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In-flight validation of Aura MLS ozone with CAFS partial ozone columns

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[1] A comprehensive data set of partial ozone columns was derived from the charge-coupled device (CCD) Actinic Flux Spectroradiometer (CAFS) measurements taken during the Polar 2005, Houston 2005, and Costa Rica 2006 Aura Validation Experiments (AVE). It was used to validate the colocated daytime Aura Microwave Limb Sounder (MLS) partial ozone columns along the aircraft tracks over diverse geophysical conditions. Results show that the MLS v.1.5 and CAFS ozone columns agree to better than 3% at pressure levels of 100 and 146 hPa, and to better than 5% at 215 hPa level. The partial ozone column differences between the two systems were the largest during the Polar AVE (PAVE) 2005 campaign (polar region, ∼250 hPa pressure level), and the smallest during the CRAVE 2006 campaign (tropics, ∼100 hPa pressure level). Overall, the averaged bias between the MLS and CAFS partial ozone column is about 2%, and the standard deviation of the differences is about 2%. The v.2.2 update of the MLS data tends to reduce the bias to less than 1%. In addition, the AVE 2005 campaign uncovered an altitude-dependent bias, where the MLS partial ozone columns above 100 and 146 hPa pressure levels were about 1% higher than the CAFS derived columns, while the bias increased to about 3 % in partial columns integrated above 215 hPa. However, the MLS and CAFS data track each other closely over a wide range of atmospheric conditions, and the differences lie within the combined uncertainties of the two data sets.

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1. Introduction

[2] The Earth Observing System (EOS) Aura Mission was developed to study the Earth's atmosphere, and, in particular, to determine if the ozone layer is recovering as predicted by atmospheric models (*Schoeberl et al.* [2006], *Froidevaux et al.* [2006], *Waters et al.* [2006], *Levelt et al.* [2006], and other papers in the 2006 IEEE Aura special issue, *IEEE Transactions on Geoscience and Remote Sensing*, May 2006, volume 44, issue 5). The four instruments on the Aura platform were designed to monitor a number of different atmospheric constituents and processes in different altitude ranges. All four instruments, the High Resolution Dynamics Limb Sounder (HIRDLS), the Tropospheric Emission Spectrometer (TES), the Microwave Limb Sounder (MLS), and the Ozone Monitoring Instrument (OMI), currently provide ozone measurements over a large range of altitudes. Accurate validation of the satellite instrument measurements has been addressed in the Aura Validation Plan to meet the validation needs [*Newman et al.*, 2001; *Froidevaux and Douglass*, 2001]. The Aura Validation Experiment (AVE) is designed to provide as many correlative measurements as possible from the NASA DC-8 and WB-57 aircraft at a variety of locations. Since ozone is measured by all Aura platform instruments the need for independent ozone measurements is crucial in the validation effort. Total ozone column and tropospheric ozone have high-priority needs for instrument validation. The MLS measures the chemistry of the lower stratosphere and upper troposphere [*Waters et al.*, 2006]. The retrieved ozone profiles [*Livesey et al.*, 2006] are available at multiple pressure levels in the atmosphere, and at roughly 250-km horizontal resolution (MLS footprint).

[3] The accuracy of the MLS ozone profile retrieval can be of the order of a few percent at altitudes above the 100 hPa level [*Froidevaux et al.*, 2007]. The MLS stratospheric ozone profiles have been shown to agree well (within 5 to 10%) with other well established satellite data sets such as SAGE II and HALOE [*Froidevaux et al.*, 2006, 2007; *Yang et al.*, 2007]. *Yang et al.* [2007] show that MLS stratospheric column ozone abundances agree better with SAGE II values than with those from SAGE III or HALOE, and that the MLS v1.5 columns down to 215 hPa are 1 to

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3% higher than the SAGE II coincident values. This small level of disagreement is reduced to 1% when MLS v2.2 data are used [*Froidevaux et al.*, 2007]. MLS partial stratospheric column ozone values for v2.2 have also been compared to ozonesonde partial columns [*Jiang et al.*, 2007], and although there is often variability of order 5 to 10%, the mean differences are 1 to 2%, with MLS values on the high side, on average. The estimated accuracy for MLS column abundances down to near 215 hPa is 4%, based on sensitivity tests and simulated retrievals. *Livesey et al.* [2008] have provided additional validation results for MLS ozone (and CO), with a focus on the upper troposphere and lower stratosphere, including lidar and in situ data taken during the AVE aircraft campaigns.

[4] In this work, the charge-coupled device (CCD) Actinic Flux Spectroradiometer (CAFS) measurements are used to derive partial ozone column data above the aircraft altitude. These results are important in helping to validate MLS stratospheric column values and can be used to study tropospheric ozone residual columns [e.g., *Ziemke et al.*, 2006] by differencing from the OMI total ozone. As well, column validation using sondes does not cover the total ozone overburden, while the aircraft data provide a good opportunity for colocated measurements in space (along the MLS suborbital track) and to some extent, in time. In addition, the CAFS ozone column is derived at different pressure levels, and thus partially validates the upper tropospheric and lower stratospheric ozone values.

[5] Another advantage of using the aircraft data is to obtain information on the ozone variability at the satellite subpixel level. Thus, the horizontal variability of the stratospheric ozone column in the MLS footprint is also investigated. The accurate solar radiation data from the CAFS instrument in conjunction with an accurate algorithm provide the column ozone data needed for this MLS validation analysis.

[6] The paper is organized by results from individual campaigns. This is done to address specific objectives of each campaign. Three campaigns addressed the spatial and temporal variability in the stratospheric ozone column over the three distinctly different geographical regions. The PAVE05 campaign studied ozone variability primarily over the northern polar region, whereas the AVE05 campaign addressed ozone variability over the northern middle latitudes, while the CRAVE06 campaign sampled ozone over the tropical region. Comparison of results from different campaigns helps to define the MLS ozone column accuracy over different regions and under different observational conditions.

[7] Analyses of the measurement quality and data comparisons typically require the use of statistical parameters. Since various definitions are used in different research fields, here we define parameters as we use them in the paper. The accuracy is the degree to which calculated or measured data match true or accepted values. The precision is defined as the degree to which repeated measurements or calculations show the same results. The uncertainty of a measurement is defined as a spread of multiple measurements over the range of values that surround the true value. When the sample of multiple measurements is randomly distributed (random errors), the uncertainty in the bias is the combined contribution of the standard error of the two mean measurements compared (standard deviation of the mean). The uncertainty of the retrieval (or retrieval errors) is defined as the departure from the truth due to inaccuracies of the modeling or the measurement. The bias (or offset) is the mean difference between compared data sets.

2. CAFS Measurements and Ozone Retrieval

[8] One objective of the Aura ozone validation activities was met by deploying solar radiation measurement instrumentation on the NASA WB-57 and DC-8 platforms for the determination of ozone column abundances. The instruments deployed on the WB-57 aircraft were the CCD based Actinic Flux Spectroradiometers (CAFS) that determine the down and upwelling UV and visible actinic flux as a function of wavelength. The instrument was developed by R. Shetter of the Atmospheric Investigations and Measurements group at the National Center for Atmospheric Research, Boulder shortly before the first Aura Validation Experiment (AVE) campaign and flight tested in TC4 campaign in the summer of 2004 [*Shetter et al.*, 2003]. The instrument design, details of calibrations and the description of measurements are briefly summarized in the paper by *Petropavlovskikh et al.* [2007], whereas a more detailed information is available from the paper by S. Hall et al. (manuscript in preparation, 2008).

[9] The CAFS instrument was initially deployed on the WB-57 in October 2004 for the AVE campaign in Houston, Texas, in the fall of 2004 (AVE04). The next CAFS deployment was during the Polar AVE (PAVE05) campaign in January and February of 2005, when the instrument was flown onboard the NASA DC-8 aircraft. Later in the year 2005 another AVE campaign (AVE05) was organized out of Houston, Texas, where the CAFS was flown onboard the NASA WB-57 aircraft. Another AVE campaign was held in Costa Rica (CRAVE06), in January and February of 2006, when the CAFS instrument was flown onboard of the NASA WB-57 aircraft. Prior to the AVE 2005 campaign, the temperature control systems were redesigned to provide more consistent control of the instrumental temperature at high altitude. In addition, the data algorithm development team felt that the near horizon radiation was degrading the accuracy of the retrieval algorithm. Therefore, the downwelling instrument artificial horizon was modified to remove the scattered light below approximately 10 degrees Sun elevation angle (further specified as “the restricted field of view”). The detailed angular response of the system with the modified horizon was determined and provided as a model input for the ozone column algorithm.

[10] During the AVE05 and CRAVE06 campaigns, the calibration of the instrument was routinely completed on the ground, prior to the NASA WB-57 flights, and at the surface temperature and pressure. The instrument was also pressure sealed and temperature controlled during all NASA WB-57 flights. The optical collector design was also modified to insure the sealing of the enclosure. It was also discovered that in warm weather the wavelength assignment of the CCD showed a slight dependence on the CCD temperature. In an attempt to eliminate this shift and to better represent in-flight thermal conditions, external cooling was employed for ground calibrations.

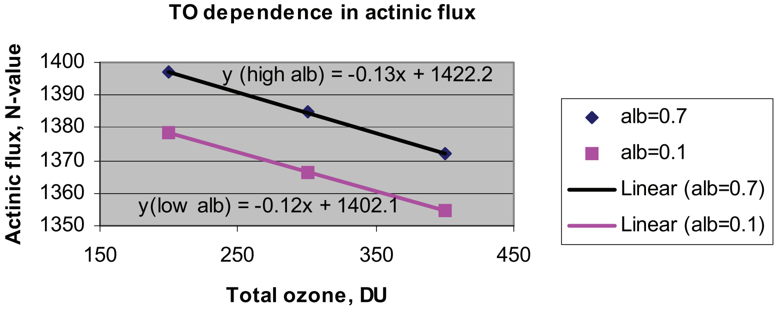

Figure 1. Change in N value of actinic flux at 310 nm wavelength as function of total ozone. N value unit is defined as 100 × $\log_{10}$(flux). Results are simulated by the tropospheric ultraviolet and visible (TUV) radiation model code at 30 degrees solar zenith angle. Effect of surface albedo on actinic flux is also shown.

[11] Unusually low temperatures observed in the tropical tropopause during the CRAVE06 campaign exceeded the instrument's heating capability, and the temperature drifted downward. Following the CRAVE06 mission, laboratory measurements were performed to check the sensitivity of the wavelength assignments in all CAFS channels due to temperature changes. All AVE05 and CRAVE06 data were corrected on the basis of the temperature-induced wavelength shift observed during the flights, and corrections were applied to the ozone retrieval. As for the earlier PAVE05 campaign, the instrument was flown within the NASA DC-8 cabin under stable temperature conditions and thus did not experience temperature related problems.

[12] The spectrally resolved UV actinic flux obtained inflight is used in conjunction with radiative transfer calculations (tropospheric ultraviolet and visible (TUV) radiation model radiative transfer code described by *Madronich and Flocke* [1998]) to obtain ozone column abundances above the aircraft. At high-Sun and clear-sky conditions, the direct actinic flux is a major contributor to the total actinic flux. Therefore, it could be expected that the direct Sun source rather than the secondary scattering initiates most of the diffuse actinic flux. Following results are presented in N value units, $N = 100 \times \log_{10}(\text{actinic flux})$, whereas the actinic flux is measured at each spectral channel of the CAFS instrument, it is a product of extraterrestrial solar flux (F), atmospheric attenuation (I), and instrumental constant (K) integrated over the channel band pass.

[13] Our studies demonstrate that there is a strong correlation between total ozone (TO) column and N values at UV wavelengths (see Figure 1). However, contribution from the scattered light depends on the underlying surface albedo (snow, tropospheric aerosols or clouds), and can produce a sizable effect on the N value measured at a single wavelength (see example for high-albedo results in Figure 1). Our analyses show that when actinic flux measurements at several wavelength pairs are combined, most of the instrumental and background uncertainties can be successfully removed [*Brewer et al.*, 1973]. The difference between N values measured at two spectral channels (for example, CAFS channels centered at 320 and 310 nm) is called the single-pair N value. The difference between N values measured at two wavelengths implicitly removes instrumental bias (instrumental constants K, when they are spectrally independent), such that: $N = (\log_{10}(F \times I \times K) = \log_{10}(F \times I) + \log_{10}(K))$, $N' - N'' = \log_{10}(F' \times I') - \log_{10}(F'' \times I'')$, where $'$ and $''$ denote measurement at two different spectral channels. At the same time, the residual between two single-pair N values, one is taken at longer (330 and 320 nm) and another at shorter (320 and 310 nm) channels, is called the double pair N value. The method works well when the spectral contribution from the underlying albedo, cloud or aerosol interferences in the measured actinic flux can be linearly approximated. A combination of actinic flux measurements taken at several wavelength pairs (double-pair method) provides a simple tool for minimizing these interferences from the retrieval (see Figure 2). The method is similar to the double-pair Dobson direct Sun technique [*Dobson*, 1931; *Hudson and Planet*, 1993] or multiple wavelength combination of the Total Ozone Mapping Spectrometer (TOMS) technique [*McPeters et al.*, 1998] and the Brewer ozone algorithm [*Kerr et al.*, 1988].

[14] The partial ozone column product is derived from the upward looking actinic flux measurements on the basis of techniques described in the paper by *Petropavlovskikh et al.* [2007]. The method relies on a set of actinic fluxes simulated in the UV-visible part of solar spectrum at 0.05 nm resolution. The lookup tables provide the reference for the CAFS measurements as a function of altitude, solar zenith angle, wavelength, and total ozone column, which is represented by a set of standard ozone profiles between 225 and 575 DU at 50-DU increments. The choice of the wavelength pairs for the CAFS retrieval minimizes interference from absorbing tropospheric aerosols, varying surface albedo or underlying clouds. Even then, the retrieved ozone column can be overestimated with an upper limit of 5% (details of CAFS ozone retrieval uncertainties are given by *Petropavlovskikh et al.* [2007, Table 3]). The remaining CAFS retrieval uncertainties can be attributed to the following factors. The effect of atmospheric variability on the CAFS ozone retrieval is estimated as one standard deviation in retrieved ozone data over ~250-km distance (a size of the MLS foot print) of a flight at a constant altitude. During all four AVE campaigns a typical atmospheric variability was ~2%, whereas the effect of the temperature variability can be almost twice as large [*Petropavlovskikh et al.*, 2007]. The CAFS profile sensitivity test implies that the retrieval uncertainty is of the order of 2%, whereas it could increase at large solar zenith angles (SZA) (beyond 82 degrees SZA) and at lower altitudes (below ~12 km) to as much as 10%. Figure 3 displays the typical range of retrieval uncertainties associated with an imprecise knowledge of an ozone profile.

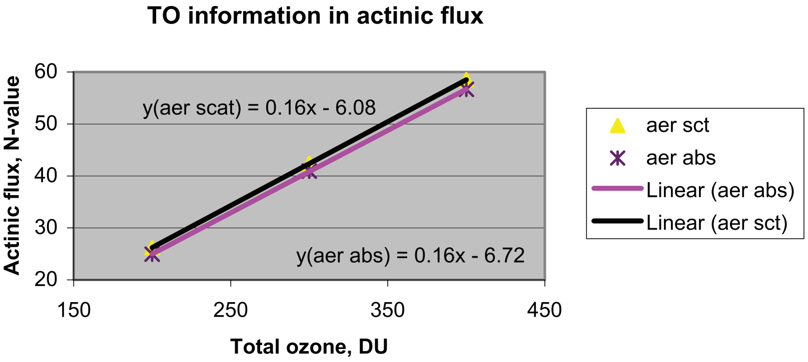

Figure 2. Change in N value for a double wavelength pair (actinic flux ratio) as function of total ozone. Results are simulated by the TUV code for Sun elevation at 30 degrees zenith angle, at the sea-surface level (double pairs), and for surface albedo of 0.7 (or 70% reflectivity). Results for absorbing and nonabsorbing aerosols are shown. Clear-sky data (not shown) are very similar to nonabsorbing aerosols.

Results presented in Figure 3 are based on the subset of the MLS profiles observed during the AVE 2005 (left) and PAVE 2005 campaign (right) campaigns, and, therefore, reflect sensitivity of the retrieval to the MLS observed variability of the vertical ozone distribution. The CAFS partial ozone column products were validated against other references available from the AVE airborne campaigns, such as ozone in situ measurements by the Ozone Dual Beam UV Photometer [*Proffitt and McLaughlin*, 1983] and balloon-borne ozonesondes, other platforms including satellites (Total Ozone Mapping Spectrometer (TOMS) and Solar Backscatter Ultraviolet (SBUV) instruments [*Bhartia*, 2007]), and ground-based total ozone measurements including Dobson Ozone Spectrophotometers, Brewer Spectrometers, and Microtops Sun photometers [*Köhler*, 1999]. Results imply that the CAFS partial ozone column retrievals are accurate to about 3% (details and references are provided by *Petropavlovskikh et al.* [2007]).

3. MLS and CAFS Matching Criteria

[15] In order to create data sets for satellite/aircraft comparisons, we use the following method for data matching. In the following comparisons the MLS v1.5 data are used [*Livesey et al.*, 2005]. The full set of v2.2 data was not available at the time of writing. The v2.2 data include more refined data screening for cloudy scenes and improved retrieval [*Froidevaux et al.*, 2007; *Jiang et al.*, 2007; *Livesey et al.*, 2008]. We analyzed MLS v2.2 data from 6 days of the PAVE06 campaign and 3 days of the AVE05 campaign to assess changes in the MLS ozone profiles and the resulting effect on the comparisons. Analyzed data indicate about a 1% reduction in the MLS integrated ozone column values. However, the standard deviation of the differences between the MLS and CAFS partial ozone columns did not change. Therefore, we believe that the overall results presented in this paper are valid for the discussion of uncertainties in the MLS ozone column data down to 100, 147, and 216 hPa pressure levels.

[16] The following method of screening was applied prior to the data comparison. First, the satellite ozone profiles were selected within the full range of latitudes encompassing the aircraft location on the date of the flight. In order to improve the matching of atmospheric conditions observed by the two systems, the difference between the satellite and aircraft zonal locations was limited to less than 10 degrees.

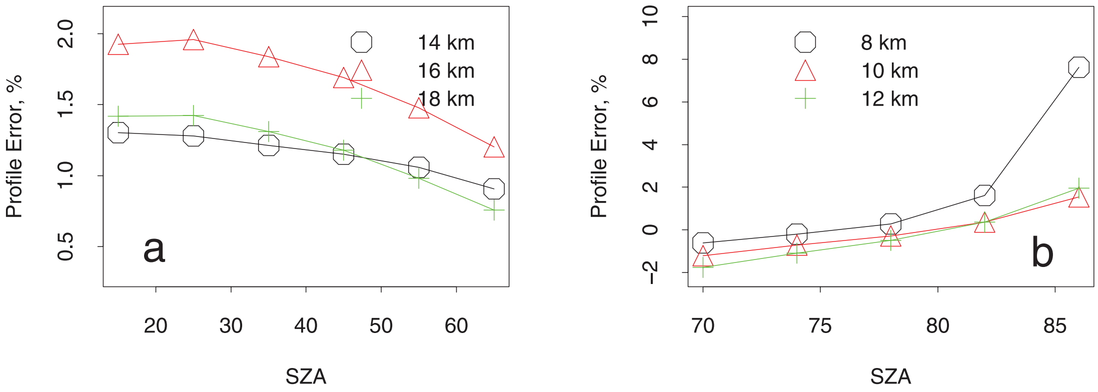

Figure 3. A sample of profile uncertainties in the retrieved charge-coupled device (CCD) Actinic Flux Spectroradiometer (CAFS) ozone columns as function of solar zenith angles (SZA) and altitude: (a) estimates for CAFS measurements with restricted field of view at 14-, 16-, and 18-km altitude, which represents the typical range of the NASA WB-57 operational altitudes during the AVE05 and CRAVE06 missions; (b) estimates for CAFS measurements with full field of view at 8-, 10-, and 12-km altitude, which represents the typical range of the NASA DC-8 in-flight altitudes during the PAVE05 campaign.

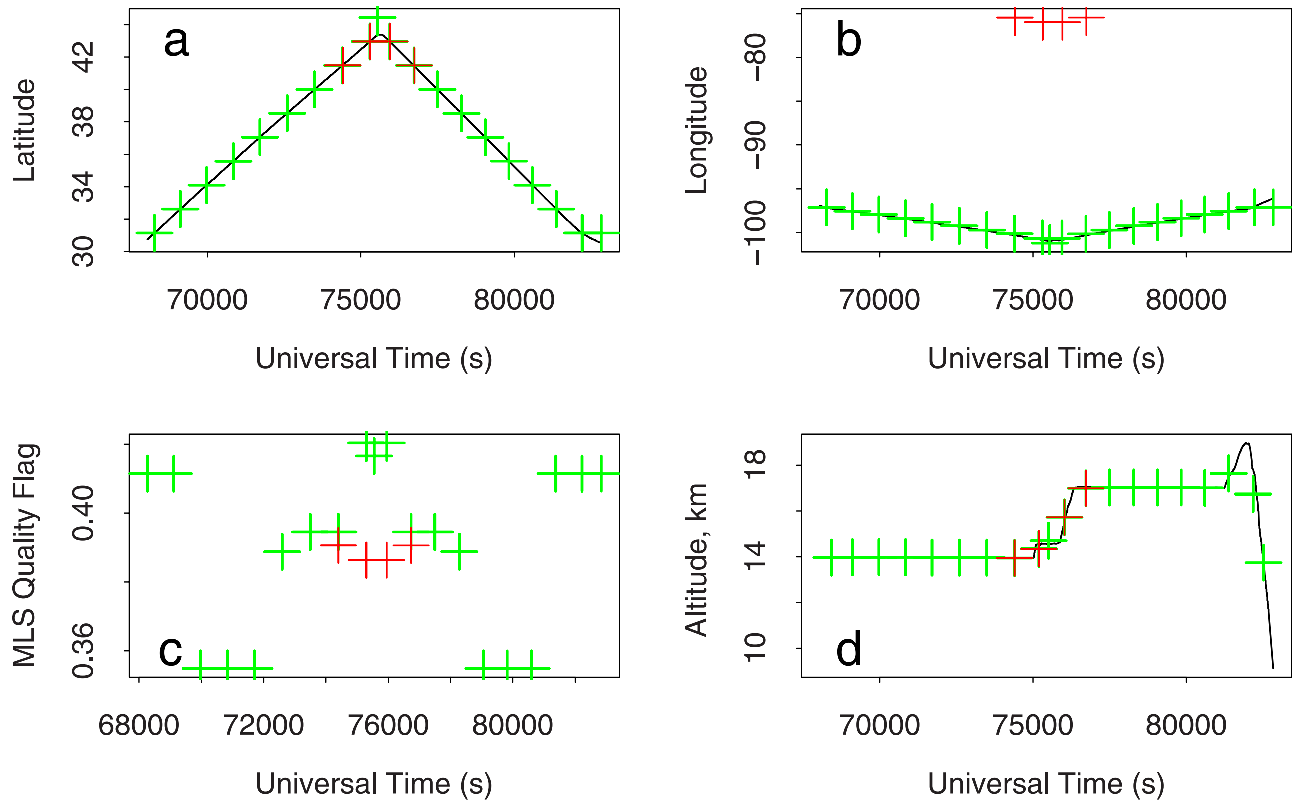

Figure 4. Selection criteria for a CAFS and the Microwave Limb Sounder (MLS) match for the 22 June 2005 AVE flight. The latitude, longitude, MLS quality flag, and altitude are given as functions of the flight time. CAFS data are shown in black, MLS data are marked as pluses, where green is used for longitude matches better than 10 degrees, and red pluses mark outliers.

The closest CAFS and MLS coincidences were used with the aircraft tracks generally very close (less than 200-km away) to the suborbital MLS tracks. In addition, the MLS profiles were screened for the MLS quality and status flags, such as the v1.5 quality values were chosen to be larger than 0.1, and the MLS status parameter was checked for clear-sky scenes and for cloudy scenes [*Livesey et al.*, 2005]. Results of MLS and CAFS ozone column comparisons over cloudy scenes are discussed in sections 4, 5, and 6. In order to account for the spatial variability of ozone across the satellite footprint, the subset of the CAFS data was averaged over the 250-km flight distance centered at the matching satellite's latitude, and the CAFS data were limited to less than a 1-km change in aircraft altitude. Both pitch and roll of the aircraft can alter the measured actinic flux by changing angular contribution of the scattered light in the instrument field of view in the way that is not accounted for in the lookup tables. Therefore, the CAFS data were screened for the aircraft's pitch and roll registration of less than 2 degrees to minimize errors of the CAFS ozone retrieval. Finally, the selected satellite profiles were integrated above the averaged pressure level, which was calculated from the matched subset of CAFS aircraft data.

[17] Figure 4 shows several parameters used in the matching selection for the 22 June 2005 AVE flight. The black lines in Figures 4a and 4b represent changes of the aircraft's latitude (Figure 4a) and longitude (Figure 4b) registration as a function of time. The crosses indicate matching locations of the MLS profiles, where green and red indicate the location of the MLS profile within or outside of the longitude matching criteria (closer then ten degrees of longitude). Figure 4c provides information on the MLS quality flag as function of time. Figure 4d indicates changes in the altitude of the aircraft with time. The same matching method is applied to all campaigns.

4. PAVE 2005 Campaign

[18] During the PAVE05 campaign, a total of eight science flights were carried out by the NASA DC-8 aircraft flying at altitudes of 12 km and below, and primarily under low-Sun and high ozone variability conditions that are characteristic of Arctic polar vortex conditions. The satellite/aircraft matching criteria for the PAVE campaign proved to be of great importance. The results of comparisons were highly sensitive to the sampling criteria due to high variability in the ozone field along the aircraft track. Figure 5 shows the spatial and temporal variability in the ozone column derived from the CAFS measurements taken mainly at about 200 hPa pressure or 11-km altitude level (scaled data, shown as the magenta line) during the DC-8 flight on 29 January 2005. The CAFS data are shown in black with the CAFS. Two sets of blue lines represent the combined uncertainties in the retrieved CAFS ozone column due to the measurement noise and the retrieval model assumption. Retrieval uncertainties are due to sensitivity of the retrieval

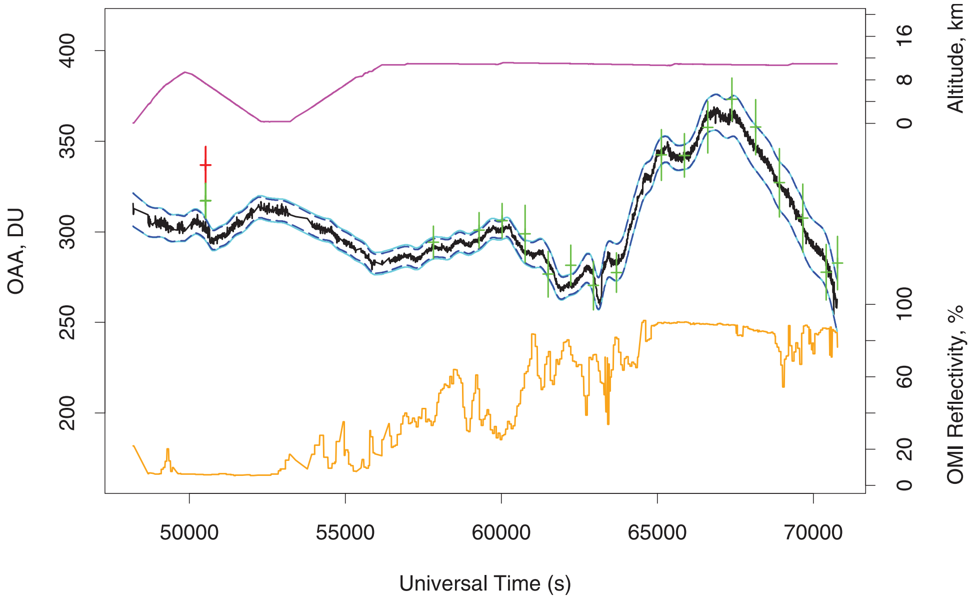

Figure 5. Time series of the ozone column integrated above aircraft altitude (OAA) (magenta line) of the DC-8 flight on 29 January 2005. The CAFS data are shown by a black line, the typical CAFS ozone retrieval uncertainty over a dark surface is shown by a dark blue dashed line, while the CAFS retrieval uncertainty in the presence of bright surfaces is shown by a light blue solid line. Vertical green lines mark coincidental MLS ozone columns above the pressure of the aircraft. The magenta line provides reference for relative altitude changes during the flight, while the yellow line shows Ozone Monitoring Instrument (OMI) Total Ozone Mapping Spectrometer (TOMS) derived reflectivity at 360 nm (both scales are shown on the right side of the plot).

to the interpolation of the lookup tables to the aircraft altitude and corresponding SZA, the interference from underlying clouds and aerosols, assumptions of the vertical ozone distribution and constant surface albedo, the choice of the temperature profile and the absorption cross section for the ozone column retrieval. These uncertainties are summarized by *Petropavlovskikh et al.* [2007, Table 3]. The vertical ozone distribution uncertainties are recalculated by applying the averaging kernel matrix to the difference between the CAFS model ozone profile and the coincident MLS retrieved ozone profile. After interpolation to the altitude and SZA of the CAFS measurement the combined uncertainty is calculated as the root mean square of individual uncertainties. The dark blue dashed line in Figures 5, 7, and 9 represents CAFS retrieval uncertainties over scenes with low reflectivity, while the light blue solid line represent uncertainties for measurements over bright surfaces (high reflectivity). The latter could be considered as the upper limit of CAFS ozone retrieval uncertainties in the presence of clouds or over snow covered surface. The surface reflectivity data derived from the OMI backscatter measurements at the 360 nm wavelength channel provide reference to the selection of the lower (dark blue dashed line) or upper (light blue solid line) CAFS uncertainty limit for corresponding lower- or higher-reflectivity scenes. The OMI data are coincident with the CAFS airborne measurements in latitude and longitude domain, but not necessarily coincident in time domain (i.e., during the PAVE05 campaign the difference between the beginning of the DC-8 flight and the OMI overpass orbit was as much as 5 h).Vertical green lines mark coincident MLS ozone column using the MLS profiles integrated above the aircraft flight pressure. The estimated precision for individual MLS column ozone values down to pressures of 100 to 215 hPa is 3%, and the estimated accuracy is 4%, based on the analyses by *Froidevaux et al.* [2007]. The length of the vertical bars in Figure 5 (and in Figures 7 and 9) represents 4% accuracy estimate for the MLS data. Figure 6 presents a summary of comparisons between the matched CAFS and MLS data for six flights during the PAVE05 campaign (27, 29, 31 January and 3, 5, 7 February). The limitation of coincidence to less than 10 degrees in longitude separation and less than 1-km flight altitude variability provides the bias of 2%. Considering the large range of ozone columns encountered during the campaign and the unfavorable choice of SZAs for the CAFS retrieval, these results can be interpreted as an overall good agreement between two systems, within 5% of uncertainty (one standard deviation). (The 5% value is calculated as a square root of combined uncertainty of the MLS ozone column (4%) and the CAFS ozone column (3%)).

5. AVE 2005 Campaign

[19] Prior to the June 2005 AVE campaign; the CAFS design was modified to reduce sensitivity to the variability of the scattered light over an inhomogeneous background. As a result, CAFS observations became more sensitive to the aircraft roll and pitch movements. Therefore, all CAFS data were screened to eliminate ozone retrievals whenever the aircraft's pitch or roll angles were in excess of 2 degrees. During the AVE 2005 campaign out of Houston, Texas, a

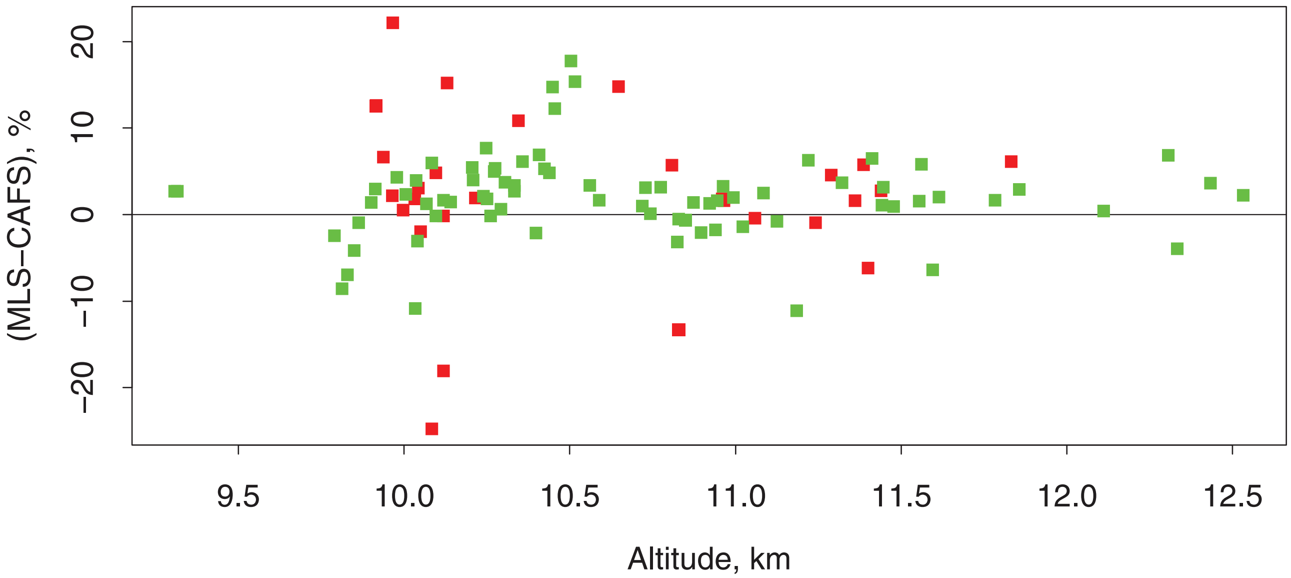

Figure 6. A 6-day summary of comparisons between colocated CAFS and MLS partial ozone columns during Polar AVE campaign in 2005. A difference between the matched MLS and CAFS partial ozone columns is shown as a function of altitude. The green symbols mark subset of data selected by limitations of the WB-57 altitude variations to less than 1 km, zonal location match to better than 10 degrees, and MLS status of no clouds, whereas the rest of the data (not matching the criteria) are marked with red.

total of seven flights were carried out over midlatitudes, with a range of flight altitude between 12 and 18 km. Figure 7 demonstrates results of the ozone column time series derived from the CAFS measurements (black lines) during the flight on 22 June 2005. The flight was tracking the MLS footprints between 29 and 43 degrees of northern latitude and between approximately 96 and 101 degrees of western longitude. Moreover, the aircraft flight path on the way back to the airport in Houston, Texas, was retracing the outbound flight path, but at higher altitude (17 km versus 14 km for the outbound flight). In addition, the reduction of the ozone column above the aircraft following the change of latitude (from 30 to 20 degrees north) can be seen in the first half of the time series shown in Figure 7. Profile sensitivity errors

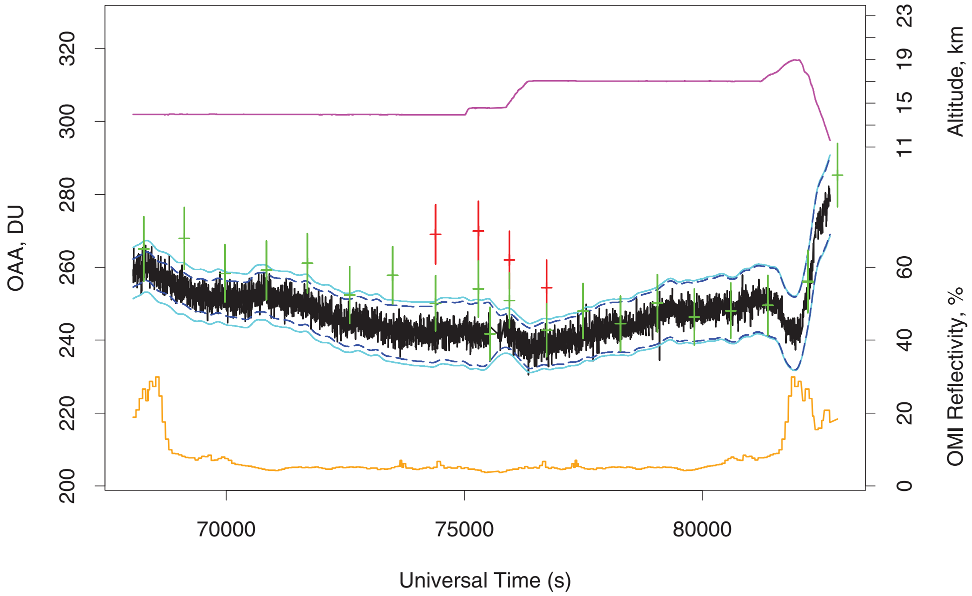

Figure 7. The same as Figure 5, but for the NASA WB-57 flight on 22 June 2005 during the AVE05 campaign. Vertical red (outside of 10 degrees) and green (within 10 degrees in longitude collocation) lines mark coincidental MLS ozone profiles integrated above pressure of the colocated aircraft measurement.

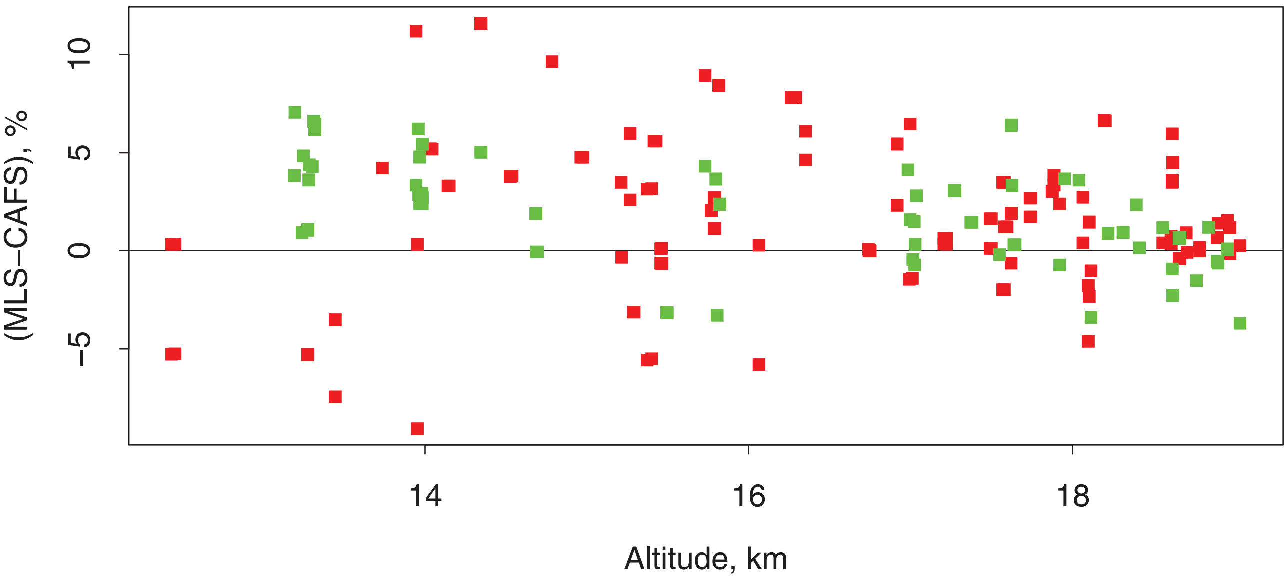

Figure 8. The same as Figure 6, but for a 7-day summary of comparisons between the colocated CAFS and MLS partial ozone columns taken during the Houston AVE campaign in 2005. The partial ozone columns are calculated above the altitude levels shown on the *x* axis.

for this flight were estimated to be less than 2% (blue lines above and below black lines). The matching MLS data are shown as small horizontal bars crossed by long vertical lines that represent the estimates of 3% precision for MLS ozone retrievals at altitudes below 100 hPa [*Froidevaux et al.*, 2007]. Green (red) indicates less (more) than 10 degrees difference in zonal colocations of the CAFS and MLS measurements. Comparisons of the MLS and CAFS ozone data estimate a mean bias of about 2% across the full latitude and altitude range of the flight.

[20] The AVE 2005 campaign determined that the overall agreement between the MLS and CAFS matching data was at the 2% level for biases, with a standard deviation of 2%. Results are based on the total of 298 matches found between coincident MLS ozone profiles and CAFS ozone columns. An examination of Figure 8 indicates that the prevailing altitude for the matching criteria is between 17 and 19 km (or above 100 hPa pressure level), the mean bias between the matched MLS and CAFS integrated ozone columns is less than 1%, and the variability in the data is about 2% (standard deviation). For altitudes between 15 and 17 km (or 146 and 100 hPa atmospheric pressure, respectively) the average bias is about 2.5% with less than 4% standard deviation. However, additional screening of the MLS data for presence of clouds (cloud at low altitude, marked in the MLS data file as status 34) reduces the bias to about 1%. On the other hand, analysis of a subset of the matching data at altitudes below 15 km (or below 146 hPa pressure level) indicates a bias less than 3%, while approximately 2.5% standard deviation could be associated with spatial variability observed in the data. Regrettably, very few matching points were found at altitudes below 12 km (or below 216 hPa pressure), which is insufficient to yield a statistically significant result. Thus, we cannot make any conclusion about the MLS accuracy at these altitudes. A small (less than 2%) increase in the CAFS retrieved ozone related to the underlying cloud was observed during some flights. The Averaging Kernel (AK) analysis [*Rodgers*, 2000] has shown a reduced sensitivity to horizontal ozone variability along the flight track as compared to the previous campaign.

6. CRAVE 2006 Campaign

[21] The CAFS instrument was flown onboard the WB-57 aircraft during the CRAVE 2006 campaign. The instrument was calibrated and prepared in the laboratory before installation on the WB-57 in Houston, Texas, in early January 2006. After instrument test flights, the WB-57 flew a transit to San Jose, Costa Rica on 14 January 2006. From 17 January 2006 to 7 February 2006, fourteen science flights were performed. The CAFS instruments collected data on all of the flights. Ozone column above the aircraft level was retrieved using the algorithm described by *Petropavlovskikh et al.* [2007]. During the CRAVE06 campaign partial ozone columns, primarily above 18 km, were derived from the CAFS observations, under a variety of Sun elevation and low ozone variability conditions over the tropical region, and with flights sometimes over cloud formations. The modified CAFS optical design was implemented to reduce sensitivity to the variability of scattered light over inhomogeneous background after the June 2005 AVE campaign.

[22] The aircraft spent a great deal of time in the coldest region of the atmosphere during the science flights and the instruments had a difficult time maintaining a consistent temperature. Instrument calibrations were performed at different temperatures on the ground in the field in an attempt to determine the wavelength and spectral response of calibration temperature shifts during the mission. Final calibrations were performed over a wide range of conditions in the laboratory at NCAR after the deployment to further study the temperature effects on the instrument response. This testing led to some small corrections in the wavelength assignment and spectral response of the instruments. These

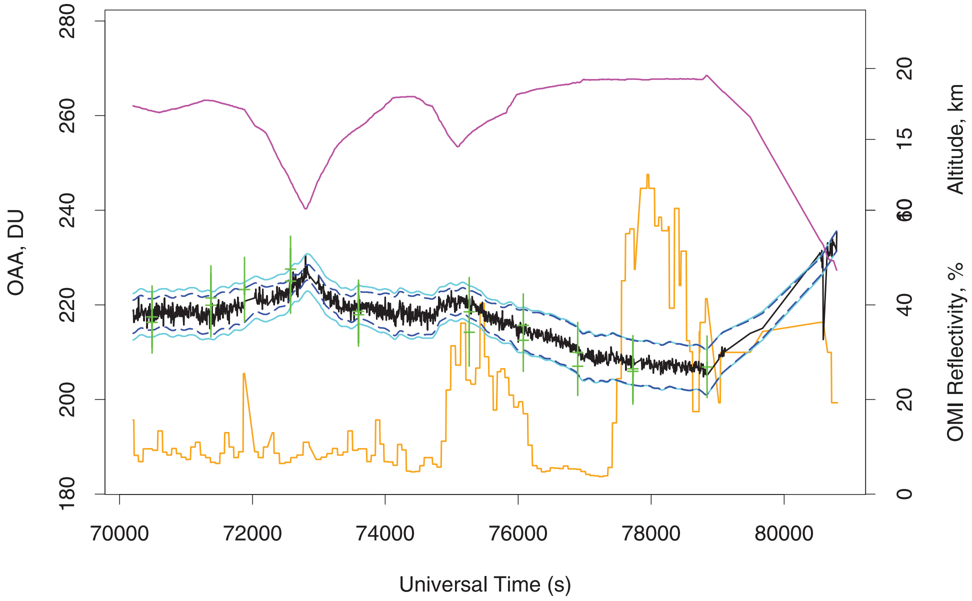

Figure 9. The same as Figure 5, but for the CAFS ozone retrievals on 22 January 2006 during the CRAVE06 campaign.

corrections to the actinic flux values were applied, the data were reprocessed and the corrected ozone column values were resubmitted for archiving [*Petropavlovskikh et al.*, 2007; S. Hall, manuscript in preparation, 2008].

[23] The CAFS ozone retrievals on 17 January 2006 were referenced against auxiliary ozone measured in Costa Rica by other colocated instruments. The reference for the CAFS data was derived as a difference between the total ozone column above the surface measured at San Jose airport by the handheld Microtops instrument (cross-referenced against Dobson instrument in Boulder, CO) and the ozonesonde profile integrated below the aircraft level, while the balloon was launched at the time of the WB-57 flight over San Jose airport. Multiple pairwise measurements were carried out through the rest of the CRAVE campaign to monitor the quality of the CAFS measurements [*Petropavlovskikh et al.*, 2007]. Comparisons between CAFS ozone columns above ~19-km altitude and combined Microtops-sonde references show the mean bias of less than 1% with the standard deviation of about 3%, whereas the overall variability of the CAFS retrieved ozone along the satellite track is less than 1%.

[24] An example of the Aura validation is shown in Figure 9, where the CAFS retrieved ozone above the aircraft level is plotted as function of time (black line). The MLS profiles are selected to match the WB-57 geolocation. To compare against CAFS data, the MLS profiles are integrated above the mean altitude of the WB-57 aircraft which is determined for each coincident profile. The MLS data are shown as green vertical lines that represent the 3% standard deviation errors [*Froidevaux et al.*, 2007]. The agreement between the MLS and CAFS data is within a few percent.

[25] The summary of comparisons for 6 days in January 2006 during the CRAVE campaign is shown in Figure 10. Results are based on the total of 141 matches found between coincident MLS ozone profiles and CAFS ozone columns. An analysis of these comparisons found no significant differences between the MLS and CAFS integrated ozone columns at flight altitudes between 17 and 20 km (or above 100 hPa pressure level). In addition, a standard deviation of 1.5% was found for the matched data. At flight altitudes between 15 and 17 km (or 146 and 100 hPa atmospheric pressure, respectively) the average bias was less than 1% with less than 1% standard deviation. The analysis of the matched data at altitudes below 15 km (or below 146 hPa pressure level) indicated less than 1% bias between the MLS and CAFS ozone columns. The analysis of the data over entire range of altitude between 13 and 19 km shows that the agreement between the two systems is within 3% (two standard deviation level). In addition to the limit of less than 10 degrees longitude difference in matched data sets, screening of the MLS data retrieved in the presence of the underlying clouds (low altitude, status 34) was applied; however it had no effect on the results. Regrettably, very few matching points were found at altitudes below 12 km (or below 216 hPa pressure) which were insufficient to yield a statistically significant result, thus, we cannot make any conclusion about the MLS accuracy at these altitudes.

7. Discussion and Conclusions

[26] In this work, the CAFS measurements were used to derive partial ozone column data above the aircraft altitude. These results are important in helping to validate MLS stratospheric column values, as these can be used [e.g., *Ziemke et al.*, 2006] to study tropospheric ozone residual columns, by differencing from the OMI total ozone. As well, column validation using sondes does not cover the total ozone overburden, while the aircraft data provide a good opportunity for colocated measurements in space (along the MLS suborbital track) and to some extent, in time. In addition, the CAFS ozone column is derived at different pressure levels, and thus indirectly validates the upper tropospheric and lower stratospheric ozone values.

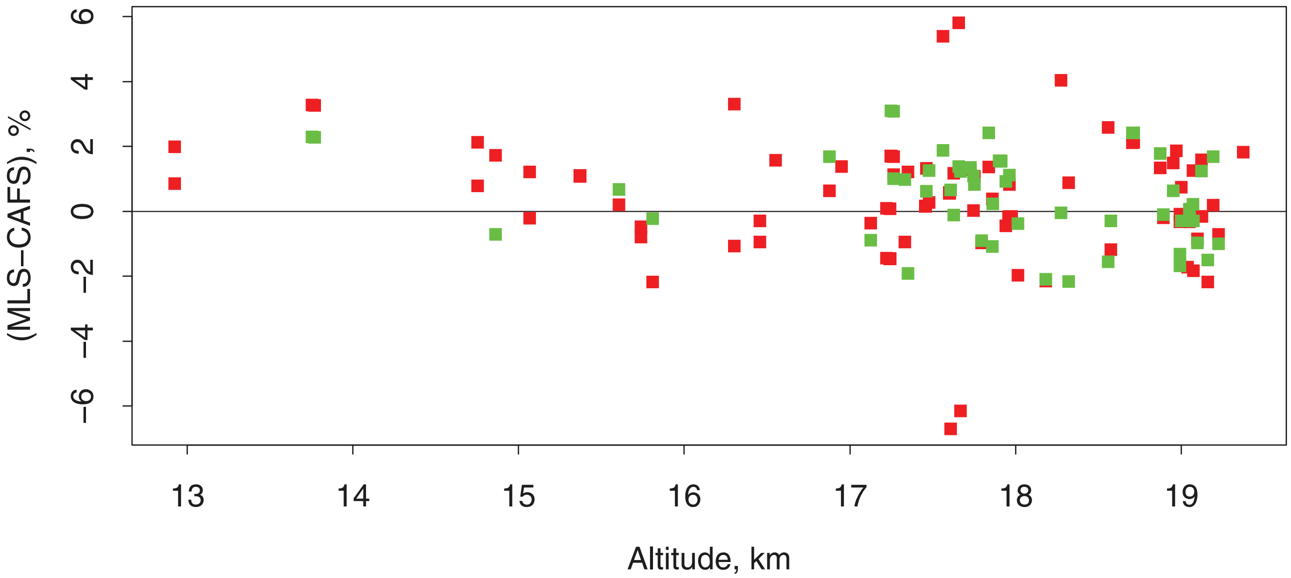

Figure 10. The same as Figure 6, but for a 6-day summary of comparisons between the colocated CAFS and MLS partial ozone columns taken during the CRAVE campaign in 2006. The partial ozone columns are calculated above the altitude levels shown on the x axis.

[27] The CAFS-derived information on variability of ozone column along the longitude/latitude tracks of the aircraft was regularly provided for the Aura satellite instrument validation activities. The CAFS derived ozone data supported the reevaluation of the MLS ozone column uncertainties at 100 hPa levels and below. The results of three validation campaign discussed in the paper (see summary in Table 1) imply that the MLS and CAFS ozone columns down to 100 hPa pressure levels agree to better than 3%, while for columns down to 215 hPa pressure level the agreement is better than 5%. Furthermore, the MLS and CAFS data appear tracking each other very well over a wide range of atmospheric conditions, while an overall excellent agreement is found within the combined uncertainties of the two data sets.

[28] The MLS and CAFS data comparisons were accomplished over the high, middle, and low northern latitudes, and during the summer and winter time periods. Results from the three AVE campaigns discussed in this paper addressed spatial and temporal variability of the MLS retrieved ozone data. The PAVE05 campaign results helped to define accuracy of the MLS retrieved data over the northern polar region and over the bright surfaces. The AVE05 campaign concentrated on ozone column measurements over the middle latitudes and during the summer months. And finally, the CRAVE06 mission addressed the accuracy of the MLS stratospheric column data over the tropical latitudes and under the cold tropopause conditions. Table 1 summarizes results of three campaigns. The differences between campaigns are related to the spatial and temporal variability of the stratospheric ozone column. Results of comparisons were based on the MLS v1.5 data, and revealed, on average, a small bias between the two systems of about 2% at 146 hPa level or 3% at 215 hPa. On the other hand, for MLS v2.2 data, the bias was reduced by roughly 1%.

[29] Analysis of the scatter between the MLS and CAFS matched ozone data helps to confirm MLS ozone column precision estimates. Assuming that 1.5% is the best estimate of the random error for the CAFS column retrievals, the combined expected precision for both MLS (3%) and CAFS (1.5%) data is about 3.5%. From analysis for the PAVE05 campaign, about 5% standard deviation between the MLS and CAFS matched data is found. It could mean that there is a small additional component (of the order of 4 or 5%) coming from the atmospheric variability affecting the MLS and CAFS measurements in different ways, possibly largely because of temporal differences between the fast satellite overpass and the much longer aircraft flight. For that reason, the CAFS ozone column data set from 31 January 2005 was analyzed for temporal changes. It happened that two sections of the NASA DC-8 flight were flown over the same latitude (65.0–67.3°N) and longitude (89.5 and 86.5°W) range, but about 3 h apart. At the same time, in both sections, the aircraft altitude remained mostly unchanged at about 10.4 km. Results of comparisons indicate that the CAFS retrieved ozone column was changed by about 5%

Table 1. Summary of MLS and CAFS Partial Ozone Comparisons From Three AVE Campaigns[a]

	Bias and 1 Standard Deviation, Percent		
Aircraft Pressure Level, hPa	P-AVE, 2005	AVE, 2005	CRAVE, 2006
<100	N/A	<1 (2.2)	∼0 (1.5)
$100 < P < 146$	N/A	1 (3.2)	<1 (1.0)
>146	2 (5)	3 (1.8)	<1 (3.0)

[a] Results are separated in three groups on the basis of nominal Microwave Limb Sounder (MLS) pressure levels (indicated in the left column). The mean bias and standard deviation, in percent, are given relative to the averaged charge-coupled device (CCD) Actinic Flux Spectroradiometer (CAFS) ozone column above the aircraft pressure level.

over ~3-h flight period. Thus, the 5% standard deviation that was found in the matched CAFS and MLS ozone column data comparisons during the PAVE05 campaign is likely attributed to the time-dependent ozone variability.

[30] In the case of the AVE05 or CRAVE 06 campaigns, the standard deviation of the MLS and CAFS differences was about 3%. This result shows that the scatter between the MLS and CAFS data sets is very close to the combined estimated precision (which mostly comes from 3% estimate for the MLS column precision). Thus, it confirms that the MLS column precision is not larger than 3%, as additional perturbations arising from sampling differences would tend to add more scatter.

[31] The CAFS measurements will continue to provide validation for the MLS integrated ozone columns during the future AVE campaigns. An opportunity to validate the lower part of the MLS ozone profile in the scenes with high- and low-altitude clouds should be explored. This goal can be accomplished with the help of the CAFS data taken at different altitudes in flights over clouds.

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