ELECTROMAGNETIC PROPAGATION
(ALT, TEC)

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ABSTRACT

For electromagnetic propagation, the ionosphere plays a key role. This paper will present some results deduced from the Topex/Poseidon mission regarding the impact on the range measurement, then focus on the ability of the model available to recover the state of the ionosphere and finally give some implications of the "Space Weather" program over altimetric or localization missions.

1. INTRODUCTION

1.1. Range Effect

The presence of free electrons in the ionosphere modifies the propagation of radio waves. To the first order, the effect on range measurement is proportional to the total number of electrons along the ray path (TEC for Total Electronic Content) and inversely proportional to the square of the frequency of the radio wave.

$$Iono\_corr = 40.25 \cdot \frac{TEC}{f^2} \qquad (1)$$

For satellite radar altimeters intended to perform space measurements of the distance between the satellite and the sea surface height using 13 GHz frequency radio waves, this effect is typically of order of 30 cm (nearly 150 TECU or 15 10^{17} e/m^2). We have at this frequency the following relation :

$$Iono\_corr(mm) = 2.16 \cdot TEC(TECU) \qquad (2)$$

This magnitude is comparable to the amplitude of large oceanic signals. To correct from this effect, one may use a dual-frequency system or an empirical model to determine the TEC value for single frequency systems. As examples, we can recall that :

- the altimeter onboard Topex use Ku (13.65 GHz) and C (5.2 GHz) frequency,
- DORIS use 2.036 GHz and 401.25 MHz frequency,
- and GPS use 1.574 and 1.2276 GHz frequency

1.2. Attenuation Effect

The other key impact of the ionosphere is the attenuation. It is negligible at the Ku altimeter frequency.

We can note that for the C band :

- ➢ less than 1% of the points will be affected by an attenuation of 1 dB,
- ➢ less than 1‰ by an attenuation of 6 dB,
- ➢ and at the latitude of 40° North the mean attenuation is of order of :
  - 1 dB for 100 MHz
  - .1 dB for 400 MHz
  - .01 dB for 1 GHz

However we can note that the attenuation may reach very high levels. Some might be as high as 40 dB at 1GHz for the worst cases and due to the level of the attenuation in the next solar cycle some GPS receivers may be not be able to work properly during the maximum of the solar activity.

1.3. Conclusion

The characterization of the ionosphere is of key interest for any mission based on range determination. Specially, the range effect which will affect all determination made by a single frequency system. Our main interest will so be the TEC values. We should deal with GPS, Doris or Argos positioning systems but the Topex/Poseidon mission has provided a tremendous set of data which are really useful to describe the main characteristics of the ionosphere. We will so present this mission in the following section, then use the data sets to determine some key characteristics of the ionosphere.

2. TOPEX/POSEIDON

2.1. The mission

The Topex/Poseidon mission launched in 1992 is designed to monitor the Sea Level and its variations . It carries on :

- ☛ a dual-frequency radar altimeter (Topex, NASA),
- ☛ a single frequency radar altimeter (Poseidon, CNES),
- ☛ a DORIS receiver (CNES),

- a GPS receiver
- a three frequency radiometer and a Laser Reflector Array

The orbit is not sun synchronous (meaning that we are spanning all the local time), with an inclination of 66° and an altitude of about 1340 kms. It is a repeat orbit with a repeat cycle of about 10 days. Since the beginning of the mission, 220 cycles have been completed and the geophysical products (GDR) have been sent to about 250 laboratories in the world. Among other corrections for the purpose of sea level studies, we can find on these data sets 3 different ionospheric corrections :

- Topex dual frequency derived correction
- Doris derived correction (mainly for the Poseidon correction)
- Bent correction

2.2. Ionospheric Correction Specification

For oceanographic studies, we need the best ionospheric correction (a determination of the TEC with an accuracy of a few TECU). This will not be a problem with dual-frequency radar altimeters, but we still need another source of correction (see bellow). For single frequency radar altimeter, the model used might provide a one centimeter (about 5 TECU) accuracy correction every where, any time (specification given for the Geosat Follow ON satellite).

2.3. Topex ionospheric correction

By using both frequencies and the known dispersion curve, the dual frequency altimeter instrument calculates its own ionospheric correction. This very accurate determination of the TEC will allow us to describe the main signals of the ionosphere. As we can see on the figure 1, the Topex mission covers only from mean to low solar activity (from 1992 to 1998). The determination available is only the nadir TEC over the ocean surfaces while any positioning system will be affected by the slant electronic content. Due to orbit parameters, it covers from –66° to 66° and as we have seen above, we will span all local time. From one cycle to the other, the local time difference at the equator will be about 2 hours.

The figure 2, display a sample of Topex TEC. In terms of spatial signature, the TEC is mainly correlated with geomagnetic latitude (showing maxima in the tropics). The common features of the TEC are well illustrated with the 2 bumps along the geomagnetic equator. The TEC evolves from about 10 TECU at high latitudes to about 100 TECU.

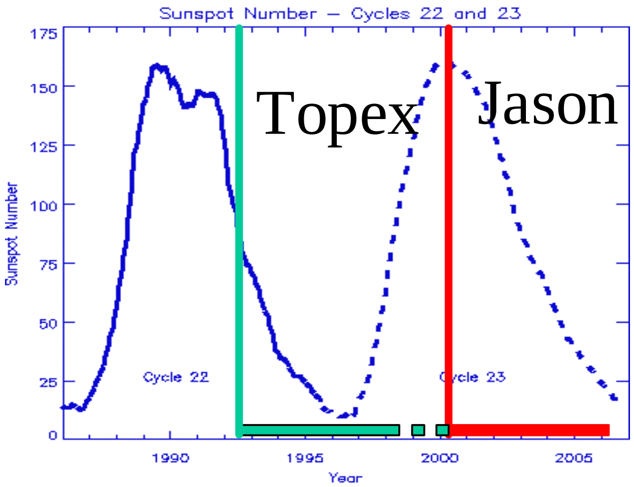

Figure 1. Sunspot Number during Topex and Jason missions

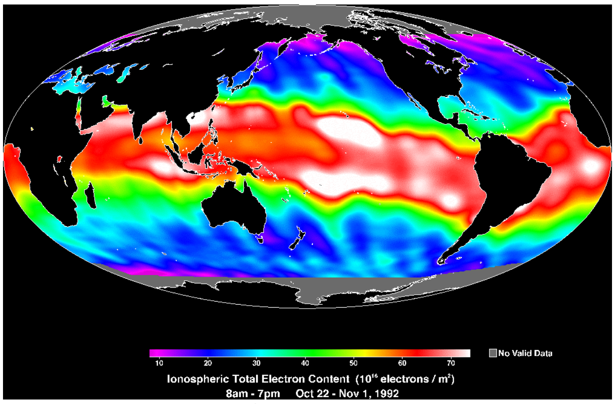

Figure 2. Topex TEC for the cycle 4 (Oct 22 to Nov 1, 1992 – local time at the equator : 16h30)

Several groups have used those data. Among them, we can quote :

- Determination of a Global Ionospheric Climatology from TOPEX/Poseidon, by J. L. Johnson, H. R. Anderson and G. Lagerloef (available on the JPL web site)
- used for validation purposes of the model or assimilation techniques (JPL Ionospheric workshop, , …)
- used as a reference for validation purposes as part of the "Space Weather Program “ applications

The next views will be extracted from the work of J. L. Johnson, H. R. Anderson and G. Lagerloef. We will be able with their work to characterize the solar activity impact as well as the local time impact on the TEC.

2.4. Solar activity impact

As illustrated by the figure 1, the solar activity was quite low since the beginning of the mission. However, we can separate 2 main periods. One with a mid solar activity from 1992 to July 1994, and one with a very low activity after July 1994.

The first map bellow (figure 3) displays the mean TEC, for a F10.7 above 90 and a universal time (UT) between midnight and one hour. As expected, we can see that the maximum of the TEC is concentrated along the equator. Along the geomagnetic equator, we can note that the peak of the distribution is obtained near 210° while the minimum value is obtained near 60°. Meaning that the maximum is observed in the early afternoon (around 3 PM) and as expected the minimum is obtained during the night (5 AM). The second map (figure 4) illustrate the same situation (UT between 0 and 1) but for a F10.7 bellow 90. The maximum reached is still around 210° but it is much lower than in the previous plot. The peak of the distribution is in the first case around 60 TECU and around 40 TECU in the second one.

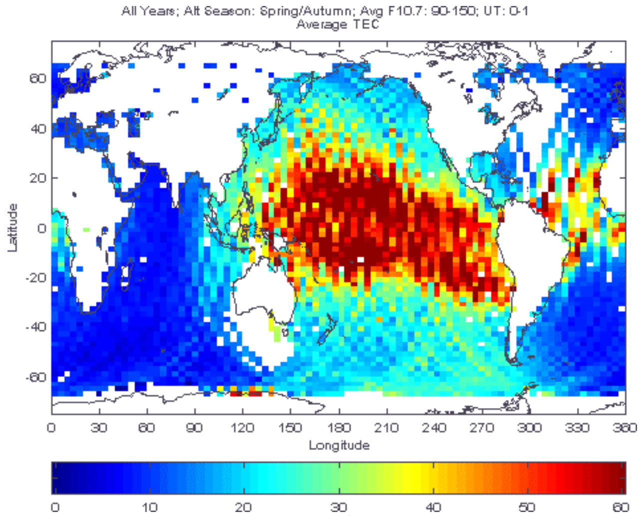

Figure 3. TEC in TECU for mid solar activity

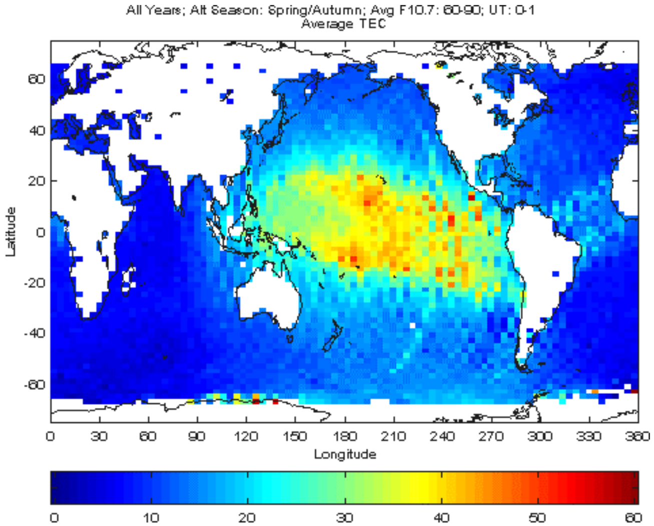

Figure 4. TEC in TECU for low solar activity

The high values observed at low latitudes (around –66°) are believed to be due to ice interaction with the range measurement and are not valid estimates of the TEC.

Finally we can note that the main spatial variations are on large scales, which indicates that for scales less than 1200 km, variations of sea surface height are larger than the apparent height changes induced by the ionosphere.

2.5. Local time impact

As we can note on the above maps, the local time as a clear impact on the ionosphere. But another important point is the variability of the TEC. For operations which require knowing the state of the ionosphere, the regions or times of greatest variability are of interest. A map of the variability (not displayed in this paper) shows that the maximum can be as high 20 TECU and varies mainly with the TEC itself. To see how closely the standard deviation of TEC scales with the average, we can plot the normalized standard deviation (standard deviation divided by TEC). The following map displays the normalized TEC variability for a UT around midnight. We can clearly note that the maximum is reached around 320°.

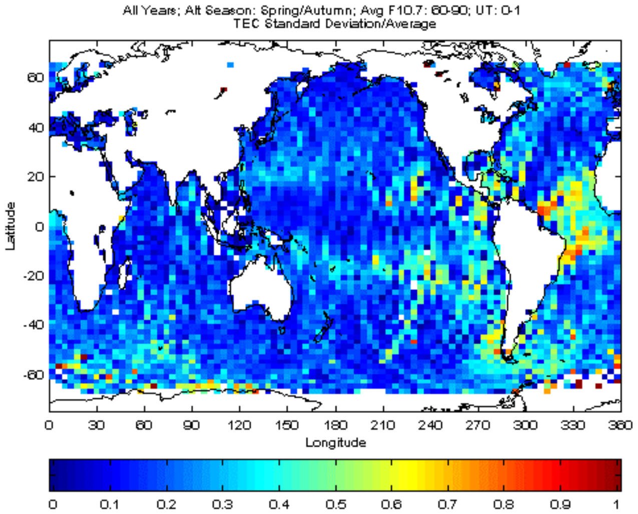

Figure 5. Normalized variability of the TEC

It corresponds to a local time of about 10 PM, the sunset. This map illustrates the fact that the variability is higher between 8 and 10 PM local time. Ionospheric layers become turbulent at that time and develops small scale irregularities of electron density. After sunset, the high density plasma in the F-region often becomes unstable and develops intense irregularities of electron density. The plot bellows illustrate this fact.

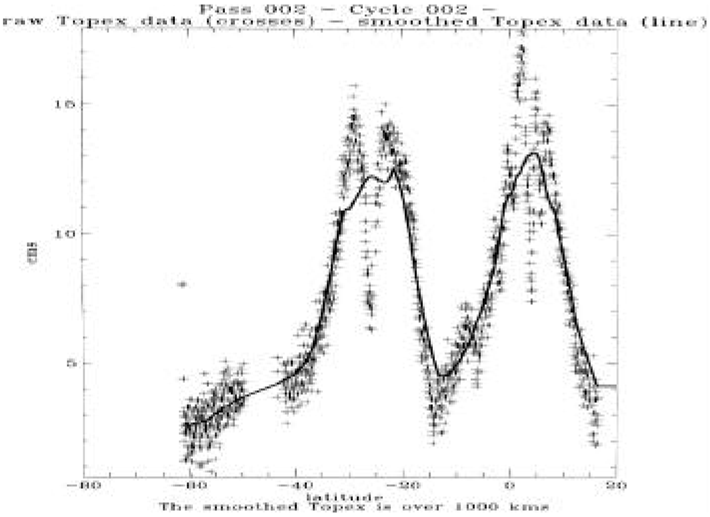

Figure 6. TEC evolutions during sunset

We have for a single pass the Topex raw data (crosses) and the average value over 1000 kms to illustrate the small scale variability. This plot displays the ionospheric correction at the altimeter frequency in centimeter. We can note on the 2 bumps some very important evolutions. Those are due to the recombination effects which occurs mainly right after the sunset (the local time at the equator for this pass is around 10.30 PM). We can display too the difference between the raw data set and the smoothed one. The smoothing is made over a window of 1000 kilometers to display the ability of model or assimilation techniques with such a resolution. As we can see, the difference can be as high as 6 centimeters, with small scale features that are similar to eddies when you are computing the sea level height.

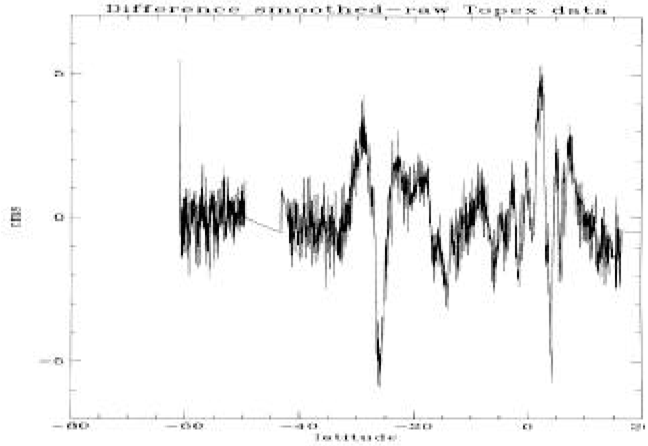

Figure 7. TEC evolutions during sunset

One conclusion is that such features are really difficult to estimate with empirical models or assimilation techniques. The local time corresponding to the sunset will therefore be a really challenge for the determination of the correction to be applied to any single-frequency mission (like the ERS1 and ERS2).

2.6. Conclusion

The Topex data appears to be really accurate. The very large number of data, covering the whole ocean and all the local times, is a unique opportunity for studying the TEC and its evolutions. This data set presents too a major interest for the calibration of models or assimilation techniques. We will in the next section present the Doris based ionospheric correction as an example of an assimilation technique.

3. DORIS BASED IONOSPHERIC CORRECTION

3.1. Introduction

To achieve its goal of a root mean square (rms) less than 2 cm in altimetry, one may use a dual-frequency system, an empirical model such as the IRI95 or the Bent, or use the Doris or GPS dual frequency measurements to estimate TEC maps. Doris is a dual-frequency system in operation since 1990 (onboard SPOT2). It's main purpose is the orbit determination. It has been put onboard Topex and the Doppler measurements has been used to determine the TEC under the satellite ground track. We will not present into further details the assimilation technique used to recover the state of the ionosphere. Just notice that the spatial resolution of such a model is of order of 1000 kilometers.

It has been used to date :

- to correct the Poseidon I single frequency range measurement,
- as validation purposes of the ionospheric correction derived from the dual-frequency Topex measurements,
- as another source of correction in case of failure of the C band,
- as another source of correction in specific areas where the dual-frequency correction is not really accurate (coastal, lakes, ice applications, …),
- and to insure the continuity of the correction whatever the surface type is.

This system used a ground segment of about 50 beacons spread all the world (see figure 8). The visibility circles are for the SPOT2 altitude (around 830 kms). We can note the really good coverage of this system. The dots are the sites for future installations.

Figure 8. Doris network

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Of course the coverage at the subionospheric altitude is worse. But we can see bellow that it is still really good. A major interest of the Doris network is its really good coverage of the southern hemisphere.

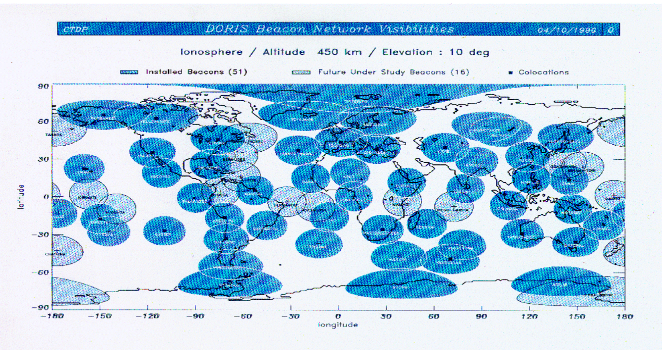


Figure 9. Doris coverage at the sub ionospheric point altitude

3.2. Doris versus Topex

In comparison with the Topex ionospheric correction over the whole mission, we find a mean difference of about 1 cm between the 2 corrections. The figure 10 display the mean value of the difference (upper part) and the standard deviation (lower part) for the cycle 001 to 200 (September 92 to March 1998).

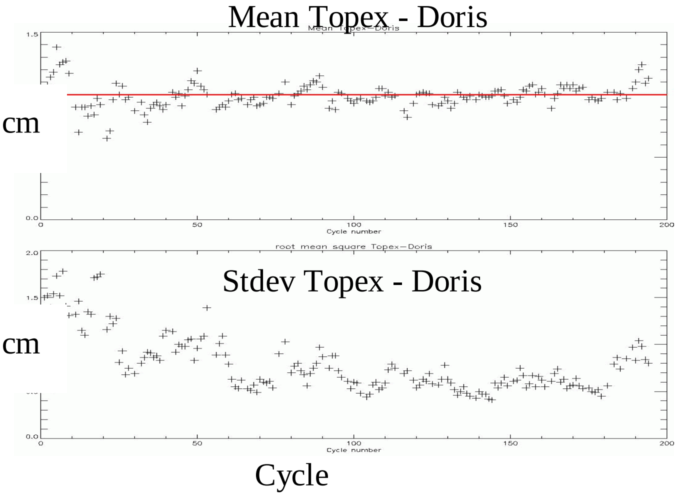


Figure 10, Mean and Stdev of Topex – Doris

The mean difference is really stable over the whole mission and is believed to be due to a miss calibration of the Topex altimeter C band. On the standard deviation plots, we can note the solar activity impact (the stdev is decreasing while the solar activity and so the TEC is) and the local time impact (some evolutions with a frequency of 6 cycles might be observed). At the end of the period, the stdev is increasing showing us the increase of the solar activity occurring since 1997.

The ability of the Doris network to recover the TEC is around a few TEC (about 7 mm or 3.5 TECU during the minimum of the solar activity and about 15 mm or 7 TECU at the beginning of the mission). But some maps show areas where the agreement is not as good.

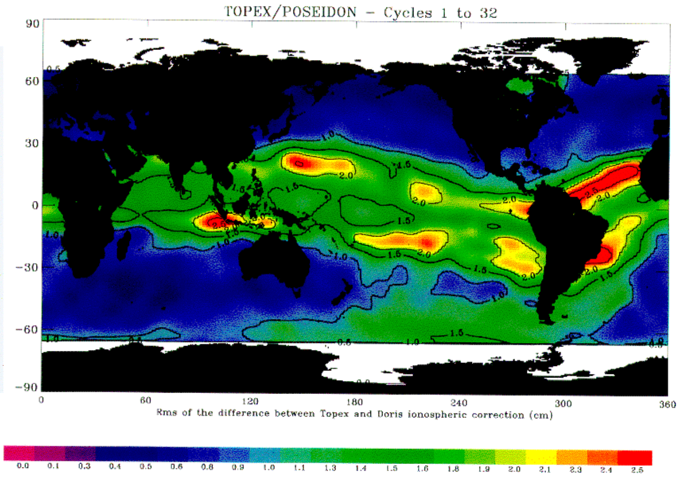


Figure 11. Map of the Stdev Doris versus Topex

This map displays the standard deviation of the difference Topex versus Doris for the first year of data. We can note some regions where the standard deviation reach some high levels. Especially around the geomagnetic equator, where the TEC is higher. Unfortunately, in those regions the oceanic signals are low. A comparison of the error made with Doris in regards with the variability of the signals will display that in those regions the use of the Doris correction represent as much as 50% of the variance of the ocean. Meaning that when you are using this correction instead of the direct correction provided by the dual-frequency altimeter, you will have an error in the oceanic signals estimate of about 50%.

3.3. Models ability

As for Doris, we can use the Topex data set to assess the quality of the models available. Two differents models have been used for the comparison :

- ➢ the Bent model
- ➢ the IRI95 one

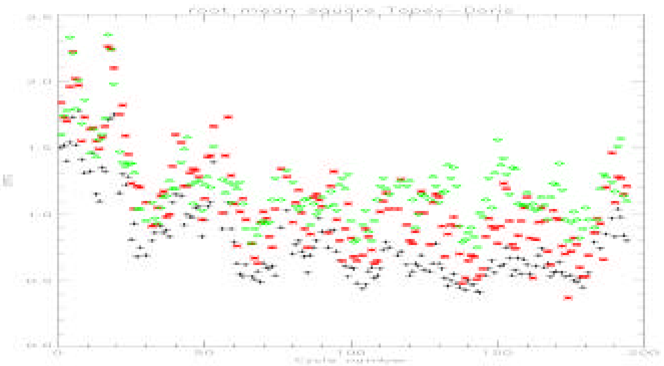


Figure 12. Stdev of Bent, IRI95 and Doris versus Topex

On this plot we have the standard deviation in comparison with Topex for the Doris estimate (cross), the Bent estimate (star) and the IRI95 estimate (diamond). As we can see, the Doris estimate is the more accurate while the IRI95 does not seems to be better than Bent. As it is the case with the Doris estimate, such empirical models will not be able to recover the TEC with enough accuracy. This is illustrated by the above plot, where we have the variability of the Topex estimated TEC along 240°, for the lower solar activity and for a UT around midnight. Prism results are blue and IRI95 are magenta. In these latitude cuts, high TEC shows highest variability at the equator anomaly. This variability is a real variation of TEC, and not a scatter resulting from measurement techniques (the accuracy of the Topex TEC estimate is about 2 TECU). This scatter suggests a limit to the possible of an unadjusted model.

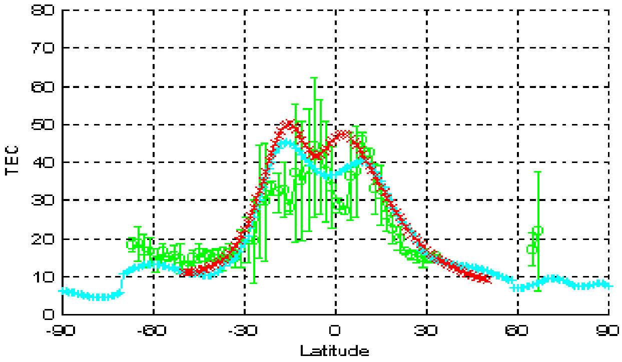
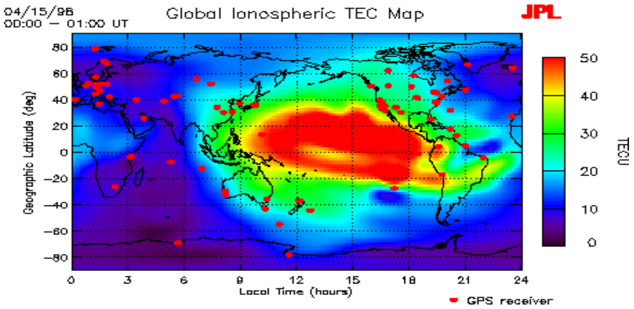


Figure 13. Variability of Topex along 240°, IRI and PRISM.

3.4. GPS accuracy

As last example, we will look at some samples of GPS Ionospheric Maps produced by JPL. The use of the IGS network (about 100 stations spread all the world), and the visibility of at least 4 GPS satellites, allow a computation of TEC all over the world. The Figure 14 display a sample of GIM data and the GPS network is presented too.



We have get 6 days of GIM maps and the table 1 summarize the comparison for each day.

Cycle 18 – March 1993				
Day	Topex/Doris		Topex/GPS	
	mean	stdev	mean	stdev
93/03/12	.9	1.6	-1	2
93/03/13	.9	1.8	-.4	2
93/03/14	1.1	1.4	-.7	2

Cycle 94 – April 1995				
Day	Topex/Doris		Topex/GPS	
	mean	stdev	mean	stdev
95/04/06	.7	.8	.3	.7
95/04/07	1.1	.9	.3	.9
95/04/08	1	.8	.4	.7

Table 1. Mean and stdev in centimeters

To explain the bad results for 1993, we can indicate that the GPS network was much sparse and the solar activity was higher at that date. Much interesting are the results for 1995, we can note that the mean difference Topex versus GPS is about .3 centimeter so about 1.5 TECU, with Topex measurement higher than the GPS one. However, the Gps measurement includes the upper part of the ionosphere (above the Topex altitude) which is believed to represent a few TECU. So we have another indication of a potential over evaluation of the TEC made by Topex.

Conclusion

The Topex data set is of great interest for the evaluation of the ability of the different models available to date.
To achieve its goal of a good determination of the range, one may use a dual-frequency system, an empirical model such as the IRI95 or the Bent, or use the Doris or GPS dual frequency measurements to estimate TEC maps. The global characteristics of those data sets can be assessed by using the Topex determination as a reference. This can provide us a very good idea about the ability of this correction to recover the TEC and can be a basic method to evaluate the

different models used for example in a program like Space Weather.

However, we have to keep in mind that modeled ionospheric correction are of great interest :

- to correct any single frequency range measurement,
- as validation purposes of the ionospheric correction derived from the dual-frequency measurements,
- as another source of correction in case of failure of one of the 2 bands,
- as another source of correction in specific areas where the dual-frequency correction is not really accurate (coastal, lakes, ice applications, … for the altimeter),
- and to insure the continuity of the correction whatever the surface type is.

Furthermore, the Jason mission (launch scheduled in May 2000) will carry a dual-frequency radar-altimeter and near real time products (3 hours latency) including the TEC estimates will be available and might be useful as an input for assimilation or for validation of the model prediction.

Another point is the fact that oceanographic studies need more than one altimetric mission to recover all the wavelengths of oceanic signals. Due to cost impacts, one possibility is to have a really precise mission as a reference (like the Jason one) and one or two other complementary missions with a single frequency radar-altimeter. The ionospheric correction will therefore be based on a model or assimilation techniques and any key improvement of the quality of the models available is of great interest for the overall quality of such low costs missions.