IMPROVED RESOLUTION AND ACCURACY OF TEMPERATURE RETRIEVALS FROM GPS OCCULTATIONS

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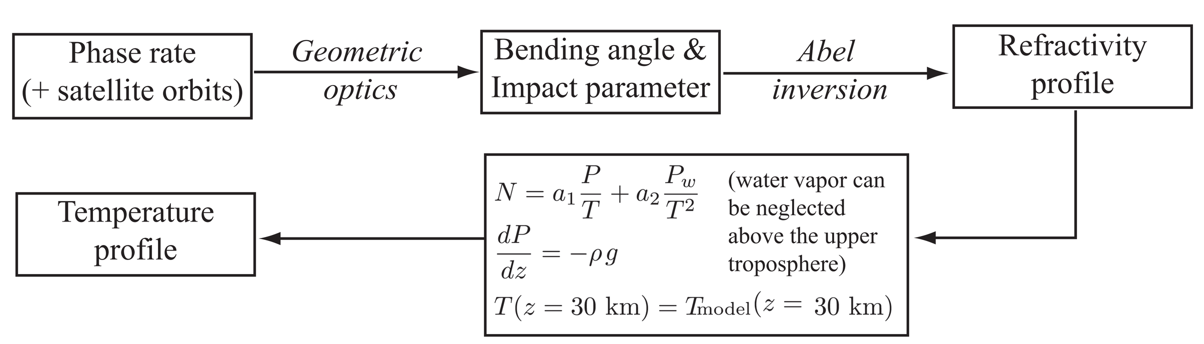
SUMMARY

- GPS occultation data are well-suited for the studies of fine-scale structures in the middle atmosphere due to its global coverage, good accuracy, and high vertical resolution.
- Analysis of coincident CHAMP & SAC-C occultations strongly suggests that sub-Kelvin accuracy is achievable in the temperature retrieval.
- With diffraction-based retrieval methods, GPS occultation provides temperature profile which has vertical resolution comparable to high-resolution radiosonde sounding. Sharp tropopause and fine-scale wavy structures in the stratosphere are resolvable by occultation.
- Application to tropopause analysis yields cold point tropopause (CPT) temperatures which are generally lower than ECMWF analysis.

BACKGROUND

- GPS occultations provide active limb sounding of the Earth's atmosphere (and ionosphere) in the L-band (L1=19.0 cm & L2=24.4 cm). A low-earth orbiter (LEO) carrying a GPS receiver makes accurate measurements of the amplitude and phase of the signal transmitter by a GPS satellite as it rises and sets behind the Earth [Figs. 1 & 2].
- GPS occultations offer the following advantages for climate and meteorological applications:
  global coverage; self-calibrating (no instrumental bias or drift);
  operate under all-weather conditions; high vertical resolution.
- JPL routinely process occultation data collected by the CHAMP and SAC-C spacecraft (both launched in 2000), which have a combined throughput of about 500 soundings per day since mid-2001.
  [Data are available from http://genesis.jpl.nasa.gov/]
- Standard retrieval method is based on the law of geometric optics and spherically symmetric atmosphere [*Hajj et al.* 2002a]. A simplified version of the retrieval system is shown below:



- A drawback of the standard retrieval method is that it cannot handle diffraction effects. Thus the vertical resolution of the retrieved profiles is limited by diffraction to the diameter of the first Fresnel zone [*Melbourne et al.* 1994] [Fig. 3].

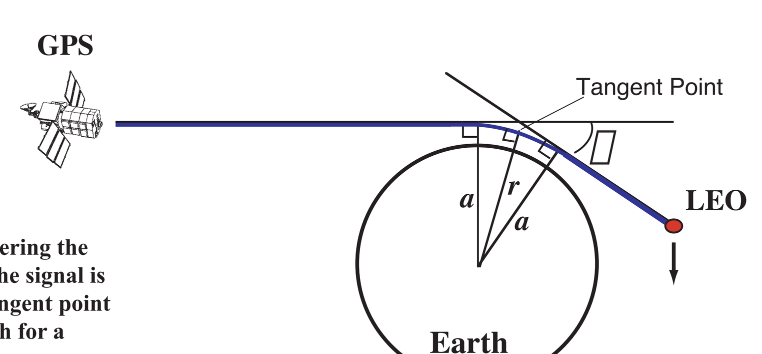


Fig. 1: GPS occultation geometry. Upon entering the atmosphere with impact parameter *a*, the signal is refracted with bending angle . The tangent point refers to the closest distance of approach for a raypath.

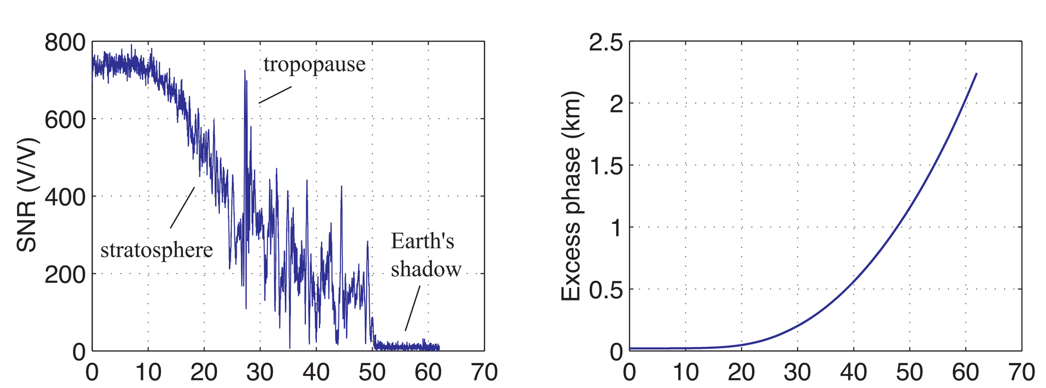
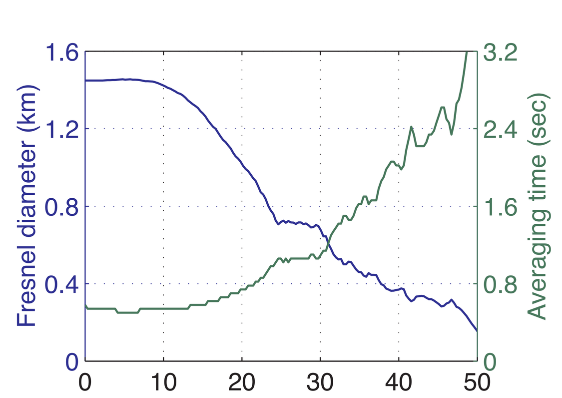


Fig. 2: An occultation taken by SAC-C on July 11, 2001, 23:09 UT with tangent points near (60 N, 162 W). The figure shows the L1 signal amplitude (in terms of voltage receiver signal-to-noise ratio or SNR) and phase (in excess of the straight-line trajectory connecting the GPS and the LEO).

Fig. 3: Standard method of occultation retrieval requires smoothing of the phase data to remove diffraction effects. The relevant scale is the diameter of the first Fresnel zone:

$$F \approx 2\left(\frac{\mathrm{SNR}}{\mathrm{SNR}_o}\right)\sqrt{\lambda D}$$

where *D* is the distance of the LEO from the limb and SNR_o is the SNR in the absence of the atmosphere. Typically, *F* decreases from about 1 km in the lower stratosphere to 200 m near the surface. The Fresnel diameter determines the time interval used for smoothing.



CHAMP & SAC-C COINCIDENCE ANALYSIS

- Theoretical analysis has shown that the temperature retrieval from GPS sounding is accurate to 0.5 K between 5-25 km altitude and to 0.2 K at the tropopause [e.g., *Kursinski et al.* 1997]. In practice, it is difficult to substantiate such claim due to the lack of correlative measurements or models with comparable accuracy.
- The presence of two different spacecraft carrying out occultation measurements simultaneously allows us to compare occultation data independently of model [*Hajj et al.* 2002b].
- From July 10, 2001 to June 9, 2002, a total of about 37000 CHAMP and 38000 SAC-C occultations were successfully retrieved. 60 pairs of coincident occultations are selected based on the following criteria:
  spatial: distance between each occultation pair must be < 200 km for at least one height below 30 km.
  temporal: the pair of occulations took place within 1/2 hours of each other.
- Some of the spatially closest pairs of temperature profiles are shown in Fig. 4. Coincident occultation retrievals are well-matched. Fig. 5 shows the temperature difference between each pair of data points as a function of the distance between them. The RMS difference tends to grow with separation, reflecting atmospheric variability.
- Statistical analysis shows that the standard deviation of the temperature difference increases with distance of separation. It remains at sub-Kelvin level up to 25 km altitude for separation less than 150 km [Fig. 6].
- Strictly speaking, the intercomparison of CHAMP and SAC-C temperature retrievals establishes only consistency, not accuracy. However, coincident soundings are found to show correlation in the finer-scale structures of the retrieved temperature profiles (cf. Fig. 3). Such a high level of consistency also suggests a high degree of accuracy.

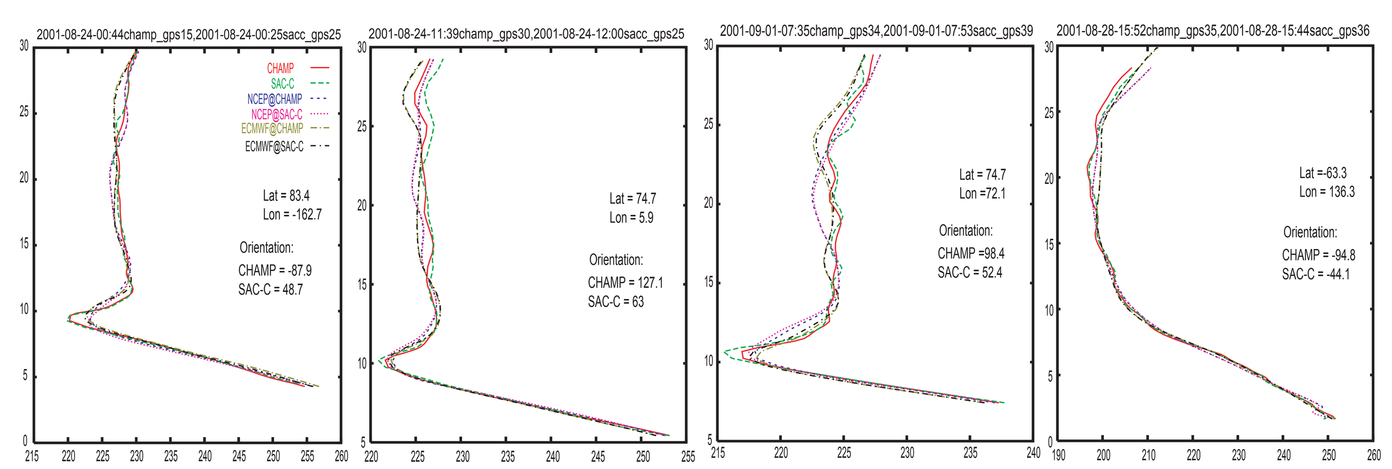


Fig. 4: Temperature profiles for 4 pairs of coincident CHAMP and SAC-C occultations. Also shown are the NCEP and ECMWF analyses at the CHAMP and SAC-C locations and times, the average latitudes and longitudes of the occultations, as well as the orientations of the occultation links (measured in degrees counterclockwise from East).

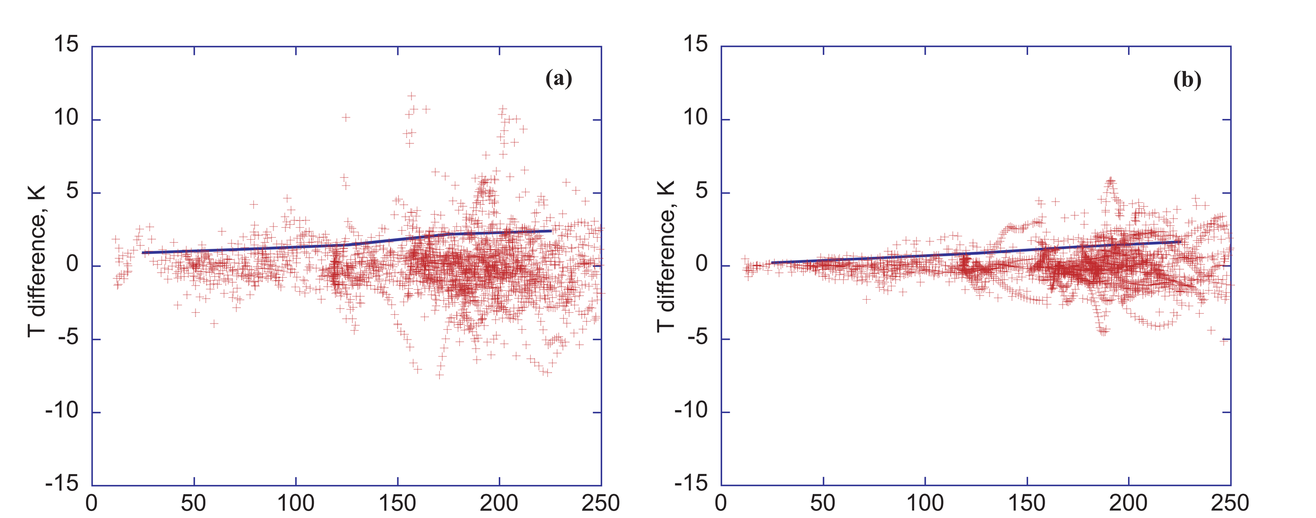
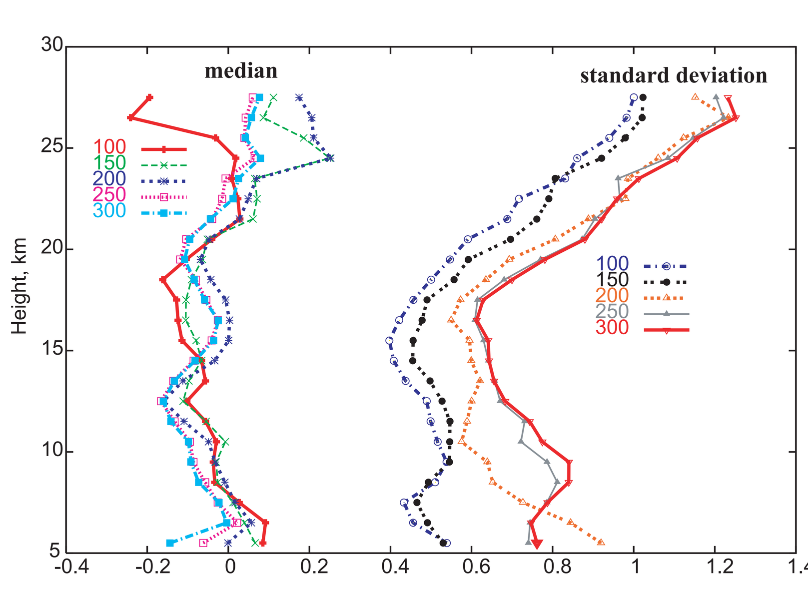


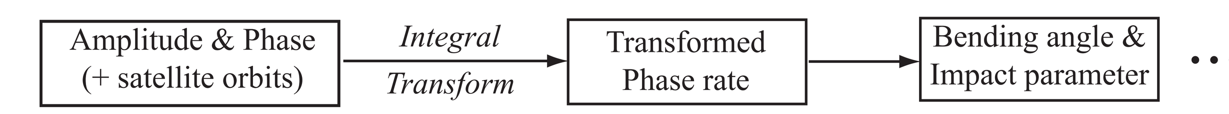
Fig. 5: Temperature difference between 60 pairs of coincident CHAMP and SAC-C occultations as a function of the separation distance between the data points for (a) occultation retrievals and (b) NCEP at the locations and times of the CHAMP and SAC-C pairs. Solid lines indicate the RMS values, which grow as the separation distance increases.

Fig. 6: Statistical analysis (median and standard deviation) of the temperature difference based on the points shown in Fig. 5a. The different curves labeled by numbers correspond to results with different cutoff separation distances *d* (from 100 to 300 km). Median curves are close to zero with little dependence on *d*. The standard deviation curves shift to the right as *d* increases; for *d* < 150 km, the standard deviation remains at sub-Kelvin level up to 25 km in altitude.



DIFFRACTION-BASED RETRIEVAL

- While the standard retrieval method works well, the necessity of Fresnel smoothing means that it is not yielding the maximum information possible from an occultation measurement.
- Since the Fresnel diameter varies as square root of the LEO limb distance, if we could manage to place the LEO closer to the tangent point, we can reduce diffraction effects by shrinking the size of the Fresnel zone and improving the vertical resolution.
- The reduction in diffraction effects can be realized using a procedure known as *backpropagation*, where the signal is propagated backward in vacuum using an integral transform derived from the Helmholtz wave equation [*Karayel and Hinson*, 1997]. Backpropagation (BP) is akin to Kirchhoff migration, a popular method in seismic inversion. The retrieval system is modified as:



- Since the final aim of the integral transform is to produce bending angle and impact parameter, we use a generalized BP method known as the canonical transform (CT) method that yields these quantities more directly [*Gorbunov*, 2002].
- Examples of the improved resolution using CT based on simulations and real data are shown in Figs.7-9.
- With BP or CT, the vertical resolution of the temperature retrieval is essentially limited only by observational constraints such as the size of the data length, sampling interval, and system noise.
  (A detailed study is forthcoming.)

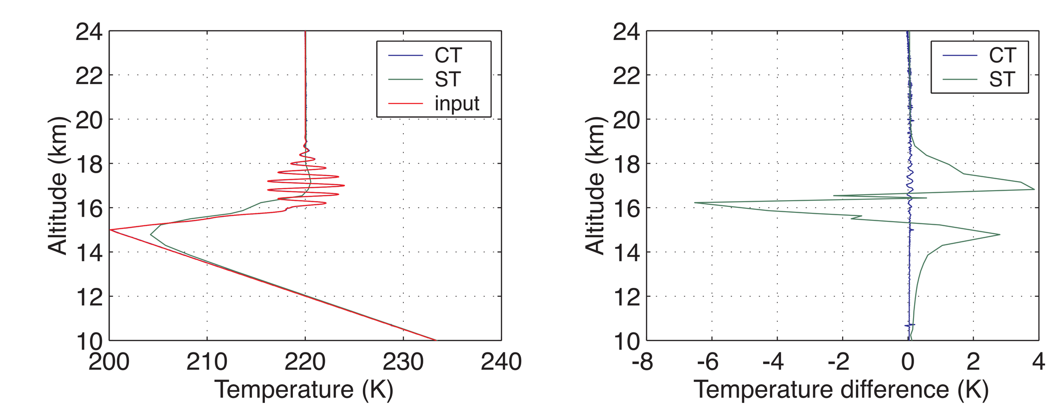


Fig. 7: Temperature retrievals for a simulated occultation with an input temperature profile showing a sharp tropopause and wavy structures above it. The standard (ST) method lacks the resolution to resolve such fine-scale structures due to Fresnel smoothing. However, the diffraction-based CT method yields temperature retrieval which is identical to the input profile.

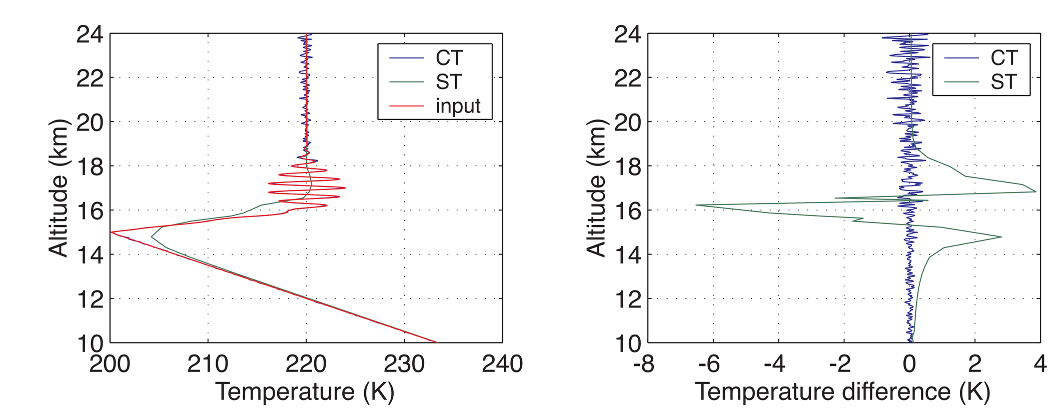


Fig. 8: Same as Fig. 7 except that realistic level of Gaussian random noise is added to the simulated amplitude and phase. CT retrievals are obtained with a smoothing window of 100 m. The fine-scale structures are still clearly resolved.

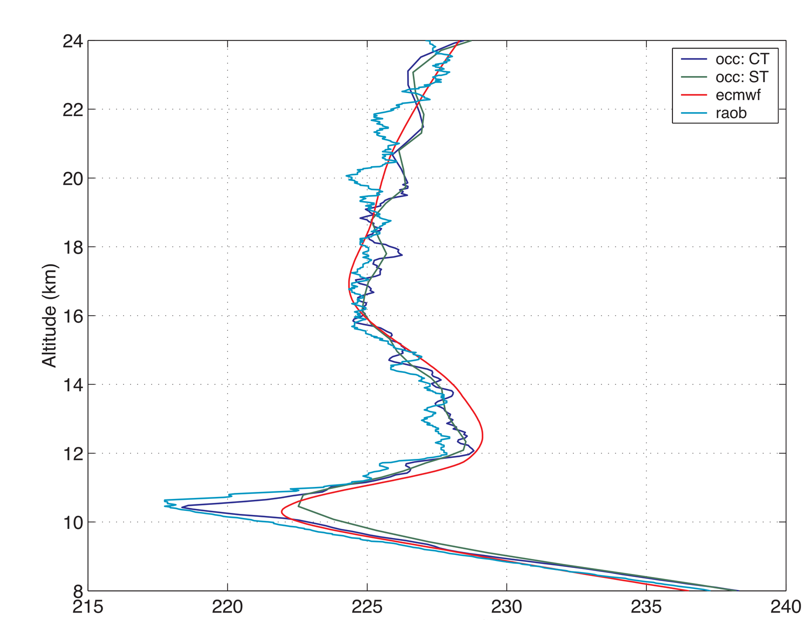


Fig. 9: Temperature retrievals for the SAC-C occultation shown in Fig. 2. For comparison, we show a high-resolution temperature profile taken at a nearby radiosonde station (Bethel, AK) on July 12, 2001, 00:00 UT and located about 90 km from the occultation tangent points. Also shown are the ECMWF profile interpolated to the times and locations of the occultation. CT retrieval captures the sharp tropopause at about 11 km altitude. The wavy structures above the tropopause as retrieved by CT (and ST, for the larger scale structures) appear to correlate well with the radiosonde observation.

THERMAL TROPOPAUSE

- The thermal structure of the tropopause plays a key role in the dynamical coupling of the stratosphere and the troposphere as well as the transport and mixing of atmospheric constituents. Its spatial and temporal variability are important links for understanding climate change.
- The temperature retrievals from GPS occultation data can be very useful in clarifying tropopause structure due to the high vertical resolution and global coverage [*Nishida et al.* 2000; *Randel et al.* 2002].
- An important quantity to characterize is the temperature of the cold point tropopause (CPT), which has direct implications on the stratosphere-troposphere exchange of water vapor. Below, we present a glimpse of how occultation data could contribute towards CPT analysis [Figs 10 & 11].
- In general, the higher vertical resolution of occultation retrievals, in particular with CT, give slightly colder CPT temperature than ECMWF. Systematic differences in the CPT temperature between occultation retrievals and ECMWF show clear dependence on latitude.

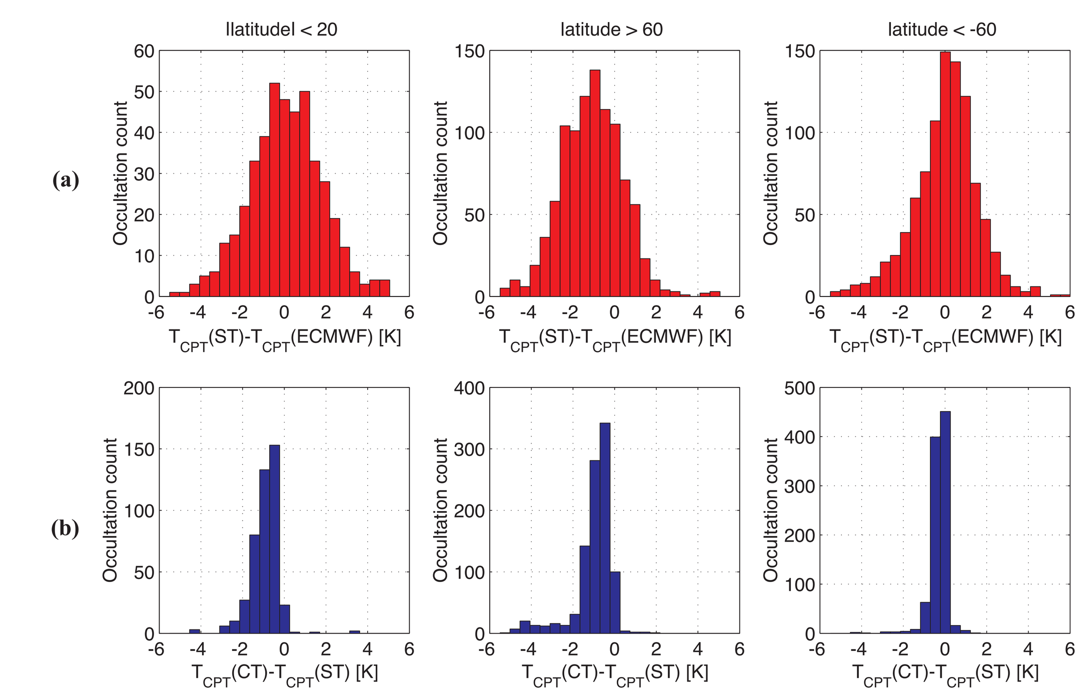


Fig. 10: Histogram of cold point tropopause temperature differences between (a) standard occultation retrieval and ECMWF and (b) CT retrieval and standard retrieval. Results are based on the July 2002 occultations from CHAMP. In general, the high vertical resolution of CT gives slightly colder CPT temperature than standard retrieval. The distribution of the differences between occultation retrieval and ECMWF is skewed and shows interesting latitude dependence.

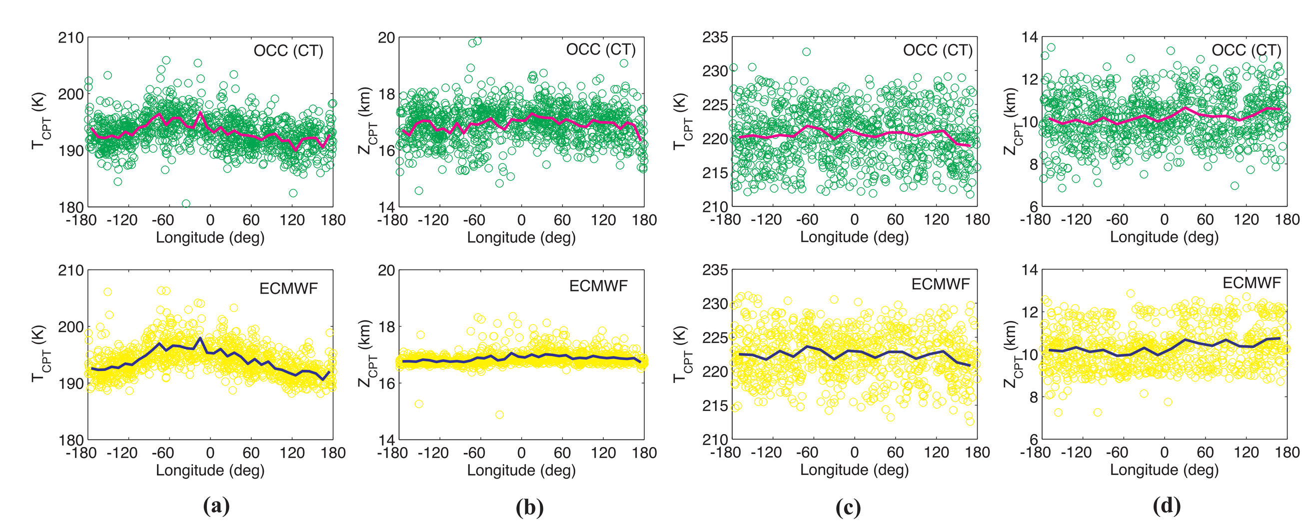


Fig. 11: Scatter plot for CPT temperature and height as a function of longitude based on the July 2002 CHAMP data. (a) and (b) show the temperature and height from CT retrieval and ECMWF in the tropical region (20S to 20N); (c) and (d) are the corresponding results for the arctic region (60N to 90N). ECMWF mean values agree quite well with occultation retrievals in the tropical region but show a warm bias in the arctic region.

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