12.0%; MSISE-00 model gives bias=-0.24 g cm^{-3} and MRD=9.3%. Unlike the results for solar minimum, the retrieved gas densities manifest worse accuracy than the empirical models provide. This contradicts the results obtained for Millstone Hill (M2012) where the efficiency of the proposed method was shown to be higher for solar maximum activity compared to solar minimum.

Comparison COSMIC IRO with Millstone Hill Incoherent Scatter Radar observations

ISR observations provide the most accurate Ne(h) profiles. We have compared available simultaneous Millstone Hill ISR and COSMIC RO hmF2 and NmF2 (with tangent points at the F2-layer maximum height within (6° in latitude and longitude of Millstone Hill ISR (42.6N, 288.5E).

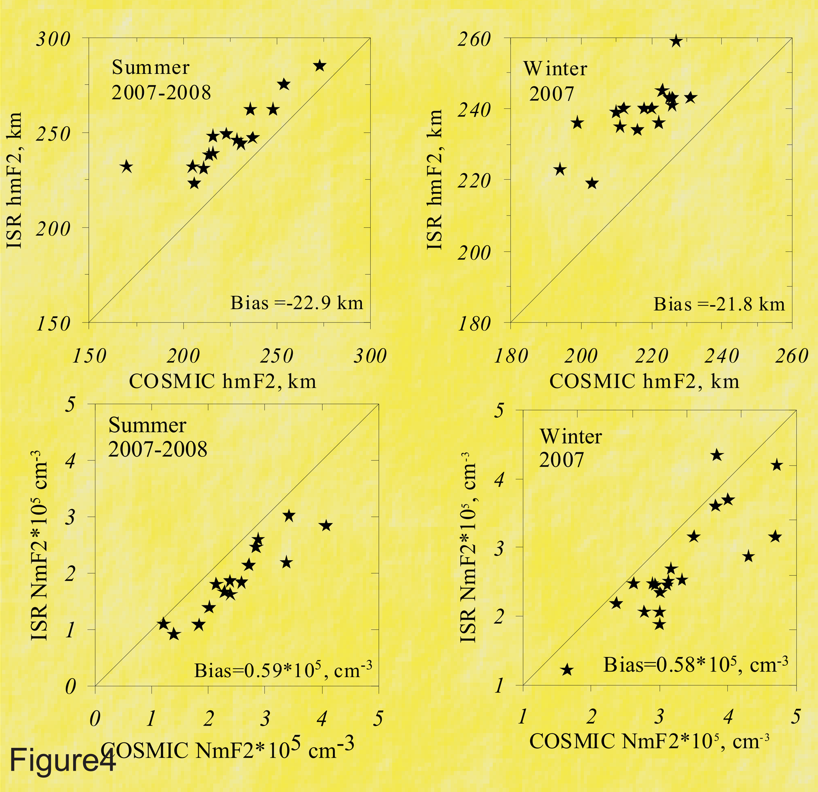


Figure4

Scatterplots of hmF2 and NmF2 determined by Millstone Hill ISR versus IRO method.

IRO hmF2 and NmF2 manifest systematic bias with respect to IRO observations.

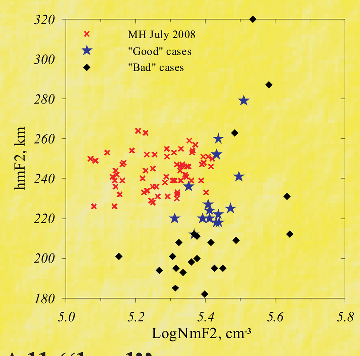


Figure 5 Observed at Millstone Hill ISR in July 2008 daytime hmF2 vs LogNmF2 in a comparison with COSMIC 'good' cases which gave the solutions and 'bad' cases when no solutions were obtained.

All "bad" cases are seen to be strongly outside the area of ISR values demonstrating an incorrect hmF2-NmF2 relationship.

Comparison with IRI model

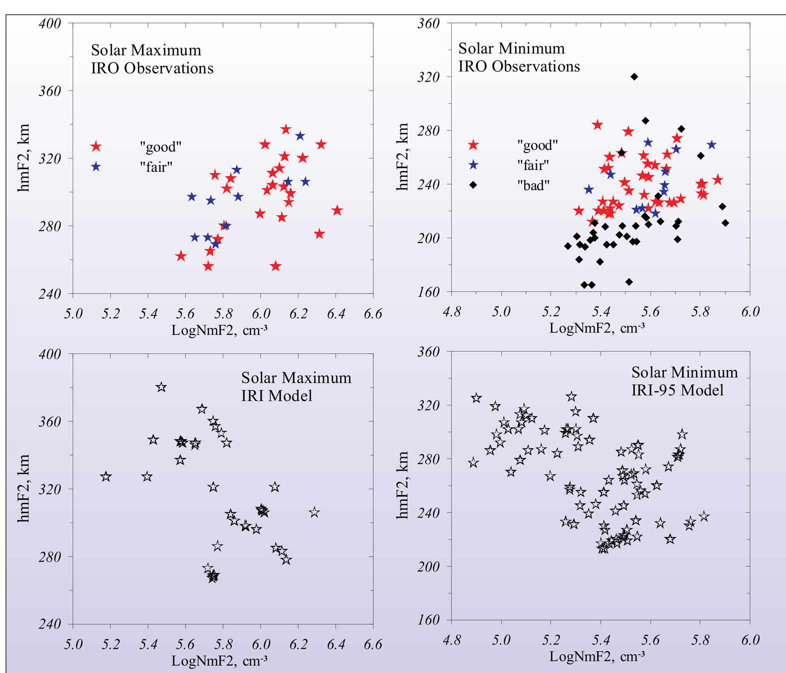


Figure 6. Scatter plots of hmF2 v.s. LogNmF2 for all the analyzed IRO observations in a comparison with the climatologic IRI-95 model for solar minimum and solar maximum conditions.

For solar minimum similar to Fig. 5 all "bad" cases occupy the lower part of the plot manifesting very low hmF2 while there are no points in IRI with hmF2 ≤ 200 km. Practically all IRO points are located below 280 km, while IRI gives many points above the 280 km height. Similar results demonstrate a comparison with IRI for solar maximum condition – the majority of hmF2 IRO observations are below the IRI model values. Low hmF2 results in low retrieved neutral gas density. This may explain the tail in the ρ_{cal}/ρ_{obs} distribution (Fig. 1) with low retrieved ρ_{cal} values.

Figure 6 demonstrates one more inconsistency related to IRO observations. The IRO hmF2 v.s. LogNmF2 dependence on average is a direct one, while IRI gives an inverse dependence: larger hmF2 correspond to lower logNmF2 values. The inverse type of hmF2 v.s. NmF2 dependence is a correct one – this follows from the mechanism of the mid-latitude F2-layer formation

Conclusion

1. For the first time the method to retrieve the main thermospheric parameters (Tn, [O], $[N_2]$, $[O_2]$) from electron density profiles in the daytime mid-latitude F2-region was applied to radio occultation (RO) Ne(h) observations conducted under solar minimum (2007-2008) and maximum (2002) conditions.

2. It was shown that daytime mid-latitude RO profiles technically can be used to retrieve the main thermospheric parameters. A comparison with CHAMP neutral gas density observations under solar minimum conditions has shown that the neutral gas density can be retrieved with an inaccuracy close to the absolute inaccuracy (10-15)% of CHAMP observations. Empirical models JB-2008 and MSISE-00 being compared to the same observations provide less accurate results.

3. However IRO observations manifest a large percent (≈50%) of rejected Ne(h) which cannot be used with our method due to their insufficient accuracy. The method is very sensible to the quality of the Ne(h) and any inconsistency between NmF2 and hmF2 or any incorrectness in the Ne(h) shape (inevitable in RO observations) prevents from getting a solution. Large percent of rejections tells us that IRO profiles cannot be considered as usual Ne(h) vertical profiles and our mid-latitude daytime F2-layer formalism cannot be routinely applied to such profiles.

4. The only available for solar maximum conditions CHAMP IRO Ne(h) are obtained at heights ≤ 400 km. This is not sufficient for getting a correct solution as the upper boundary should be specified at heights ≥ 550 km under solar maximum. For this reason the retrieved neutral gas densities manifest a systematic (≈20%) bias. Additional IRO observations up to ≥600 km under solar maximum are required to check the efficiency of our method under high solar activity.

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