Issue 2: Comparability of CHAMP and COSMIC (and other?) GPS satellite systems

The same questions as in Issue 1 arise, but in this case both the mean differences and the spread seem larger. In theory different GPS-RO satellite systems should give similar results. A comparison of co-located soundings (again by latitude bands as well as land and ocean) from the different satellite systems could prove its reliability.

1) *Comparability of CHAMP and COSMIC GPS satellite systems*

a. Define the question

Questions from this issue are raised from slide 7 of Ho et al. (AMS COSMIC presentation, 2008), which is re-plotted in **Fig. 1**. Here we compare dry temperature profiles from COSMIC from June 2006 to July 2007 to those from collocated CHAMP profiles, where CHAMP was launched in 2001 and COSMIC was launched in April 2006. COSMIC-CHAMP dry temperature pairs within 90 minutes and 250 km apart, within 90 minutes and 100 km apart, and within 60 minutes and 50 km apart are compared in **Figs. 1a, b and c**, respectively. The same software packages were used in COSMIC CDAAC to process the COSMIC and CHAMP data. This is to demonstrate the long-term stability of GPS RO data, which is critically important for climate benchmarks.

b. Direct CHAMP and COSMIC comparison

For the COSMIC-CHAMP pairs within 90 minutes and 250 km apart (~3000 pairs, Ensemble 1, **Fig. 1a**), the dry temperature difference between 300 mb (~8km) and 10 mb (~30 km) ranges from 0.02 K (at 10 mb) to -0.03 K (at 300 mb) and their mean difference is about -0.06 K (**Fig. 1a**). The relative large mean dry temperature differences between COSMIC and CHAMP pairs below 500 mb (less than 2 K) may mainly because different signal tracking algorithms are used by CHAMP (phase lock loop tracking) and COSMIC (open loop tracking), which allows much more accurate retrievals of the COSMIC refractivity in the lower troposphere than those for CHAMP.

To quantify the impact of sampling errors (temporal and spatial mismatch) on the CHAMP-COSMIC comparisons, we compare global collocated COSMIC and CHAMP profiles in much smaller temporal and spatial constraints (within 90 minutes and 100 km apart, Ensemble 2, **Fig. 1b**; within 60 minutes and 50 km apart, Ensemble 3, **Fig. 1c**) than that of Ensemble 1 (**Fig. 1a)**. The normalized standard error of the mean difference is in horizontal black line. The mean MAD (Median Absolute Deviation, in blue line) from 300 mb to 50 mb for Ensemble 1 decrease from 2 K (**Fig. 1a)** to 1.83 K for Ensemble 2 (**Fig. 1b**) and to 1.44 K for Ensemble 3 (**Fig. 1c**). The mean CHAMP and COSMIC dry temperature differences between 300 mb and 10 mb also decreases from -0.06 K for

Ensemble 1 (Fig. 1a) to -0.038 K for Ensemble 2 (Fig. 1b) and -0.036 K for Ensemble 3 (Fig. 1c), where tighter temporal and spatial constraints are used for Ensemble 2 and Ensemble 3.

c. Differences between CHAMP-COSMIC and COSMIC-COSMIC comparison

To see if the CHAMP-COSMIC comparison is consistent with that of COSMIC FM3-FM4 comparison, we also apply the same temporal and spatial constraint (within 50 km and 60 minutes) for CHAMP-COSMIC Ensemble 3 (F**ig. 1c**) to COSMIC FM3-FM4 pairs (see **Fig. 2**). The MAD for COSMIC-CHAMP pairs for Ensemble 3 is from 1.4 K at 300 mb (~8km) to 2 K at 50 mb (~20 km), which is in general larger than that for COSMIC FM3-FM4 pairs, where MAD for FM3-FM4 pairs is about 0.5 K at 300 mb and about 1 K at 50 mb (**Fig. 2**). This relative larger MAD for COSMIC-CHAMP pairs than that of COSMIC FM3-FM4 pairs may mainly be due to:

a) the thermal noise of CHAMP data is higher than those of COSMIC;
b) the speed of CHAMP satellite is different than those of COSMIC;
c) the altitude of CHAMP satellite is different than those of COSMIC;
d) the different atmospheric paths are used in CHAMP-COSMIC comparisons.

Although all above reasons seem increasing MAD (random errors) of CHAMP-COSMIC pairs comparing to that of FM3-FM4 pairs, the mean dry temperature difference between 300 mb to 10 mb for both CHAMP-COSMIC pairs (~-0.036 K) and COSMIC FM3-FM4 pairs (~0.01 K) are less than 0.05 K.

d. The comparability of CHAMP to each COSMIC receiver

To demonstrate the comparability of CHAMP to each COSMIC receiver, we compare CHAMP profiles with those from different COSMIC receivers within 90 minutes and 100 km apart (**Fig. 3**). The mean dry temperature differences from 300 mb to 50 mb among each CHAMP-FM1 (**Fig. 3a**), CHAMP-FM2 (**Fig. 3b**), CHAMP-FM3 (**Fig. 3c**), CHAMP-FM4 (**Fig. 3d**), CHAMP-FM5 (**Fig. 3e**), and CHAMP-FM6 (**Fig. 3f**) pair are computed. The mean dry temperature differences from 300 mb to 50 mb for all CHAMP and COSMIC pairs are less than 0.1 K, except for CHAMP-COSMIC FM2 pairs, where
30-50 less sample pairs are collected than other CHAMP-COSMIC pairs. Results from **Fig. 3** also demonstrate the comparability of dry temperature profiles from different COSMIC receivers where CHAMP dry temperature profiles are used as references.

e. The comparability of CHAMP to COSMIC data with different operational modes

To demonstrate the comparability of CHAMP to COSMIC data with different operational modes (rising/setting), we compare CHAMP data to collocated

COSMIC data with rising mode (**Fig. 4a**) and setting mode (**Fig. 4b**). CHAMP and COSMIC data within 90 minutes and 100 km apart are paired and used for this comparison. **Fig. 4** demonstrates the consistency of RO data between COSMIC rising mode and setting mode.

f. The comparability of CHAMP to COSMIC data at different latitudinal bands

To further demonstrate the comparability of CHAMP to COSMIC profiles at different latitudinal bands, we generate contour plot of 10-degree latitudinal mean CHAMP-COSMIC differences in dry temperature from surface to 10 mb over the global (both land and ocean) in **Fig. 5a**. A larger color scale is used to cover large dry temperature difference below 500 mb. CHAMP-COSMIC pairs are within 90 minutes and 250 km apart (Ensemble 1 in **Fig. 1a**). Corresponding contour plots for sample number and MAD are also generated in **Fig. 5b** and **Fig. 5c**, respectively. Because there are not many COSMIC-CHAMP RO pairs at high latitudes (less than 60 pairs), where we can expect larger temperature gradient at summer and winter within 90 minutes and 250 km apart (results in to larger sampling errors), here we compare results between 75°S to 75°N in **Fig. 5**. In addition, because of much smaller sample size for CHAMP-COSMIC pairs than that for COSMIC FM3-FM4 pairs, we didn’t further separate CHAMP-COSMIC pairs for those over oceans and lands, though we know that mean dry temperature difference in 40°N-60°N is more representative to land comparison, and that in 40°S-65°S is more for ocean comparison.

In general, the global 10-degree latitudinal mean CHAMP dry temperature is very consistent to that of COSMIC above 300 mb (~8 km) to 10 mb (~30 km) and over mid-lat above 800 mb (**Fig. 5a**). Relatively large mean differences are found near the Tropics near 400 mb, south of 60°S above 50 mb, which are mainly dominated by the sampling errors (see **Fig. 5b**).

g. Remaining sampling errors in CHAMP and COSMIC comparison

Note that, because COSMIC satellites are not fully deployed to operational orbits during the early stage of its mission, we have to generate statistics based on COSMIC-CHAMP pairs with a much larger temporal and spatial mismatch (COSMIC-CHAMP pairs collocated within 250 km and 1.5 hours) to ensure enough samples in our comparisons. To further reduce uncertainty due to temporal and spatial mismatch between COSMIC and CHAMP, we use N18/N16 AMSU brightness temperatures (Tbs) as cross references to compare to COSMIC and CHAMP separately. This is to estimate of the compatibility of the COSMIC and CHAMP data indirectly where we assume the quality of NOAA18 (N18) and NOIAA 16 (N16) AMSU Tbs is not changing in the same month (see below).

2) *Comparability of CHAMP/COSMIC and AMSU*

a. Methodology of CHAMP/COSMIC and AMSU comparison

Ho et al. (2008) (linked in the suggested reading list) have demonstrated the usefulness of COSMIC data to inter-calibrate N15, N16 and N18 AMSU Tbs to the synthetic COSMIC Tbs. Here we try to first quantify the compatibility of COSMIC and AMSU and that of CHAMP and AMSU, then use the defined relationship of COSMIC-AMUS pairs (calibration coefficients) and that of CHAMP-AMUS pairs to examine the compatibility of CHAMP and COSMIC (as shown below).

b. CHAMP/COSMIC vs. N18 AMSU comparison

An AMSU fast forward model is used to convert both COSMIC and CHAMP dry temperature profiles to AMSU Ch9 measurements (e.g., temperature in the low stratosphere, TLS), whose weighting function covers atmosphere from 300 mb to 10 mb and peaks at 110 mb (**Fig. 6**). COSMC and CHAMP simulated AMSU Tbs are defined as Tb_{COSMIC} and Tb_{CHAMP}, respectively. The collocated AMSU Ch9 Tbs from N16 and N18 (Tb_{AMSU_N16}, and Tb_{AMSU_N18}) within 30 minutes and 50 km of COSMIC and CHAMP profiles for Sep. 2006 are collected. The scatter plots for the CHAMP-N18 and COSMIC-N18 Tb comparisons are shown in **Fig. 7a** and **Fig. 7b**, respectively. The slope and offset of the CHAMP-N18 and COSMIC-N18 pairs are also defined in Eq. (1) and Eq. (2), respectively:

$$Tb_{CHAMP\_N18} = 0.973 \times Tb_{AMSU\_N18} + 6.90 \qquad (1)$$

$$Tb_{COSMIC\_N18} = 0.96 \times Tb_{AMSU\_N18} + 8.68, \qquad (2)$$

where Tb_{COSMIC_N18} is COSMIC calibrated N18 AMSU Tbs, and Tb_{CHAMP_N18} is CHAMP calibrated N18 AMSU Tbs (Tb_{CHAMP_N18}). Note that N18 pairs in Eq. (1) are different with those to generate Eq. (2). To quantify the compatibility of COSMIC and CHAMP, we apply the same N18 Tbs from CHAMP-N18 pairs to Eqs. (1) and (2) to find Tb_{COSMIC_N18} and Tb_{CHAMP_N18}. The scatter plot of Tb_{COSMIC_N18} and Tb_{CHAMP_N18} is shown in **Fig. 7c**. The correlation coefficient of Tb_{CHAMP_N18} and Tb_{COSMIC_N18} is equal to 1.0 and the mean bias between Tb_{COSMIC_N18} and Tb_{CHAMP_N18} is very close to zero (~0.07 K). The very tight fit of Tb_{COSMIC_N18} and Tb_{CHAMP_N18} (the standard deviation is about 0.1 K) demonstrates the compatibility of COSMIC and CHAMP dry temperature profiles from 300 mb to 10 mb.

c. CHAMP/COSMIC vs. N16 AMSU comparison

To see if we can find a similar conclusion for the GPS RO calibrated AMSU Tbs from other NOAA satellites, we repeat the above procedures but replace Tb_{AMSU_N18} with Tb_{AMSU_N16}, where COSMIC calibrated N16 AMSU Tbs (Tb_{COSMIC_N16}) and CHAMP calibrated N16 AMSU Tbs (Tb_{CHAMP_N16}) can be computed using the following equations when the same N16 Tbs from CHAMP-N16 pairs are used as inputs:

$$Tb_{CHAMP\_N16} = 0.984 \times Tb_{AMSU\_N16} + 4.05 \qquad (3)$$

and

$$Tb_{COSMIC\_N16} = 0.978 \times Tb_{AMSU\_N16} + 5.50. \qquad (4)$$

The scatter plots similar to **Figs. 7a and 7b** are shown in **Figs. 8a and 8b**, respectively. It is shown in **Fig. 8a** that we have fewer N16-CHAMP pairs when compared to that of N18-CHAMP pairs (**Fig. 7a**). This is because the distribution of CHAMP data is more synchronized to that of N18 than that of N16 in this month. The fact that the mean difference (-0.07 K) and standard deviation (~0.1 K) between Tb_{COSMIC_N16} and Tb_{CHAMP_N16} is compatible to those from Tb_{COSMIC_N18} and Tb_{CHAMP_N18} demonstrates that even with fewer samples (from CHAMP-N16 pairs in this month), because of the high precision of GPS RO data, we can still define robust slopes and offsets for NOAA-CHAMP pairs which are consistent with those derived from NOAA-COSMIC pairs. The scatter plot of Tb_{COSMIC_N16} and Tb_{CHAMP_N16} is shown in **Fig. 8c**, which also demonstrates the compatibility of Tb_{COSMIC} and Tb_{CHAMP} where N16 Tbs are used as cross references, although different N16 samples are used for N16-CHAMP and N18/N16-COSMIC pairs.

d. Summary

Above results indicates that, even though we cannot directly compare Tb_{COSMIC} and Tb_{CHAMP}, by comparing Tb_{COSMIC_AMSU} and Tb_{CHAMP_AMSU}, where slopes and offsets from N18/N16-COSMIC and N18/N16-CHAMP pairs respectively are used, we can still define the precision between Tb_{COSMIC} and Tb_{CHAMP}. The ±0.07 K mean differences of converted COSMIC-CHAMP pairs and ~0.1 K of standard deviation may still be related to the natural variability within 50 km separation distance and 30-minute time difference. Yet, results here shall give us confidence to the compatibility of CHAMP and COSMIC GPS satellite systems.