Results from the 1995 Stratospheric Ozone Profile Intercomparison at Mauna Loa (MLO3)

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Abstract. In August 1995 multiple instruments that measure the stratospheric ozone vertical distribution were intercompared at the Mauna Loa Observatory, Hawaii, under the auspices of the Network for the Detection of Stratospheric Change. The instruments included two UV lidar systems, one from JPL and the other from Goddard Space Flight Center, ECC balloon-sondes, a ground-based microwave instrument, Umkehr measurements, and a new ground-based FTIR instrument. The MLS instrument on the UARS satellite provided correlative profiles of ozone, and there was one close overpass of the SAGE II instrument. The results show that much better consistency among instruments is being achieved than even a few years ago, usually to within the instrument uncertainties. The different measurement techniques in this comparison agree to within ±10% at almost all altitudes, and in the 20 km to 45 km region most agreed within ±5%. The results show that the current generation of lidars are capable of accurate measurement of the ozone profile to a maximum altitude of 50 km. SAGE agreed well with both lidar and balloon-sonde down to at least 17 km. The ground-based microwave measurement agreed with other measurements from 22 km to above 50 km. One minor source of disagreement continues to be the pressure-altitude conversion needed to compare a measurement of ozone density versus altitude with a measurement of ozone mixing ratio versus pressure.

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1. Introduction

Significant changes in total column ozone have been documented [*Stolarski et al.*, 1991, *WMO*, 1995], but there is an open question as to the altitude at which the changes are occurring. Through a program of systematic comparison and intercalibration, the ground-based and satellite-based measurements of total column ozone have been brought into basic agreement, usually to within 2-3%. The measurement of the ozone vertical distribution is much more uncertain, with disagreements of 10% to 30% or more [*SPARC*, 1998]. In order to clearly establish the altitude dependence of ozone change, the profile measurement techniques need to be brought into agreement through a series of intercomparisons. Such intercomparisons are being supported by the Network for the Detection of Stratospheric Change (NDSC), which is charged with monitoring long term changes in stratospheric ozone and in the species that control ozone.

In the 1995 NDSC Stratospheric Ozone Profile Intercomparison at Mauna Loa (MLO3), a number of different instruments were compared at the Mauna Loa Observatory, hereafter referred to as MLO, on Hawaii (19.5°N latitude, 155.6°W longitude, 3.4 km above mean sea level). The purpose of MLO3 is to provide data to assess the capabilities and to check the consistency of the participating instruments in determining ozone profiles. The comparison was done as a blind intercomparison following the protocol established by the NDSC. The campaign was under the control of an impartial referee who was responsible for handling all the data so that, as far as possible, the participants did not see each other's results during the campaign. The measurement period began on August 15th of 1995, and ended on September 1st. The final processed data for every instrument were submitted to the referee within one month of the end of the campaign. MLO3 was a follow-up to the OPAL intercomparison [*McDermid et al.*, 1998] which was done at Lauder, New Zealand in April of 1995, and to the STOIC comparison held at Table Mountain in 1989 [*Margitan et al.*, 1995]. Lauder is the primary NDSC site for monitoring the stratosphere at southern mid-latitudes, while Mauna Loa is the primary NDSC site for the tropics and sub-tropics.
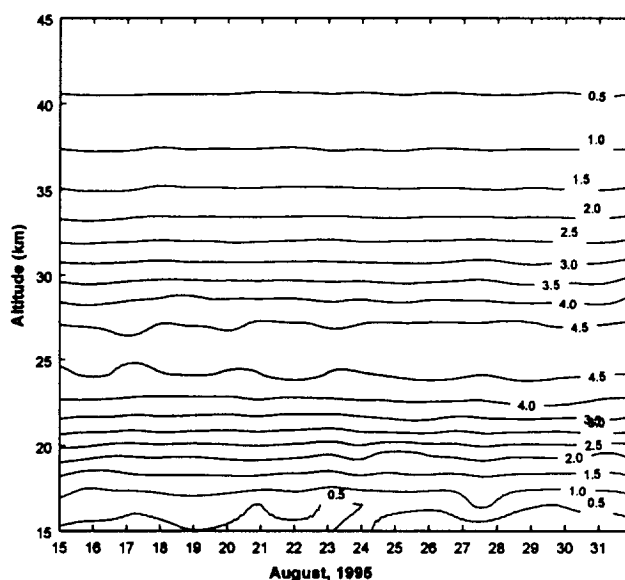

Figure 1 Ozone variability during the MLO3 comparison as observed by lidar. Ozone number density (x10^{12} molecules / cm^3) is plotted as a function of altitude and time.

Mauna Loa was chosen as the intercomparison site because it is a very clean, low aerosol marine environment, and because ozone variability is very low in the sub-tropics (see Figure 1). Low variability minimizes the uncertainty caused by the fact that not exactly the same air volume is measured by every instrument.

2. The Measurement Systems

Information on the participants and the measurements is given in Table 1. Two UV lidar systems, one from JPL and the other from Goddard Space Flight Center, measure ozone number density as a function of altitude from 15 km to above 50 km altitude. Since lidar promises to be an important technique for long term monitoring of ozone in the future, the performance of the lidar systems was of particular interest. ECC balloon-sondes, including several "triples", were flown daily to obtain profiles of ozone partial pressure along with pressure and temperature from the ground to above 35 km. The Millitech/Langley Research Center microwave radiometer measures ozone mixing ratio as a function of pressure from 56 mb to 0.1 mb. Dobson instruments provided daily measurements of total column ozone and were used to make Umkehr measurements of the ozone profile. The Microwave Limb Sounder (MLS) instrument on the Upper Atmosphere Research Satellite (UARS) provided correlative profiles of ozone mixing ratio versus pressure between 100 mb and 0.2 mb. One close overpass of SAGE II on August 30th provided an ozone number density profile from 15 km to 55 km. A few measurements were obtained from a prototype infrared Fourier transform (FTIR) instrument being developed at the University of Denver.

While measurements were taken by the SBUV/2 instrument on NOAA 14 during MLO3, the results have not been used in this comparison. NOAA 14 had only been launched that spring, and the failure of the cloud cover radiometer on SBUV/2 led to a mode change during MLO3. Questions about the initial calibration plus uncertainty about the mode change led to the decision not to include these data in this comparison. Data from HALOE, also on UARS, would have been a valuable addition to the comparison, but unfortunately the instrument was not operating during this two week period.

Table 1. Participants in MLO3. Measurements are ozone number density (ND) versus altitude, or ozone mixing ratio (MR) versus pressure. Altitude range and reporting interval are given.

Instrument	participants	measurement
Goddard lidar	T. McGee M. Gross	O_3 ND vs altitude 14 - 50 km @ 0.15 km
JPL lidar	S. McDermid	O_3 ND vs altitude 14 - 50 km @ 0.3 km
Ozonesondes	D. Hofmann B. Johnson	O_3 MR vs pressure temperature vs pressure 0 - 35 km @ 0.15 km
Microwave Radiometer	J.J. Tsou B. Connor A. Parrish	O_3 MR vs pressure 20 - 65 km @ ~2 km
Umkehr	G. Koenig S. Oltmans	O_3 MR vs pressure 15 - 43 km @ ~5 km
FTIR	F. Murcray	O_3 MR vs pressure 5 - 32 km @ ~4 km
MLS	L. Froidevaux	O_3 MR vs pressure 18 - 60 km @ ~2.5 km
SAGE II	J.M. Zawodny	O_3 ND vs altitude 11 - 56 km @ 1 km
Dobson	M. Clark S. Oltmans	total column O_3

The JPL Differential Absorption Lidar

The JPL differential absorption lidar (DIAL) system [*McDermid et al.*, 1995] consists of a 100 W, narrow-bandwidth, tunable, XeCl excimer laser providing a main beam at 307.9 nm. The reference wavelength at 353.2 nm is generated by stimulated Raman shifting of a portion of the main beam in a 400 psig hydrogen cell. The two beams are transmitted simultaneously, and the backscattered radiation is collected with a 90-cm telescope and measured using photon-counting techniques. To extend the dynamic range of the system (and the altitude range of the retrieved profile) the signal is further divided in the ratio 100:1 and directed through separate detection chains. The high intensity data are used to obtain the high altitude part of the profile, while the low intensity data are used for the lower altitudes. A composite ozone profile is created by combining the high altitude and low altitude profiles.

The JPL lidar data were collected on 17 nights between sunset and midnight with integration times of one to two hours. A typical measurement is integrated for 10^6 shots. Because of the possibility of interference between the two very similar lidar systems (which were located within 10 meters of each other) the GSFC and JPL lidar systems were operated in sequence each night, alternating early and late shifts. The intrinsic measurement is of ozone number density as a function of altitude. Data were provided for each 0.3 km, usually from 14 to 52 km (see Figure 3). The error estimate associated with each profile is obtained from counting statistics of the 10^6 shots on a given evening.

An ozone profile of mixing ratio versus pressure was also computed from the lidar data by using NCEP data and model climatological data. The conversions provided by the experimenter used pressure and temperature data versus geopotential height instead of geometric height. The difference is quite small, but in order to obtain consistent conversions for this comparison, we have converted the height versus number density profiles in the original data files by using the NCEP temperature and pressure data versus geometric height. These profiles are used in this paper when JPL lidar profile data are given versus pressure.

The Goddard Differential Absorption Lidar

The GSFC lidar [*McGee et al.*, 1991, and *McGee et al.*, 1995] is very similar to the JPL lidar. It also uses a XeCl excimer laser to produce a main beam at 307.9 nm, but the reference beam at 355 nm is produced using the third harmonic of a Nd:YAG laser. Both lasers operate at 66Hz. Backscattered light is collected by using a 76 cm telescope, separated by dichroic optics, and measured by photomultiplier tubes in photon-counting mode. Data are recorded for six channels in 1-ms bins. The backscattered beams at 307.9 and 355 nm are each split into high-intensity/low-intensity channels, with a 96%/4% split for the 308 channel and a 90%/10% split for the 355 channel. The two weaker beams are used to derive the lower altitude profile and the two stronger to derive the upper profile. The two remaining channels measure the N_2 Raman shifted backscatter at 332 and 382 nm (shifted from 307.9 and 355 nm, respectively). These last two channels' measurements can be used to correct for the effects of Mie scattering by aerosols [*McGee et al.*, 1993]. Details of the ozone retrieval are presented in *McGee et al.* [1991]. A typical measurement is integrated for 10^6 shots and takes less than two hours.

The GSFC lidar data were collected on 16 of the 18 possible nights. The native form of the measurement is number density versus height. Data were provided for each 0.15 km, usually from 15 to 50 km. The actual range resolution varies with altitude, from 1.2 km near 20 km to 6.75 km near 45 km. The GSFC lidar has a less powerful laser and a smaller telescope than the JPL system and consequently is somewhat noisier near the upper altitude limit. The conversion to mixing ratio versus pressure was obtained by using NCEP temperature and pressure data. The standard deviation estimates in the data files are obtained from counting statistics.

ECC Ozonesondes

Balloonsondes were launched each evening from the Hilo Airport, which is approximately 60 km east of Mauna Loa observatory. The prevailing winds are from the NE, so the flight

paths of the balloons tended to be toward MLO. The balloonsondes were launched just after sunset in order to be nearly coincident with the laser measurements. The flight times were about two hours with ascent rates of 6 m/s.

The balloonsondes were standard electrochemical concentration cell (ECC) ozonesondes coupled to Vaisala meteorological radiosondes that measure temperature, pressure, and humidity as the balloon ascends. The ECC devices are described in detail in *Komhyr et al.* [1995]. During operation, sampled air is pumped through a 1% potassium iodide solution, where ozone reacts to form iodine (I_2), which changes the current across the cell. The current due to ozone, the pump efficiency, the pump temperature, and the external temperature are combined to derive estimates of ozone number densities. The pump efficiency correction factor, which is critical to accuracy above 25 km, was determined empirically for each ECC sonde. Ozone mixing ratio as a function of pressure can be derived directly from measured quantities. The integrated column ozone is compared with Dobson as a quality check, but no normalization is done. Data were reported for each 0.15 km, and the maximum altitude for the ozone profile was usually around 35 km, except for the August 20th flight which only reached 24 km. The altitudes provided with the balloon data were geopotential heights. The measured temperature and pressure data were used to determine geopotential height versus pressure. These were converted to geometric heights before intercomparison with lidar and other data.

Five of the 16 flights were triple EEC flights - on August 15, 19, 22, and 30, and on September 1st. On these flights three complete ECC packages were flown on a single balloon in order to check the consistency of the sensors. It was found that the consistency averaged better than 2% as shown in Figure 2. Occasionally one channel would deviate from the other two by several percent for a few minutes (near 12 km on this flight) but then would return to agreement. Only a single set of ozone values was used for each triple flight.
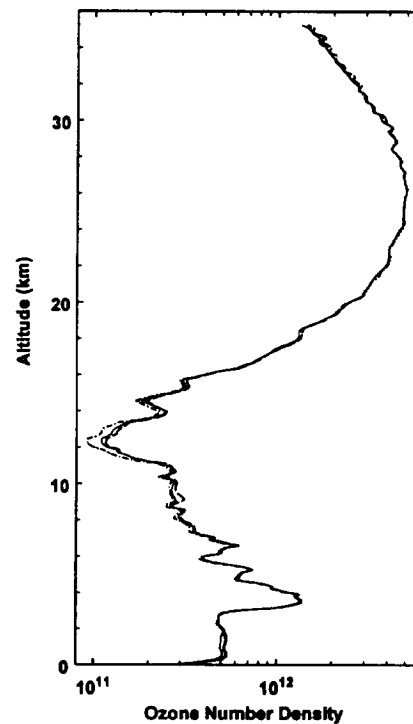

Figure 2 The result of flying 3 ECC packages on a single balloon on September 1.

Microwave Radiometer

The Millitech/LaRC microwave instrument consists of an automated microwave receiver and a 120-channel spectrometer tuned to the ozone transition at 110.836 GHz [*Parrish et al.*, 1992]. The raw data consist of ratios of the power incident from two viewing directions, one from near zenith and one from an elevation of 10° to 25°. The ozone profile is retrieved from

details of the pressure-broadened line shapes. The retrieval algorithm is discussed in *Parrish et al.* [1992] and an error analysis is presented in *Connor et al.* [1995] and *Tsou et al.* [1995]. The results of the microwave instrument measurements were provided in two data files per day for the 18 days of the intercomparison - one an average of the daytime measurements and one an average of the nighttime measurements. Comparisons made here use the nighttime measurements as a slightly better match in time of observation for the lidar and balloon profiles. Profiles of ozone mixing ratio versus pressure are derived from 56 mbar to 0.1 mbar at 23 pressure levels. The measurements were integrated for 9 hours for the nighttime measurements except on the 19th, 23rd and 24th when only 3 hours of measurements were available. NCEP data are used to convert the mixing ratio versus pressure profiles to number density versus height.

Dobson and Umkehr Measurements

Measurements from two Dobson instruments, the Mauna Loa station instrument #76 and the World Standard Dobson instrument #83, were used to compute total column ozone and Umkehr profiles during MLO3. A Dobson spectrometer normally derives total column ozone from the AD wavelengths - wavelength pairs A (305.0/325.0 nm), and D (317.5/339.9 nm). For the traditional Umkehr retrieval of an ozone profile, the C-pair (311.5/332.4 nm) is used and zenith sky measurements are made for a series of solar zenith angles (60°, 65°, 70°, 74°, 77°, 80°, 83°, 85°, 86.5°, 88°, 89°, and 90°). The measurements may be made during either sunrise or sunset. The scattering contribution function peaks at an altitude that depends on the product of the ozone cross section times the optical path. For an Umkehr retrieval, varying optical path (solar zenith angle) provides the altitude scan. The measurements are used in a maximum likelihood retrieval algorithm [*Mateer and DeLuisi*, 1992] to estimate ozone mixing ratio versus pressure. The Umkehr retrieval produces layer ozone amounts as a function of pressure for layers that increase by exactly a factor of 2 in pressure. The Umkehr retrieval is considered to provide good information in Umkehr layers 4 through 8 (from 64 mbar up to 2 mbar). A spline interpolation is used to obtain mixing ratio profiles on a finer pressure scale for comparison with other profile data.

Instrument #76 operated in a semi-automatic mode, while instrument #83 required an operator. Umkehr measurements were obtained by #76 for 16 days (15 morning and 10 afternoon measurements). Instrument #83 made measurements of total column ozone on 13 days (13 mornings and 4 afternoons). It was common for clouds to move over the station in the afternoon and dissipate in the early evening.

UARS MLS

The UARS MLS instrument measures thermal emissions in 6 mm-wavelength bands with double-sideband heterodyne radiometers centered near 63, 183 and 205 GHz by scanning through the atmospheric limb [*Waters*, 1989, *Froidevaux et al.*, 1996]. The measurements in the 183 and 205 GHz spectral bands may be used to retrieve ozone profiles. The ozone data used in this study are retrieved from the 15 channels spaced contiguously about the ozone line centered at 206.13205 GHz. Details of the retrieval algorithm are given in *Froidevaux et al.* [1996].

The UARS MLS made measurements on 11 days during MLO3, and a data file for the MLS profile closest to Mauna Loa each day was provided. These data are from a preliminary Version 4 data set (software version 4.15). Comments about the more definitive MLS data set (version 5) are provided in Section 4 below. The matched profiles were always coincident within 2° of latitude and 5° of longitude. The MLS profiles are in the form of ozone mixing ratio at pressures from 100 mbar to 0.2 mbar at 17 levels. The error bars provided make it clear that the lowermost two layers should not be used and the profiles should be cut off at 46 mbar. This is consistent with *Froidevaux et al.* [1996] who note that the ozone values for the 205 GHz retrievals are most reliable in the 22 to 0.5 mbar region.

SAGE II

The SAGE II instrument on ERBS is designed to measure atmospheric aerosols and ozone using the occultation technique [*Mauldin et al.*, 1985, *Cunnold et al.*, 1989]. Measurements are made at 1020, 940, 600, 525, 453, 448, and 385 nm during spacecraft sunrise or sunset events, about 15 of each per day. The location of the measurements are well distributed in longitude but vary slowly in latitude, sweeping between the high latitude extremes in about a month. The 600 nm channel in the center of the Chappuis absorption band is used to retrieve ozone profiles, from near the surface (if there are no clouds) to near 60 km. Details of the SAGE II ozone inversion algorithm are presented in *Chu et al.* [1989].

There were no SAGE II measurements near the latitude of MLO until near the end of the campaign. A close matchup occurred on August 30th when a measurement was made for which the tangent point was about 270 km from MLO. Ozone was retrieved between 10 km and 56 km at 1 km resolution, with some aerosol contamination being indicated between 18 and 21 km. Two sigma error bars are also provided. The ozone retrieval is of number density as a function of altitude. For comparison with instruments that measure ozone mixing ratio versus pressure, we converted the SAGE profile using NCEP data. The SAGE team normally prefers to provide only their primary data product - number density versus altitude.

FTIR

The FTIR instrument used for the retrievals included here was being installed at MLO during the ozone campaign. For that reason, data is available for the last few days only. The instrument is a 284 cm path difference interferometer (nominal 0.003 cm^{-1} spectral resolution), manufactured by Bruker Instruments, Germany. It was operated with a Mercury-Cadmium-Telluride detector and a bandpass filter covering 750 to 1300 cm^{-1}. Solar radiation is maintained on the interferometer entrance by a two-axis, servo-controlled tracking system. For these studies, two interferograms were co-added, with a total collection time of about five minutes.

Information about the altitude distribution of a particular species is contained in the line shape due to pressure broadening. In the mid-infrared, typical broadening coefficients are about 0.1 cm^{-1} per atmosphere, and the transition between pressure broadening and Doppler broadening occurs around 30 km altitude. An iterative technique for determining the profile was developed, and is described in detail in *Liu et al.*[1996]. For ozone, an isolated absorption line near 1163 cm^{-1} was used. It has an appropriate strength and low temperature dependence.

The retrieval technique starts from an initial guess profile, and iteratively adjusts the shape of the profile to improve the detailed spectral fit. In altitude regimes where the spectra provide no information, the profile stays at the initial guess. For the ozone line used here, no information came from the spectrum above about 32 km. A complete error analysis for ozone has been done for a series of observations over Japan in *Nakajima et al.* [1997].

3. Comparison Methodology

Observations were made for the intercomparison from August 15th through September 1st, 1995, so there are 18 possible days on which comparisons can be made. The schedule of observations actually made is shown in Table 2. There was only one SAGE overpass during the mission, on August 30th, when a measurement was made close to Mauna Loa. Since there were also measurements from every other instrument that day, it is instructive to examine the comparisons for that single day before looking at average comparisons.

Table 2. Observations made during MLO3.

	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	*total*
balloon	x	x	x	x	x	x	x	x		x	x	x		x	x	x	x	x	*16*
Goddard lidar	x	x	x	x	x	x	x	x	x	x		x		x	x	x	x	x	*16*
JPL lidar	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	*17*
microwave	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	*18*
MLS		x	x		x	x		x	x		x	x		x	x	x			*11*
SAGE II																x			*1*
Umkehr	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x		*16*
FTIR																x	x		*2*
I83 total	x	x	x	x	x	x		x	x					x	x	x	x	x	*13*

Figure 3 is a plot of ozone number density versus altitude for the two lidar instruments, SAGE, and the balloonsonde. The ECC sonde that day was one of the "triples" in which three independent ECC packages were flown on the same balloon, adding to the credibility of that balloon measurement. The error estimate plotted with each lidar profile is obtained from counting statistics of the 10^6 shots on that evening. For the lidars and for SAGE, altitude is the natural variable. Because balloon sensors measure both temperature and pressure, altitude can be determined directly.

The comparisons in Figure 3 show that the lidar measurements have an error based on counting statistics that varies from about 4% near 15 km, to 0.3%-0.8% near 30 km where the more sensitive range begins to be used, to about 10% at 45 km. Near 50 km the errors
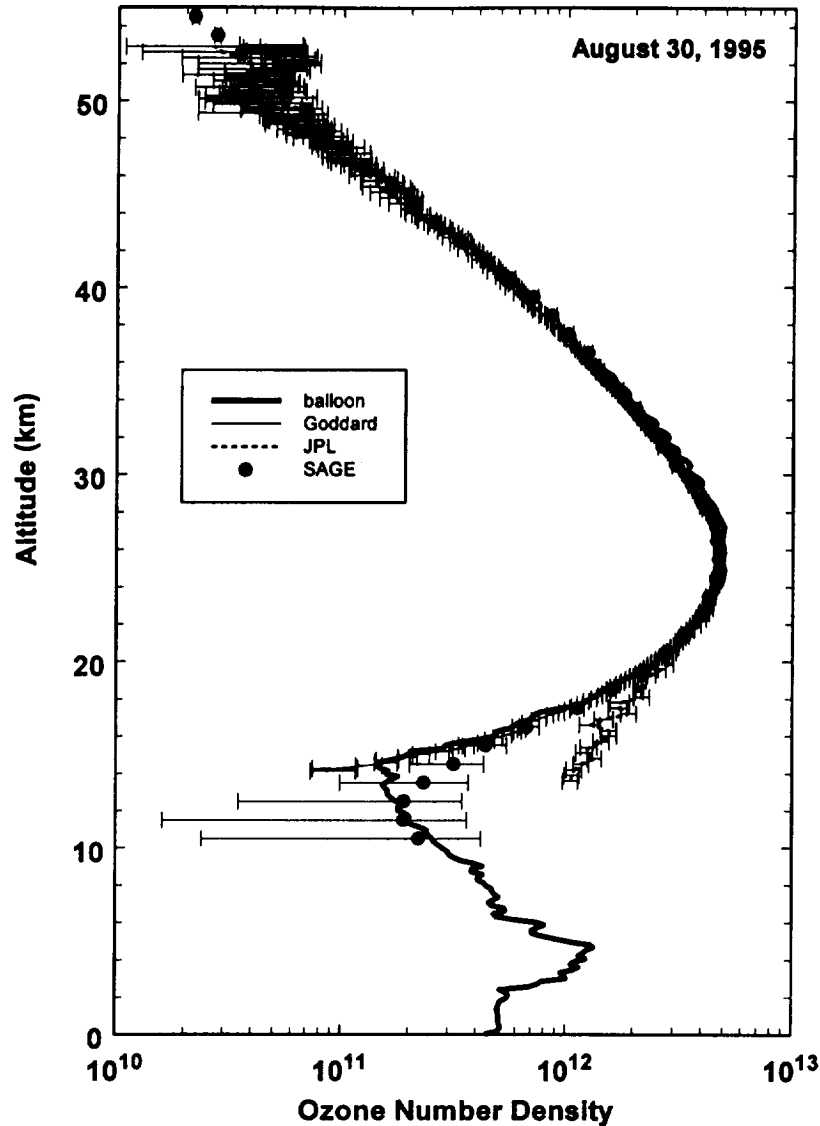
Figure 3 Plot of observations of ozone number density versus altitude on August 30th.

become much larger - near 50% for the Goddard lidar. There are algorithmic differences between the two lidars, particularly in the upper stratosphere, that have to do with the amount of vertical averaging that must be done to obtain a good profile. Neither lidar is able to measure ozone below about 15 km because the returned signal from lower altitudes is too large in the clean atmosphere over MLO and exceeds the dynamic range the systems can accept.

The Goddard profile matches the balloon profile down to the tropopause, but the JPL profile deviates significantly at altitudes below 20 km. The deviation of the JPL lidar results at low altitudes is now understood. The JPL lidar was designed to measure ozone in the upper

stratosphere and has a high power-aperture product in order to accomplish this. This can lead to signal saturation from intense returns in the lower atmosphere. This problem was anticipated and expected to show as pulse-pile-up in the photon counting detection system. This intercomparison revealed an unexpected saturation in the hardware of the detection system that did not result in pulse-pile-up and went undetected. This problem has now been remedied but the raw data obtained under these saturated conditions cannot be corrected using the normal procedures for pulse-pile-up.

Between 20 km and 42 km the agreement between the two lidars is excellent - to within $\pm 3.3\%$. Between 45 and 50 km the Goddard number density is on average 6% lower than that for JPL, varying $\pm 16\%$. This is due to the fact that the Goddard system is less powerful than the JPL system and doesn't have the signal strength to maintain accuracy above about 45 km.

The SAGE profile agrees well with the balloon profile, within 4% between 18 km and 27 km. Below 18 km this version of the SAGE II algorithm has known problems arising from an incomplete oblate Earth model and a deficiency in the atmospheric refraction calculation. SAGE agrees with the lidar profiles within 3% between 20 km and 42 km. SAGE is 6% lower than the JPL lidar result in the 45-50 km region.

Figure 4 is a comparison for the same day, August 30th, but of mixing ratio as a function of pressure. Mixing ratio comparisons are better for revealing the behavior of ozone in the middle
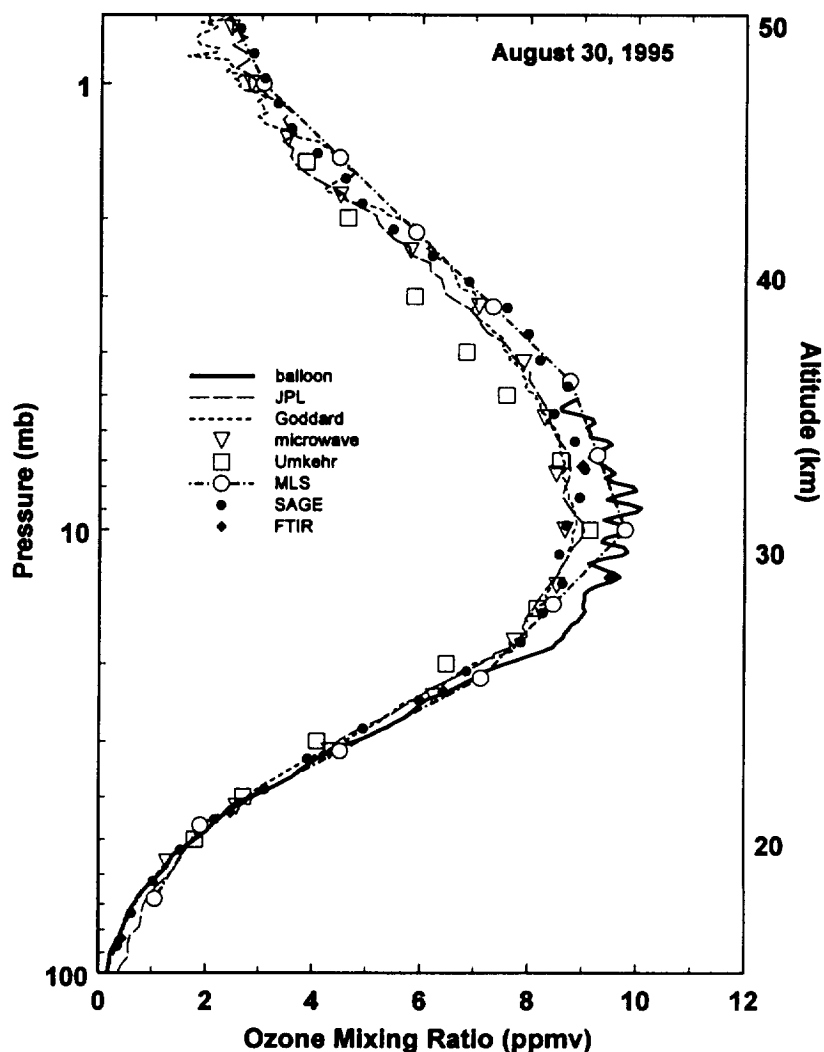

Figure 4 Comparison of ozone mixing ratio as a function of pressure for measurements made on August 30, 1995. Lidar and SAGE have been converted for this comparison.

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stratosphere, while number density comparisons are better for examining the lower stratosphere and troposphere. The balloon ECC sonde, Umkehr, MLS, microwave, and FTIR measurements are all intrinsically a function of pressure. The lidar and SAGE measurements were converted to mixing ratio versus pressure using NCEP data for that day. (The conversion introduces some uncertainty into the comparison as will be discussed in section 6.) Near the mixing ratio maximum - the 6 mbar to 15 mbar region - the Goddard and JPL lidars, the microwave, and SAGE all agree on average to within 2%. MLS is about 6% higher than the lidars, while the Umkehr mixing ratios are about 4% lower. In the upper stratosphere - the 2 mbar to 6 mbar region - the lidars, SAGE, and the microwave continue to agree to within 2%, MLS is about 8% high, and Umkehr drops to 13% lower. The FTIR profile begins to disagree with the other measurements at altitudes above about 27 km and, for the ozone line used here, has no information above 32 km. Below 27 km the FTIR ozone is 2-5% higher than balloon or lidar.

The balloon mixing ratio at altitudes above 27 km is clearly higher than all the other measurements except MLS, by about 9%. (The structure seen in the balloon profile near 30 km on this day is unusual only in its apparent regularity.) The pump efficiency correction factors, critical to accuracy above 25 km, were not the widely used results of *Komhyr et al.*, [1995], but were determined empirically for each ECC ozonesonde by NOAA/CMDL using a recently developed technique [*Johnson et al.*, 1998]. The CMDL pump correction factors were higher than those determined by Komhyr by about 2% at 100 mbar, increasing to 14% at 5 mbar. The MLO3 ozonesonde data were corrected with a conservative 0% to 6% reduction in ozone from 50 to 5 mbar respectively, to account for what was assumed to be a concentrating effect from evaporation of the sensing solution. Following MLO3, additional laboratory tests determined that the pump correction factors and the ECC cathode solution composition are closely interrelated. In the early development of the ECC ozonesonde, the sensing solution composition was optimized so that using the Komhyr pump corrections gave the best agreement with total ozone measurements by the Dobson spectrophotometer. The recent CMDL tests showed that the 1% neutrally buffered potassium iodide cathode sensing solution gives too high ozone amounts for simulated stratospheric ozone profiles when using the CMDL measured pump corrections. This apparent over measurement of ozone is likely a consequence of additional slow reactions with ozone induced by one of the buffering chemicals in the solution. When the generally accepted data processing procedures are used this solution effect is offset by the lower Komhyr pump efficiency correction factors. When using the measured pump efficiency this compensation does not occur resulting in larger calculated ozone amounts, primarily above 50 mbar.

4. Results of Comparing Averaged Profiles

It is of course more reliable to examine the average behavior of each instrument over the 18 day period of measurements than to base conclusions on only one day. The average ozone profiles (mixing ratios on the left, number density on the right) for each instrument are shown in Figure 5. (Note that the SAGE data shown are based on only one day and the FTIR on two

days, which will increase the uncertainty of these comparisons.) The averages confirm that the profile differences seen in the plots for August 30th were typical and not unique to that one day.
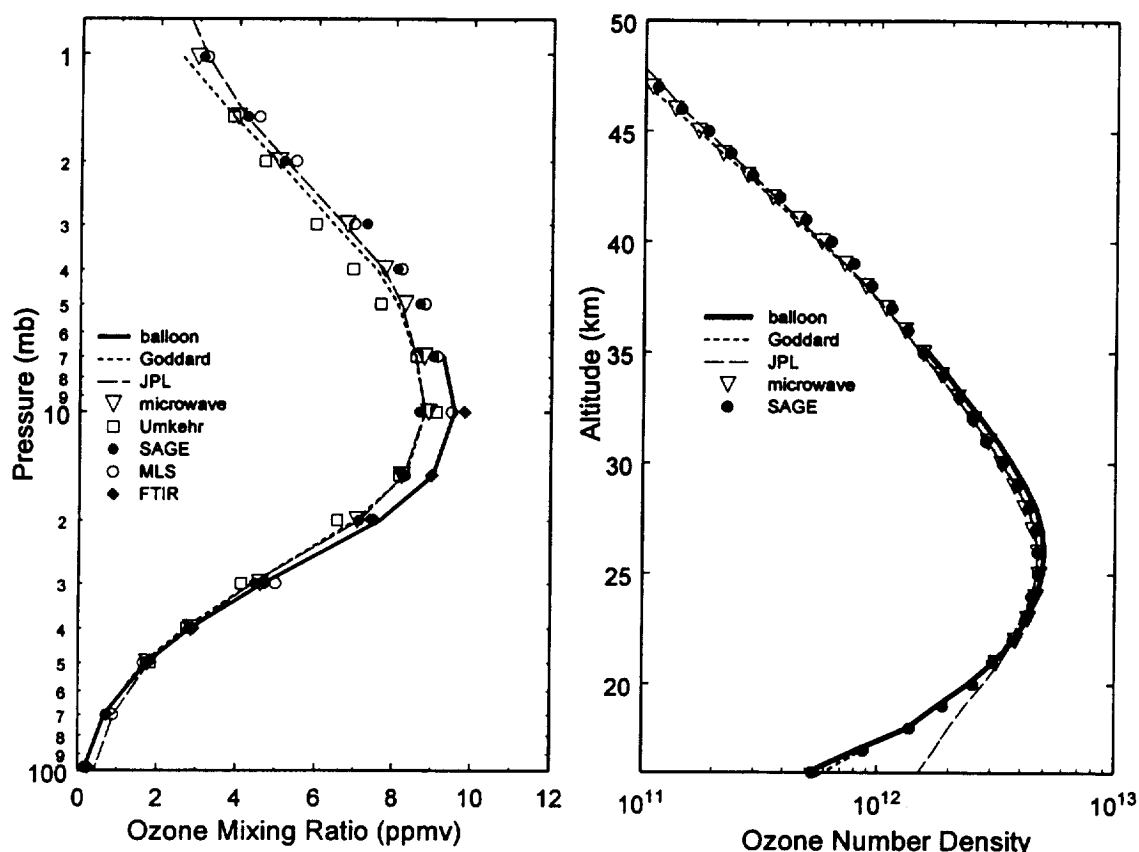

Figure 5 Ozone profiles averaged over the entire 18 day comparison.

In order to quantitatively compare profiles it is more useful to examine percent difference plots. If the true ozone profile is known, the difference plot is a powerful tool for identifying any weakness in a measurement. But for a field measurement campaign like this true ozone is not known. A strategy followed in previous inter-comparisons has been to compare each instrument's profile to the average of all the measurements. The drawback is that if there are systematic errors in one or a few of the instruments, structure will be introduced into the comparisons of other instruments that can be confusing.

In the absence of a "truth" profile, the different measurement techniques can best be evaluated on the basis of consistency. When profiles are inconsistent, a judgement must be made based on knowledge of instrument limitations. For example, the balloon profile is known to be in error above 27 km (20 mbar) because incompatible pump correction factors and

sensing solution chemistry. The JPL lidar has an identified saturation problem below 20 km, while the Goddard lidar loses sensitivity above 43 km. The MLS positive offset has been identified as algorithmic. A "consensus" reference profile was created based on instruments that have no known errors over various altitude ranges. Balloon data are used from the surface to 25 km. Goddard lidar data are used between 16 and 43 km. JPL lidar data and microwave data are used between 22 km and 50 km. SAGE data are used between 20 km and 50 km. The measurements in the consensus profile agree to within an average of ±3% and no worse than ±5%. We emphasize that the purpose of the consensus profile is to serve as a stable reference. But if three or more instruments using different physical measurement techniques are consistently in very good agreement, this is strong evidence that the results are accurate and technique independent.

   Figure 6 is a plot of the deviation of each instrument average profile from the reference profile. In order to compute differences it was necessary to spline the average profiles to consistent pressure levels, but no smoothing was done. An immediate conclusion is that almost all the instruments agree to within ±10% (which was the best that could be expected of
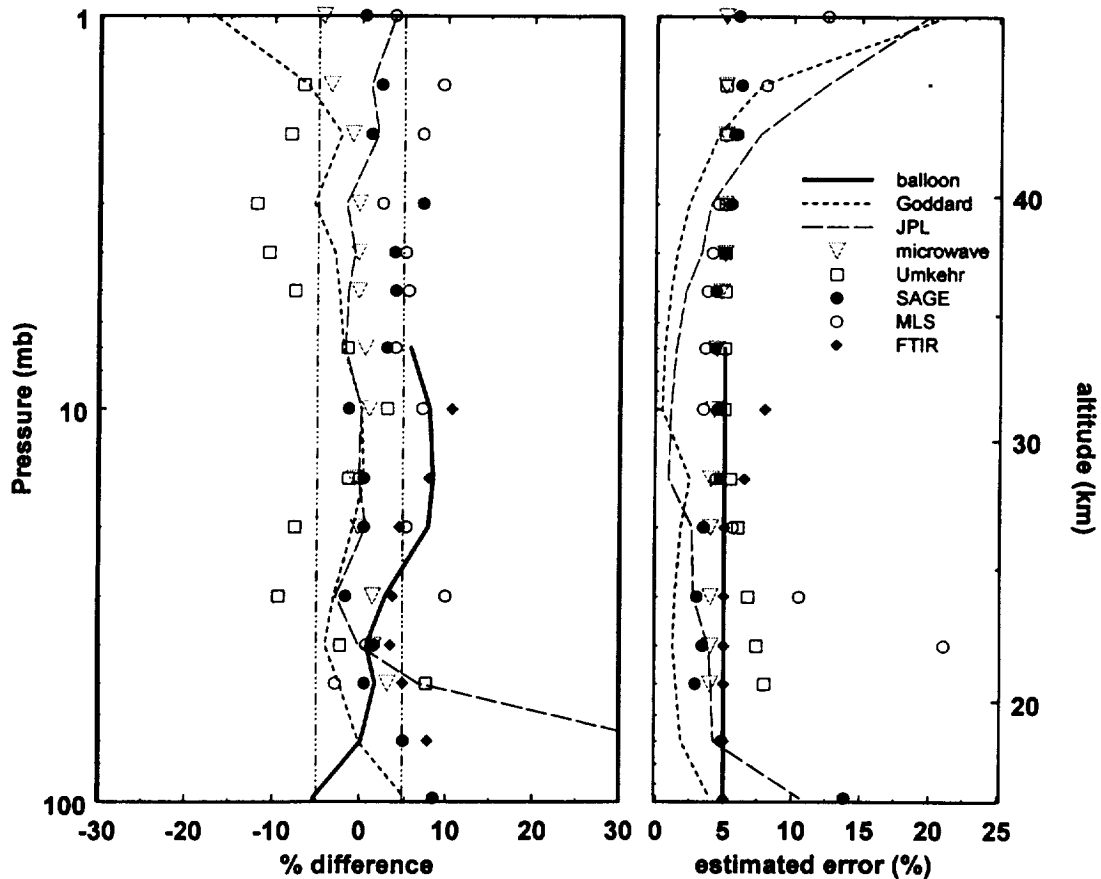

Figure 6 Percent deviation of the comparison average for each instrument from a "consensus" reference profile. The estimated percent error for each measurement shown at right.

profile measurements just a few years ago), and most of the measurements agree within ±5%. The average balloon data are higher than the reference near 30 km by about 8% for reasons explained earlier. The Goddard lidar profile is lower than the reference at 45 km and above, a region in which the signal is marginal and must be heavily averaged. The JPL lidar develops a serious positive bias at 20 km and below as noted earlier. The MLS profile tends to be consistently high relative to the reference, generally by about 5%. This will likely be remedied in Version 5 MLS data, which, at this latitude, are typically 2 to 6% lower in the 2 to 22 mb range than the version used here. The Umkehr profile is lower than the reference near 25 km by about 8%, is close to agreement near 32 km, and then is lower by about 10% near 40 km. The Umkehr measurement has lower vertical resolution than most other techniques, but there may also be some error from the correction term for the residual Pinatubo aerosol.

5. Comparison of Total Column Ozone

The measurement of total column ozone is currently far more accurate than that of the ozone altitude dependence. A well-calibrated Dobson or Brewer can arguably measure total ozone to an accuracy of ±1% [*Komhyr et al.*, 1989, *WMO*, 1995]. Measurements of total column ozone made by the world standard Dobson instrument #83 on 11 days during the comparison have been used to evaluate the overall accuracy of the profiling instruments. The results are given in Table 2. Since no instrument measures the altitude distribution from the surface to the top of the atmosphere, adjustments must be made. The average total ozone measured by Dobson #83 during the comparison was 260.3 Dobson units (DU). The integrated column measured by the Goddard lidar on the same 11 days was 241.4 DU, but this column was generally down to a minimum altitude of about 15 km. The amount of ozone between this altitude and the altitude of MLO, 3.4 km, was taken from each day's balloon profile and added to the lidar column. This amounted to an average of 26.7 DU. This gives an adjusted column for the Goddard lidar measurement of 268.1 DU, 3% higher than the Dobson average. Since the ozone from the balloon measurement added to the lidar column amounts to only 10% of the total, an error of as much as 10% in this adjustment term would introduce only a 1% error into the column. As long as the correction terms are small, they will introduce little error into the total comparison. A similar comparison for the JPL measurement results in a positive 11.8% bias relative to Dobson. This is strong confirmation that the bias below 20 km relative to the balloon measurement is indeed an error in the lidar retrieval. When the two lidar measurements are compared by integrating the column above 27 km, they agree to within 0.3%, demonstrating the high degree of consistency of the two lidar measurements in the middle and upper stratosphere.

Table 2. Comparisons of average total column ozone for 11 days on which Dobson measurements were made. Percent difference from Dobson shown in parenthesis.

MLO Dobson measurement	260.3 DU
Goddard lidar column	241.4
MLO to bottom of lidar (∼ 15 km) from balloon	26.7
adjusted Goddard Total	268.1 (+3.0%)
JPL lidar column	265.4
MLO to bottom of lidar (∼ 15 km) from balloon	25.4
adjusted JPL column	290.9 (+11.8%)
balloon column *	254.1
column from sea level to MLO	-7.1
column above balloon (∼ 35 km) from lidar	27.5
adjusted balloon column	274.5 (+5.4%)
Goddard column above 27 km	113.3
JPL column above 27 km	112.9

* based on 10 good balloon profiles

The balloon measurement can be similarly compared with Dobson. Here the amount of ozone between sea level (the balloons are launched from Hilo) and MLO (at 3.4 km altitude) must be subtracted, an average of 7.1 DU. The balloons usually reached about 35 km before the ECC sondes failed. Data for August 20th, when the balloon only reached 24 km, were not included in the average. The column above balloon maximum altitude was taken from the JPL lidar measurement and amounts to an average of 27.5 DU, again only about 10% of the total. The adjusted balloon total column amounts to 274.5 DU, 5.4% higher than the Dobson total. This is additional evidence that the ozone measured by the ECC sonde near 30 km was indeed too high.

6. Minor Error Sources

The complete intercomparison of ozone profiles obtained during MLO3 requires that all the data sets be converted to a consistent vertical scale, whether in pressure or altitude. No matter which sets are converted, additional uncertainties are introduced. Some of the participants can provide estimates of these conversions on their own while others use information from other sources (often the NCEP analysis). The information to calculate pressure/altitude conversions can be obtained from temperature vs. pressure measurements (e.g., as obtained from balloonsondes), density vs. height (e.g., as obtained from LIDAR systems), or temperature vs. height.

While the physical laws governing the relationships among altitude, pressure, density, and temperature are well-established, there are complications and opportunities for errors in applying them. Two opportunities for computational errors were encountered in working with the data sets in the intercomparison. The first, the simplest to make and to correct, was confusion over the geopotential and geometric heights normally provided in the NCEP and balloonsonde data. The conversion is simply

$$z = Z \, R/(R-Z)$$

where R is the radius of the Earth, z is the geometric height, and Z is the geopotential height. This error grows quadratically with height. The geopotential heights are less than the geometric heights by approximately 1/16 km at 20 km, 1/7 km at 30 km, 1/4 km at 40 km, and 2/5 km at 50 km. These errors lead to ozone number density errors of approximately 1%, 2%, 5% and 8% respectively, with a change in sign between 20 and 30 km. The sign of the error depends on how the height/pressure conversion is applied.

The second error involves the decrease in gravity with height and the associated change in the gradient of neutral atmosphere column amount with pressure. Because of the radius-squared dependence of gravity, the number of molecules in a column with constant cross section in the layer between, for example, 100 and 99 mbar is less than the number of molecules in the layer between 2 and 1 mbar. This must be considered in the computation of P/H from temperature or density information. One must also check to make sure that participants reporting their results as ozone vs. pressure have not incorrectly made an implicit change of variables from number of molecules in the path and the relative path length to pressure. This problem also complicates the computation of ozone mixing ratios. From computations with a standard atmosphere, one can find that the incorrect pressure estimate computed without including the decrease in gravity is related to the true pressure by

$$P_e \approx P \, (1 + (2 \, z + 14)/R)$$

where P is the actual pressure, P_e is the incorrect pressure, z is the altitude in km and R is the earth's radius in km. The ozone error is a product of the pressure error, which is approximately linear in log pressure, times the ozone gradient, which varies with pressure. Typical ozone errors might be -1.5% at 30 mbar, no error at 10 mbar, +1.2% at 3 mbar, and +0.8% at 1 mbar.

7. Conclusions

This intercomparison shows that progress is being made towards bringing the profile measurement techniques into agreement. Almost all the instruments agreed to within ±10%, which was the best that could be expected of profile measurements just a few years ago, and most agreed within ±5%.

Both lidars, the microwave instrument, and SAGE-II agree within 5% between 22 and 43 km, providing strong evidence that the lidars and the microwave instrument are making accurate measurements in this range. The JPL lidar, microwave instrument and SAGE-II continue to agree within 5% up to 50 km, providing evidence that the measurements of the JPL lidar and the microwave instrument continue to be accurate to that altitude. The Goddard lidar, sonde, and SAGE-II agree within 5% down to 18 km, providing evidence that these three are making accurate measurements down to this level. The SAGE-II disagreement with the balloon profile below 18 km is due to known algorithmic problems arising from an incomplete oblate Earth model and a deficiency in the atmospheric refraction calculation. (Conclusions about the accuracy of SAGE-II at the 5% level cannot be drawn from the single measurement.) The balloon data were used from the surface to 25 km and agreed well with the Goddard lidar and with SAGE in the 18 to 25 km region. The positive bias of about 8% near 30 km seen in this comparison resulted from using an improved pump correction factor that did not compensate for errors in the chemistry of the sensing solution. This is now better understood as a result of this intercomparison and does not indicate an intrinsic problem with the balloon measurement.

The MLS data used in this comparison, Version 4.15, tended to be high near the mixing ratio peak, by about 5%. The latest (Version 5) MLS data are expected to yield lower ozone mixing ratios, by 2 to 6%, for the mid to upper stratosphere, in better agreement with other instruments in this comparison. The Umkehr profile was low near 25 km by about 8%, was close to agreement near 32 km, but then was low by about 10% near 40 km. Although the participation of the FTIR instrument was limited to only two days, information was provided up to 32 km. The results were 2-5% high up to 24 km, increasing to about 10% high near 32 km.

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