This paper will be published in SPIE Volume 7082 as paper 7082-36 having been presented in session OP080 (Optical Engineering and Applications) at the August 2008 SPIE Optics and Photonics conference in San Diego.

Cross-validation of HIRDLS and COSMIC radio-occultation retrievals, particularly in relation to fine vertical structure.

J. J. Barnett[a+], C. L. Hepplewhite[a], S. Osprey[a], J.C. Gille[b] and R. Khosravi[b].

[a]Oxford University Department of Physics, Clarendon Laboratory, Oxford OX1 3PU, UK;
[b]Center for Limb Atmospheric Sounding, University of Colorado at Boulder, NCAR/UCB-CLAS,
3085 Center Green Drive, Boulder, CO 80301, USA.

ABSTRACT

The High Resolution Dynamics Limb Sounder (HIRDLS) instrument was launched on the NASA Aura satellite in July 2004. HIRDLS is a joint project between the UK and USA, and is a mid-infrared limb emission sounder designed to measure the concentrations of trace species, cloud and aerosol, and temperature and pressure variations in the Earth's atmosphere from the upper troposphere to the mesosphere. The instrument is intended to make measurements at both high vertical and horizontal spatial resolutions, but validating those measurements is difficult because few other measurements provide that vertical resolution sufficiently closely in time. However, the FORMOSAT-3/COSMIC suite of radio occultation satellites that exploit the U.S. GPS transmitters to obtain high resolution (~1 km) temperature profiles in the stratosphere does provide sufficient profiles nearly coincident with those from HIRDLS. Comparisons show a good degree intercorrelation between COSMIC and HIRDLS down to about 2 km resolution, with similar amplitudes for each, implying that HIRDLS and COSMIC are able to measure the same small scale features. The optical blockage that occurred within HIRDLS during launch does not seem to have affected this capability.

Keywords: HIRDLS, limb-viewing, infrared, Aura, COSMIC, radio-occultation, GNSSRO

1. INTRODUCTION

HIRDLS[1,2] is a mid infrared limb sounding spectroradiometer which was launched on the NASA Aura satellite in July 2004. HIRDLS measures infrared thermal emissions from the atmosphere which are used to determine vertical profiles as functions of pressure of the temperature and concentrations of several trace species, plus cloud top height and aerosol concentrations, in the 8-100 km height range. HIRDLS is a joint project between the UK and USA.

One of the primary goals for HIRDLS is to make measurements at a finer spatial resolution than previously in order to study important but hitherto poorly observed small scale phenomena including gravity waves (which are thought to have an important effect on atmospheric circulation), small scale mixing of species, and transport across the tropopause. Ideally the scales resolved vertically and horizontally should be commensurate for the types of phenomena occurring to obtain a coherent picture: for a vertical resolution of 1-2 km this would imply a horizontal resolution of 100-500 km. The time scale, particularly for gravity waves, may be as short as minutes, so ideally the measurements should be made nearly simultaneously.

HIRDLS suffered a blockage in its optical path during the ascent to orbit. This modified the viewing arrangements, so whereas it was intended to make vertical profile measurements over a range of azimuth angles, it is now only possible to measure profiles at a single azimuth angle of 47° away from the anti-velocity direction. The standard viewing sequence was to have provided a two-dimensional mesh of profiles along the orbit track at 500 km spacing, but now HIRDLS provides just a line of profiles although at a closer spacing of about 100 km (i.e. almost as many profiles but organised as a "curtain" along the orbit). Ironically this situation may be better for viewing the smallest scale of structures, and our collaborator Dr Joan Alexander even suggested such a viewing mode prior to launch.

[+] for correspondence: email: j.barnett1@physics.ox.ac.uk, telephone 44-1865-272901

Clearly, validation of the ability to resolve small scales is necessary. Radiosondes provide one potential means to compare with an independent measurement technique, and provide single profile measurements with tens of metres vertical resolution up to about 10 HPa pressure (31 km). However, profiles matching those of HIRDLS to of order 100 km horizontally and a few minutes in time are ideally needed, and too few matches occur. (When radiosondes are used to monitor other aspects such as the presence of temperature biases, times differences of up to several hours have to be permitted.) Global Navigation Satellite System radio occultation refractivity using the FORMOSAT-3/COSMIC suite of satellites does provide sufficient high resolution profiles nearly coincident with those from HIRDLS.

2. DATA SOURCES

2.1 COSMIC Radio Occultation Measurements

Radio occultation is an establish technique whereby a vertical profile of refractive index of the atmosphere is measured as a radio beam is occulted by the atmospheric limb due to the motion of the receiver and/or transmitter mounted on a satellite. Suggested in 1965[3] and used on early planetary missions, the technique has been developed with several Earth missions which carried receivers which monitored the U.S. Global Positioning Satellite transmissions at 1575.42 and 1227.6 MHz. The phase delay caused by the additional atmospheric path is measured, use of two wavelengths enables ionospheric effects to be largely eliminated, and thus a refractivity profile is derived. Refractivity depends upon air density and water vapour concentration, but in and above the upper troposphere the density term dominates which enables a vertical pressure/height/temperature profile to be calculated unambiguously. The FORMOSAT-3/COSMIC[4] mission employs receivers on 6 small satellites launched on the same vehicle in April 2006, and eventually elevated to an 800 km altitude orbit with 30° orbit plane separation and 72° inclination. Approaching 2000 good quality retrievals are obtained each day at quasi-random locations, normally extending down to below the altitude of useful HIRDLS retrievals, and up to 40-50 km (errors due to noise increase above about 40 km).

The FORMOSAT-3/COSMIC project makes fully processed retrievals available via the Internet (see http://www.cosmic.ucar.edu). These have recently (late 2007) been reprocessed, and that version has been used for this work. Data were used from Day 192 2006, an earliest date recommended by FORMOSAT-3/COSMIC, until Day 365 2007 the current end of the publicly released HIRDLS data although more will become available.

2.2. HIRDLS Data

An overview of the HIRDLS instrument, the optical blockage and revised algorithms to allow for it, and details of temperature profile validation are given in reference 5. Both that work and this use the data products that are currently the latest that are publicly available, being known as Version 2.04.09 within the HIRDLS Project and at the British Atmospheric Data Centre (http://www.badc.ac.uk), and Version 003 within the NASA Goddard Earth Sciences Data and Information Services Center (http://daac.gsfc.nasa.gov). The instrument scan mirror is made to scan alternately upwards and downwards, with a mean spacing between scans of 16.6 sec, corresponding to approximately 110 km along the tangent point track. Retrieved temperatures have only been used above cloud and any aerosol layers, which led to a lower level of 112 HPa (approximately 16 km) being used; this level produces sufficient profiles in the tropics, where clouds are highest, but ignores useful data lower down away from the tropics. HIRDLS retrieved temperatures for this version are valid to 0.1 HPa (65 km) so well above the level reached by radio occultation.

The HIRDLS temperature retrieval makes a correction using horizontal gradient fields obtained from the NASA Goddard Modeling and Assimilation Office (GMAO) Earth Observing System version 5 (GEOS-5.01) meteorological data. These are gridded temperature fields derived from a variety of measurements with lower vertical resolution than HIRDLS or COSMIC, and they exhibit much less vertical structure. They have been interpolated to the same horizontal locations as HIRDLS and to the same levels. Comparison have also been made against them as shown in Section 4.

2.3 Matching profiles

For each radio occultation profile any HIRDLS profile within 0.75° great circle distance, (83.3 km) and 500 sec of time was identified. For the small proportion of occultations within this range of two HIRDLS profiles, the HIRDLS profiles were averaged together. For both types of data the geolocation at approximately 25 km altitude was used. HIRDLS retrievals are fundamentally located on a pressure scale^{6,} since the radiometric measurements provide complete information for a retrieval with just a knowledge of relative heights of the measurements within a radiance profile. The retrieval algorithm generates products at intervals of 1/24 in $\log_{10}$(pressure), i.e. factors of 0.9085 in pressure and approximately 0.67 km. Consequently, HIRDLS and FORMOSAT-3/COSMIC profiles were matched using their pressure scales, with that for HIRDLS being linearly interpolated to a half spacing of 1/48 in $\log_{10}$(pressure), and that for FORMOSAT-3/COSMIC being interpolated in log(pressure) space to the same levels.

Figures 1a and 1b show example intercomparisons. The thick dashed curve is the COSMIC temperature profile, and the thick solid curve is the closest HIRDLS profile. The adjacent four HIRDLS profiles on either side along the orbit track are also shown, each being offset by an additional 4 K so that they can be distinguished from the other curves. Those to the left are for lower latitudes, and to the right for higher latitudes. These profiles span a horizontal range of about 900 km. In both figures the HIRDLS profiles show a slow evolution of features along the orbit track, with the larger scales showing a downward trend of the tropopause height towards the north in Figure 1b and the temperature peak near 30 HPa in Figure 1a showing a trend to higher altitudes towards the north. The smaller scale wave structures show features that typically last for a few profiles and slope more steeply with height which indicates a wave travelling at an angle to the vertical. The radio occultation profile (dashed line) matches the central HIRDLS profile (thick solid line) with negligible bias up to 10 HPa for Figure 1a then an increasing bias above, and a small bias in the case of Figure 1b. However, this work is not concerned with investigating such biases.

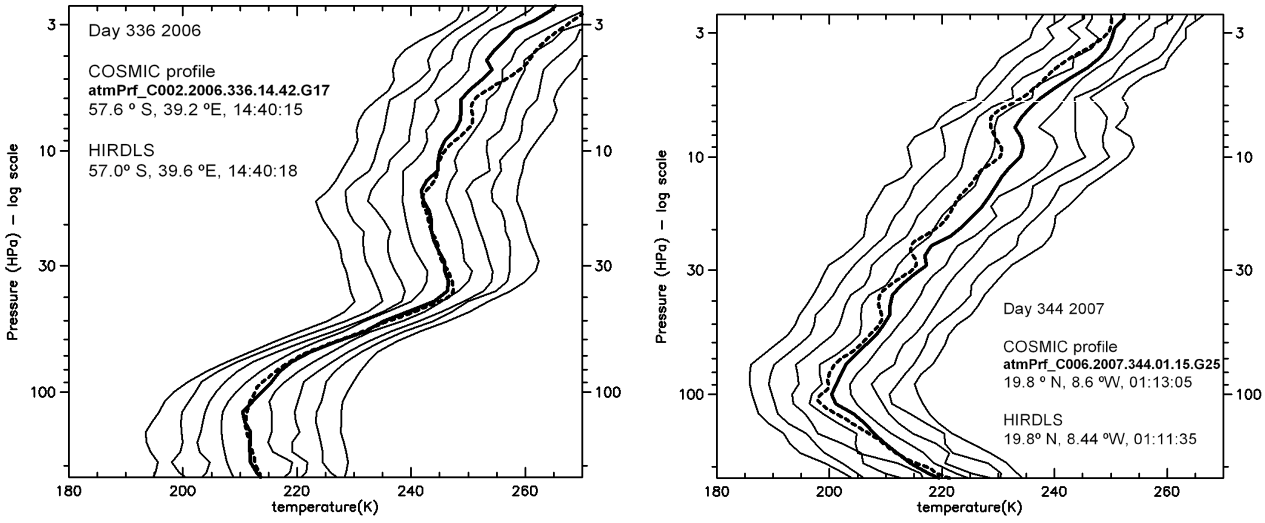

Figure 1. Comparisons of a single COSMIC radio occultation temperature profile (thick dashed line) with the closest HIRDLS temperature profile (thick solid line). The preceding and following four HIRDLS profiles at approximately 110 km intervals are also show as thinner solid lines but displaced by an additional 4 K each profile with the more southerly on the left and more northerly on the right. Figure 1a (left): Day 336 2006. Figure 1b (right): Day 344 2007.

3. INTERCOMPARISON USING A HIGH PASS FILTER

Two methods of intercomparison were used. This section describes the first, using a high pass filter.

The profiles have been high pass filtered by first smoothing each profile separately, then subtracting this profile. A cosine-bell filter of 0.5 pressure scale heights full width (approximately 3.5 km) at half height was used, as shown in Figure 2. This filter spans 13 intervals 1/48 apart in $\log_{10}$(pressure). Figure 3 shows how this procedure operates on the profiles compared in Figure 1, leading to high frequency components that in these cases have a high degree intercorrelation.

The aim was to compute the correlation coefficient over the range 2.2 to 5.4 pressure scale heights (112-4.6 HPa, 67 intervals), which ideally required the filter to extend 6 intervals beyond these end points. However, filtered profiles which spanned more than half this range, i.e. 33 intervals or 1.6 pressure scale heights were accepted, leading to 1756 profile pairs being obtained.

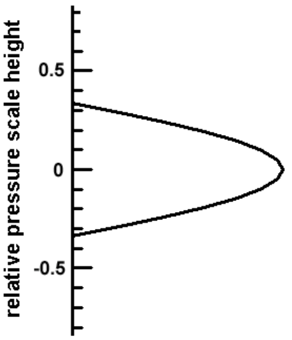

Figure 2. Low pass filter used for generating smoothed profiles.

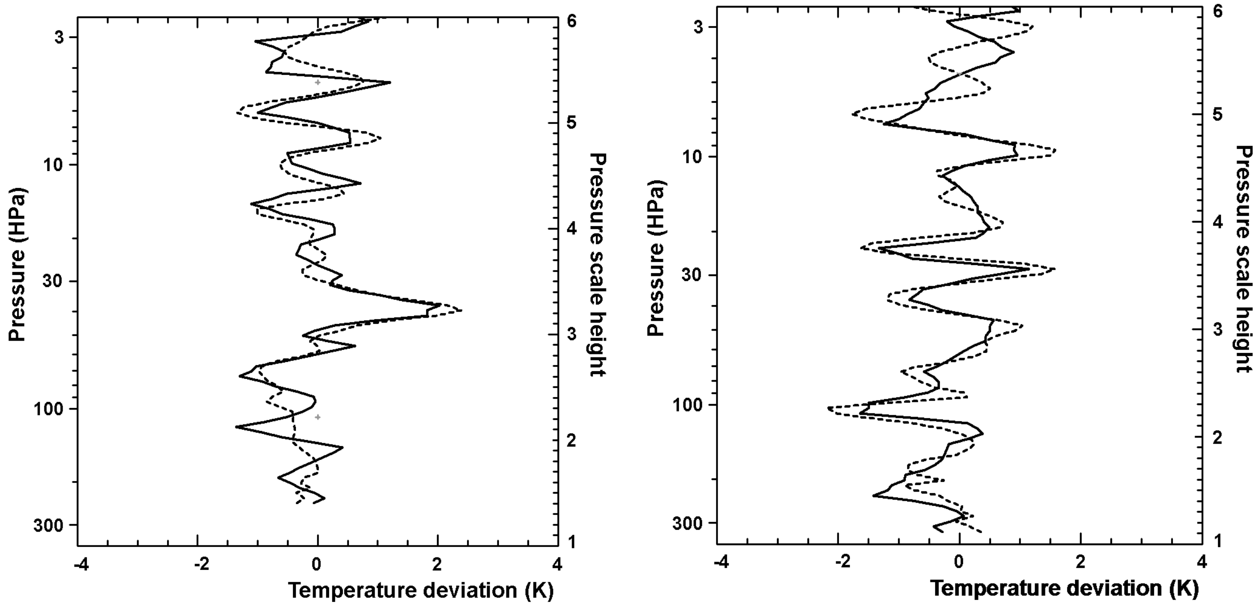

Figure 3. High pass filtered profiles derived from those shown in Figure 1. The HIRDLS profiles are show with solid lines and the COSMIC with dashed. Figure 3a (left): Day 336 2006. Figure 3b (right): Day 344 2007.

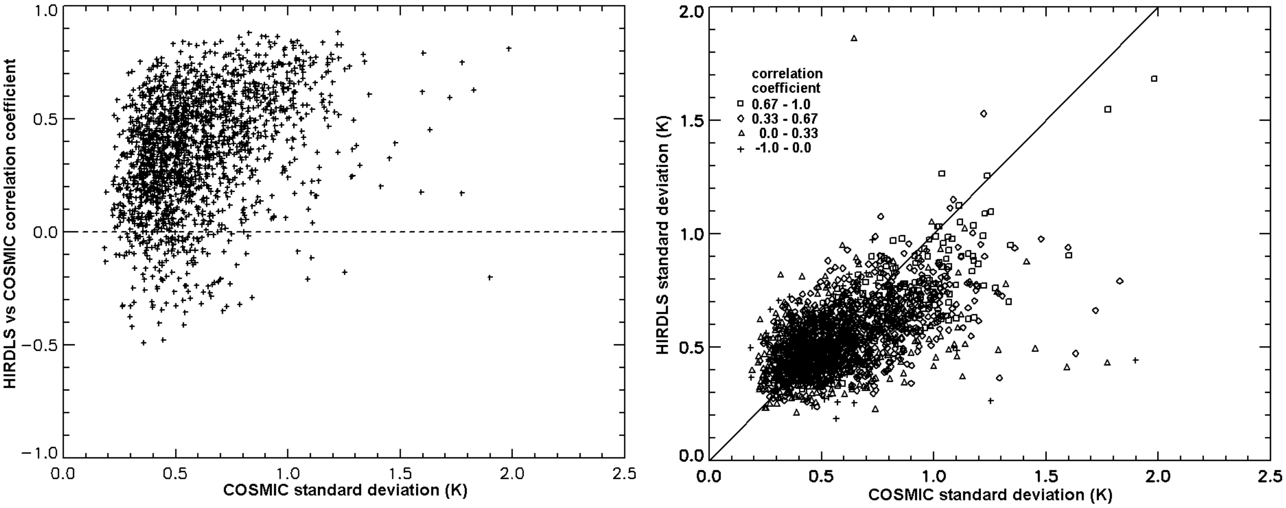

Figure 4. Results for intercorrelation between HIRDLS and COSMIC high pass filtered profiles. Each point represent one profile comparison. There are 1756 comparisons.
Figure 4a (left): Correlation coefficient vs. the standard deviation of the COSMIC profile.
Figure 4b (right): Standard deviation of HIRDLS vs. standard deviation of COSMIC. Points are shown with different symbols according to their correlation coefficient (+ for negative, triangle, diamond and square for 0 - 0.33, 0,33 - 0.67, 0.67 - 1.0 respectively). The solid line is of gradient 1 and shows the expected fit for a perfect match.

Figure 4 shows the results for all comparisons. Each profile pair yields a correlation coefficient and the standard deviation of each profile about its smoothed profile. The intercomparison relies upon there being atmospheric waves in the profile to provide a signature that should be found by both measurement systems. Where the atmospheric variation is much smaller than the measurement noises of either or both systems, we can expect correlation coefficients scattered randomly about zero. Figure 4a shows that the correlation coefficients are mainly positive, reaching 0.9, with no points below -0.5, and negative values primarily at lower standard deviations of the COSMIC system. Similar results (not shown) occur when plotting correlation coefficient vs HIRDLS standard deviations. Figure 4b shows the results of plotting HIRDLS vs COSMIC standard deviations. The symmetry of points about the unity gradient line is consistent with the two systems measuring the same structures with the same amplitudes. Although difficult to see in this figure, the points of low correlation coefficient tend to be where standard deviations are smallest; this is most easily seen in Figure 4a.

4. INTERCOMPARISON USING FOURIER DECOMPOSITION

This method of comparison uses Fourier analysis over the profile to yield information as a function of wavelength.

The range of 2.0 to 5.7 pressure scale heights was used (~15-39 km, 77 intervals). Profiles had to be present over the whole of this range so that each comparison would lead to a set of Fourier coefficients with the same wavelengths. Hence, although the vertical range was similar to that used in Section 3, the number of profiles was less, being 1481, This range was a compromise between maximising the range and maximising the number of profile comparisons.

A background profile was subtracted from each. After much experimentation, mainly with polynomials of different order, a parabolic fit was used, with a separate fit for each profile. This should attenuate the lowest wavenumber, which we need to be aware of. Higher order polynomials gave attenuation to progressively higher frequencies but left the still higher ones little changed. Unlike for the Section 3 comparisons, the background fit was to the same vertical range as the Fourier analysis, hence a slightly greater vertical range could be used for the comparison.

A classical Fourier analysis was used, i.e. each sine and cosine component was evaluated separately, rather than a Fast Fourier Transfer to avoid having to pad out to a power of 2. The data were apodised with a triangular function, but this gave essentially the same result as a cosine bell apodisation. The sine and cosine components were intercorrelated separately for each wave number.

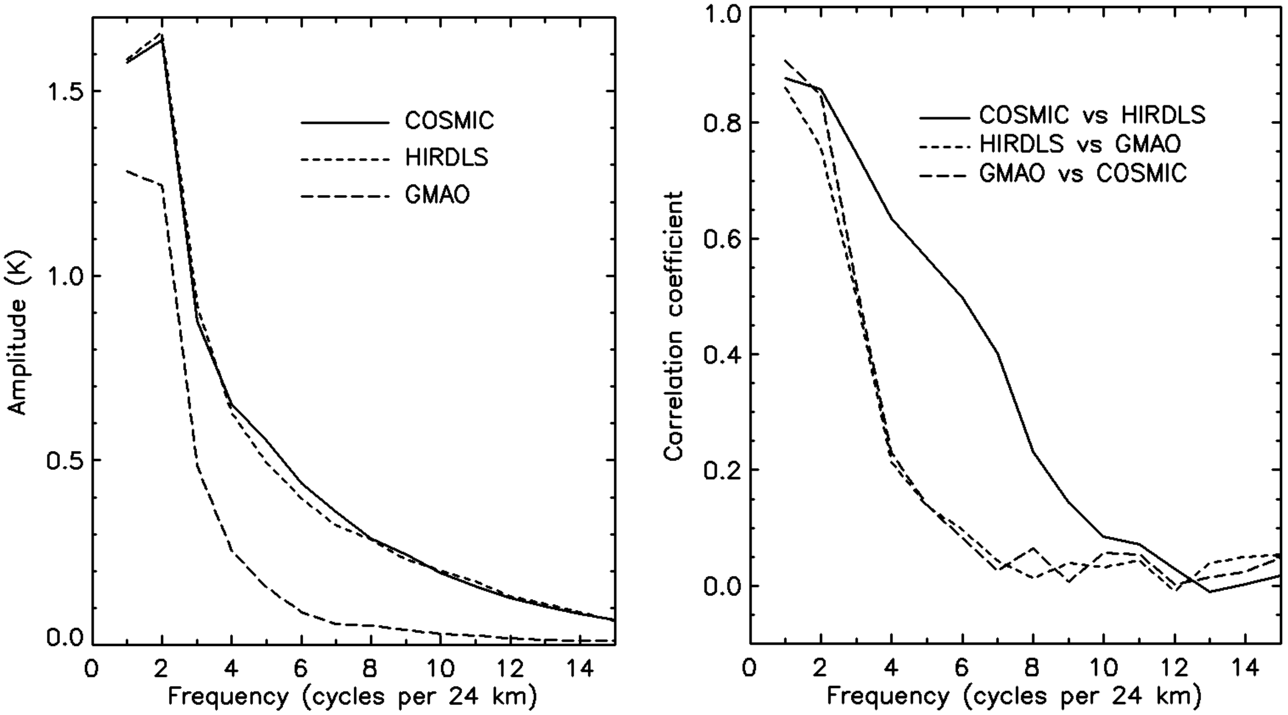

Figure 5. Results for a Fourier component intercorrelation between HIRDLS, COSMIC and GMAO profiles (after subtracting quadratic fits). It should be noted that the lowest frequency (1 cycle/24 km) is probably underestimated because a quadratic fit has been subtracted that will have removed some of the fundamental component.
Figure 5a (left) gives the root mean square amplitude of each frequency.
Figure 5b (right) gives the correlation coefficient for each frequency.

Figures 5a and 5b show the results of the Fourier intercomparison. Figure 5a shows that the amplitudes for HIRDLS and COSMIC match each other closely as a function of frequency, but that the GMAO amplitudes are slightly smaller at the lowest frequencies, becoming very much smaller at higher frequencies. HIRDLS and COSMIC have positive intercorrelations everywhere, being above 0.8 for the lowest frequencies, dropping to 0.5 at 6 cycles per 24 km (4 km wavelength or 2 km resolution). The intercorrelations of COSMIC with GMAO and HIRDLS with GMAO are very similar to each other but much lower at the higher frequencies, as might be expected from the lower GMAO amplitudes.

5. DISCUSSION AND CONCLUSIONS

HIRDLS agrees well with FORMOSAT-3/COSMIC radio occultation data down to 2 km resolution (4 km wavelength) or better. Both data sets exhibit remarkably similar amplitudes and spectral behaviour. This suggests that they have similar vertical resolutions and/or they are both are adequate to resolve the scales that are present in atmospheric temperature fields. Both techniques average along limb paths, and we might expect this to reduce the observable amplitudes of the disturbances that have shortest vertical wavelengths, since there are geophysical reasons to expect such a scaling.

Agreement on finer vertical scales is difficult to verify because of small amplitudes (for whatever reason) in both HIRDLS and FORMOSAT-3/COSMIC data. Validation of HIRDLS for still smaller scales may depend on comparison for ozone profiles since ozone perturbations sometime occur as thin sheets extending over hundreds of kilometres.

6. ACKNOWLEDGEMENTS

This work has been made possible by the dedicated work of very many colleagues in the HIRDLS Project, both before launch, and after the launch problem occurred. We are exceedingly grateful to each of them. We are also grateful for extensive assistance from staff and contractors at NASA Goddard Space Flight Center, particularly for the help that they have provided to alleviate the launch problem. We thank the FORMOSAT-3/COSMIC project for the well organised manner in which they have made their data products available to the public. The HIRDLS Project is supported by NASA in the USA under Contract NAS5-97046 and by the Natural Environment Research Council in the UK.

7. REFERENCES

1. Gille, J.C. and J. Barnett, J., `*Conceptual design of the High Resolution Dynamics Limb Sounder (HIRDLS) for the EOS Chemistry Mission'*, *Proc. SPIE*, Vol. 2830, 190-201, 1996.

2. J.C. Gille, Barnett, J.J., Whitney,J., Dials,M., Woodard,D., Rudolf,W., Lambert,A. and Mankin,W., *`The High-Resolution Dynamics Limb Sounder (HIRDLS) Experiment on Aura'*, *Proc. SPIE* 5152, 162-180, 2003.

3. Fjeldbo,G. and Eshleman,V.R., '*The bistatic radar-occultation method for the study of planetary atmosphere'*, J. Geophys. Res., 70, 3217-3225, 1965.

4. Yuei-An Liou, Pavelyev, A.G., Shuo-Fang Liu, Pavelyev, A.A., Yen, N., Huang, C.-Y. and Chen-Joe Fong, *'FORMOSAT-3/COSMIC GPS Radio Occultation Mission: Preliminary Results',* Geoscience & Remote Sensing, IEEE Trans. 45, 11, 3813-3826 (2007), 10.1109/TGRS.2007.903365

5. J.C.Gille, Barnett,J.J, Arter,P., Barker,M., Bernath,P., Boone,C., Cavanaugh,C., Chow,J., Coffey,M., Craft,J., Craig,C., Dials,M., Dean,V., Eden,T., Edwards,D.P., Francis,G., Halvorson,C., Harvey,L., Hepplewhite,C., Khosravi,R., Kinnison,D., Krinsky,C., Lambert,A., Lee,H., Lyjak,L., Loh,J., Mankin,W., Massie,S., McInerney,J., Moorhouse,J., Nardi,B., Packman,D., Randall,C., Reburn,J., Rudolf,W., Schwartz,M., Serafin,J., Stone,K., Torpy,B., Walker,K., Wateeerfall,A., Watkins,R., Whitney,J., Woodard,D., & Young,G., *'High Resolution Dynamics Limb Sounder: Experiment overview, recovery, and validation of initial temperature data'*, J. Geophys. Res. 113, D16S43, doi:10.1029/2007JD008824, 2008.

6. Gille,J.C. and House,F.B., *'On the Inversion of Limb Radiance Measurements, I, Temperature and Thickness'*, J.Atmos.Sci., 28, 1427-1442 (1971).