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The Meteor 3/total ozone mapping spectrometer version 7 data set: Calibration and analysis

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Abstract. The Meteor 3/total ozone mapping spectrometer (TOMS) data set has been reprocessed using the version 7 TOMS total ozone algorithm and a recalibration of the TOMS instrument using in-flight and revised laboratory data. To provide continuity for the analysis of long-term trends, the absolute calibration of Meteor 3/TOMS was adjusted so that the measured radiances closely matched Nimbus 7/TOMS. The residual bias in ozone is less than 1% and shows no significant latitudinal or seasonal dependence. The calibration procedure and the differences between the current and previously used calibrations are discussed. Problems in the Meteor 3/TOMS data set caused by chopper wheel synchronization problems are described, and comparisons of the resulting data with version 7 of the Nimbus 7/TOMS data are presented.

1. Introduction

The U.S. total ozone mapping spectrometer instrument on board the Russian Meteor 3 spacecraft (M3/TOMS) produced daily global measurements of total column ozone from August 23, 1991, until its failure on December 28, 1994. M3/TOMS was a nearly identical refurbished engineering model of the Nimbus 7/TOMS (N7/TOMS) instrument launched in October 1978. The data produced during the first 2 years of M3/TOMS operation provided valuable confirmation of phenomena seen by N7/TOMS, such as the decrease in ozone due to aerosols from Mount Pinatubo [Gleason *et al.*, 1993] and the 1992 ozone hole [Herman *et al.*, 1995a].

When N7/TOMS ceased operating on May 6, 1993, M3/TOMS became the only operational TOMS instrument monitoring ozone. The 1½ years of data after May 1993 have been used to monitor ozone phenomena through the 1994 ozone hole period [Herman *et al.*, 1995b] and to form a continuous 16 year record (1979–1994) when combined with N7/TOMS data [McPeters *et al.*, 1996a].

Both N7/TOMS and M3/TOMS data were recently reprocessed using the new version 7 (V7) algorithm. The V7 algorithm includes (1) the use of wavelength triplets (instead of pairs) that correct for errors linear in wavelength; (2) the use of an improved cloud height climatology and a higher-resolution terrain height database; (3) the use of profile shape selection to improve total ozone calculations at large solar zenith angles; and (4) the use of more accurate radiative transfer calculations in the retrieval process. Details of the V7 algorithm can be found in the work by McPeters *et al.* [1996b].

Along with the V7 algorithm, the reprocessing of N7/TOMS used an updated absolute and time-dependent calibration based on a reanalysis of the data and improvements in calibration techniques. Details of the N7/TOMS calibration can be found in the work by Wellemeyer *et al.* [1996].

The V7 reprocessing of M3/TOMS data also included an update to both the absolute and time-dependent parts of the calibration. To provide a continuous data set from both TOMS instruments, the absolute part of this calibration was tuned so as to normalize the radiance data to that from N7/TOMS for the 20 months of concurrent data.

This paper describes the changes to the M3/TOMS calibration published previously [Jaross *et al.*, 1995]. It also describes the techniques used to normalize the data to N7/TOMS and presents comparisons between the two data sets. The combined data set is available via anonymous ftp to jwocjy.gsfc.nasa.gov, on CD-ROM, and through the Goddard Distributed Active Archive Center.

2. Background and Summary

The M3/TOMS instrument was nearly identical to N7/TOMS in its ability to measure column ozone amounts. However, small design changes and orbital dynamics led to significant differences in the measurement of ozone.

The orbit of the Meteor 3 satellite precessed in longitude with a period of 212 days. This meant that the local time at which the Meteor 3 crossed the equator changed by 1 hour (15° of solar zenith angle) approximately every 10 days (see Herman *et al.* [1995a] for a table of orbital characteristics). When the orbit precessed so that it was close to the day-night terminator (every 106 days), data loss of up to one hemisphere could occur for about 2 weeks if it coincided with the summer or winter solstices. This happened because the instrument was in the

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Paper number 97JD00606.
0148-0227/97/97JD-00606\$09.00

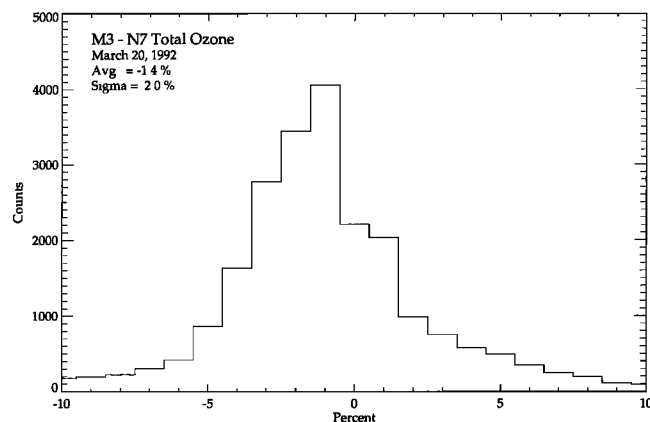


Figure 1. Comparison of ozone between Meteor 3/TOMS and Nimbus 7/TOMS for March 20, 1992 before normalization. The 1.4% offset is primarily due to calibration differences at the A triplet wavelengths (312, 331, and 380 nm).

dark on half of both the ascending and descending portions of the near-polar orbit. Smaller data loss occurred at other times of the year.

When the polar regions were dark, the instrument was also unable to make solar flux calibration measurements for a period of 5–10 weeks surrounding the near-terminator orbit. The orbital precession of Meteor 3 also meant that the solar response characteristics of the instrument's solar flux diffuser plate had to be characterized over a wide range of solar incidence angles. Since larger errors in the diffuser plate characterization occur at the higher angles, the in-flight solar calibration periods were further reduced to times when the angles were closer to normal incidence.

Wide temperature variations associated with the precession also resulted in shifts in the instrument wavelength band pass. These shifts were largest near the terminator orbits (higher temperatures), but did not have a significant impact on retrieved ozone. While errors near terminator orbits are difficult to estimate, the effect of wavelength registration errors during near-noon equator crossing-time orbits appears to be no greater than 0.5% in total ozone.

Other errors, besides calibration, occur for orbits containing extreme viewing conditions due to problems with radiative transfer models of the atmosphere at high scattering angles. These problems are particularly severe in the presence of stratospheric aerosols such as those produced by the eruption of Mount Pinatubo. Retrieval errors caused by the presence of volcanic aerosols can cause errors of 10% or more in total ozone [Torres *et al.*, 1995]. Even after these aerosols have dissipated, high solar zenith angle and high viewing angle errors of up to 5% remain. As a result, data obtained when viewed under these conditions are presently unreliable and have not been released in the M3/TOMS data set.

3. M3/TOMS Calibration

Details of the calibration and algorithm used to generate the previous M3/TOMS data set (using the version 6 algorithm) as well as some of the results have been reported in the literature [Jaross *et al.*, 1995; Herman *et al.*, 1995a]. These reports contain two key conclusions: (1) the long-term M3/TOMS instrument calibration was maintained to within a corresponding ozone

error of 1% over the life of the instrument, and (2) the agreement between total column ozone data from Meteor 3 and N7/TOMS, when both satellites viewed scenes under similar conditions, was generally within 1%.

Analysis done in preparing V7 indicated that there were several problems with the previous N7/TOMS and M3/TOMS version 6 (V6) data sets. These problems were related to both the algorithm and calibration. In particular, the A pair (312 nm and 331 nm) calibrations for both N7/TOMS and M3/TOMS had independent, offsetting errors in V6 that resulted in similar retrieved ozone amounts. A wavelength calibration error in N7/TOMS, as well as other calibration errors, was discovered that resulted in measurements of A pair ozone which were about 2% too high [Wellmeyer *et al.*, 1996]. Similarly, an error in the interpretation of M3/TOMS solar measurements led to A pair ozone amounts that were 3.7% too high. This analysis indicated an actual A pair difference between the two instruments of 1.7%.

In V7 of the algorithm, the 380 nm wavelength radiances were combined with those from the pair wavelengths to form triplets that were used to correct for any linear wavelength dependence. The triplet of wavelengths used to calculate ozone was the one most sensitive to ozone for that measurement: (1) A triplet (312, 331, 380 nm) for solar zenith angles less than approximately 60°, (2) B triplet (317, 331, 380 nm) for solar zenith angles between approximately 60° and 80°, and (3) C triplet (331, 340, 380 nm) for solar zenith angles above approximately 80°. When corrections to the known errors described above were applied to this V7 formulation, a difference of approximately 1.7% in total ozone calculated from the A triplet did appear. Furthermore, the B triplet ozone measurements of the two instruments agreed quite well, while measurements using the C triplet disagreed by an average of 3%.

Figure 1 contains a histogram of the difference in total ozone measured between M3/TOMS and N7/TOMS for March 20, 1992. The V7 algorithm was used with independently derived calibrations to generate the ozone data for both instruments. The comparison is presented on this day because the local equator crossing time (LECT) of Meteor 3 was close to that of Nimbus 7. The histogram was made by performing a grid point by grid point comparison of the TOMS level 3 gridded data products produced for both instruments (1.25° longitude by 1° latitude) over the entire Earth. The overall offset of −1.4% is predominantly due to the 1.7% difference in ozone determined by the A triplet (which is used over most of the Earth). The fact that the difference in B triplet ozone is small while the difference in C triplet ozone is large leads to the broadness of the peak.

It was concluded that these triplet ozone biases were a result of inconsistent albedo calibrations for the two instruments, having eliminated wavelength calibrations as a further source of errors. Because the V7 ozone retrieval relies on the albedo measurement and viewing conditions, adjusting M3/TOMS in all wavelength channels on a day when the two instruments have similar viewing conditions will force agreement in ozone on that day. Normalization of M3/TOMS to N7/TOMS was chosen so as to provide continuity of the ozone data record for trend calculations. An important point is that a simple scaling of M3/TOMS total ozone, or even of ozone values measured by the different triplets, will not adequately address the ozone differences under all viewing conditions.

3.1. Time-Dependent Calibration Update

The primary changes in postlaunch calibration between the version 6 and version 7 processing of M3/TOMS were adjustments to the albedo calibrations. TOMS instruments measure a quantity referred to as normalized radiance in order to determine column ozone. The normalized radiance is defined as the backscattered radiance $I(t)$ divided by the incident solar flux $F(t)$. As defined, it is the hemispherical planetary albedo in the direction of the TOMS field of view. Normalized radiances are determined from instrument radiance and irradiance signals (C_r and C_i) through factors referred to as the albedo calibrations:

$$\frac{I(t)}{F(t)} = A(t) \frac{C_r(t)}{C_i(t)}. \quad (1)$$

These calibrations are composed of an initial (absolute) portion determined prior to launch and a time-dependent portion. The procedure for adjusting absolute albedo calibrations involves comparing normalized radiances measured by the instruments under similar viewing conditions and is described in more detail in section 3.2. A crucial aspect of calibration comparisons over an extended period is that the time dependence of the calibration must be accurately known for each instrument. Errors in either instrument characterization lead to increased variance in the calibration normalization. Because of problems unique to N7/TOMS during the last 2½ years of its life (such as the lack of solar flux data and increasingly large instrument degradation) the time-dependent albedo calibration of N7/TOMS was determined using an internal calibration technique [Wellemeyer et al., 1996]. The estimated accuracy of the N7/TOMS albedo calibration during the overlap period is 0.5% for single wavelengths and for pair wavelength ratios. In contrast, the time-dependent calibration of M3/TOMS used the in-flight solar measurements.

By normalizing the measured radiances,

$$I_{\text{meas}}(t) = I(t)\tau(t)/d^2, \quad (2a)$$

with the solar flux measured using the diffuser plates,

$$F_{\text{meas}}(t) = F(t)\tau(t)/d^2, \quad (2b)$$

changes in spectrometer sensitivity, $\tau(t)$, and other sources of variation cancel. The quantity d is the Sun-Earth distance in astronomical units, and $I(t)/F(t)$ is the normalized radiance input to the ozone retrieval algorithm.

Equation (1) relates the normalized radiances to the measured signal ratios. The solar signal, C_r , is characterized in terms of diffuser reflectivity $\rho(t)$, angular response g , and other changes embodied in $F_{\text{meas}}(t)$:

$$C_r(t) \propto \rho(t)F_{\text{meas}}(t)/g. \quad (3)$$

The Earth signal is simply $C_i(t) \propto I_{\text{meas}}(t)$. Combining these signals in (1) and using (2) yields the fact that the albedo $A(t)$ is proportional to $\rho(t)/g$. Thus the time-dependent instrument calibration requires only knowledge of $\rho(t)$ and g . Since $F(t)$ is approximately constant at TOMS wavelengths [Willson et al., 1986; Schlesinger and Cebula, 1992], an estimate of spectrometer throughput, $\tau(t)$, results from inverting (3) and combining with (2b). For N7/TOMS, the postlaunch calibration $\rho(t)$ was poorly characterized, and another method was used to determine $\tau(t)$ directly [Wellemeyer et al., 1996].

For M3/TOMS, diffuser characterization was the most ac-

curate means of postlaunch calibration. The instrument's three solar diffusers were deployed with different rates of solar exposure and corresponding degradation (a continuously exposed cover plate, a working plate exposed once per week, and a reference plate exposed once per 15 weeks). This tiered system of measurements allowed M3/TOMS to make frequent solar measurements while minimizing the effects of diffuser degradation on the instrument albedo calibration [Jaross et al., 1995]. There was almost no reflectivity degradation of the reference diffuser at the end of the 3 year M3/TOMS record (<1%), nor was there much degradation of the working diffuser. Because of this, no correction was applied for spectral degradation. Reference diffuser measurements, corrected for Sun-Earth distance and angular response, are therefore a direct measure of the changes in $F_{\text{meas}}(t)$ and $\tau(t)$.

Angular corrections posed a more difficult problem than degradation for the three plates. Figure 2 contains a plot of solar signal, corrected for angular effects, as measured using the two least exposed diffusers (working and reference). The results shown in Figure 2a are the 360 nm measurements using a prelaunch angular correction. In the V6 analysis the observed solar signal oscillations using the working plate surface were assumed to have been caused by a prelaunch characterization error and were corrected by smoothing with a low-order polynomial in time. We have now determined that the oscillations are largely caused by incorrect attitude information for the M3 spacecraft. Specifically, there is a $1.4^\circ \pm 0.1^\circ$ constant error in the reported yaw angle. The magnitude of this error was determined by observing asymmetries in the scan dependence of the derived surface reflectivity at very high solar zenith angles. The attitude correction has been included in the V7 processing. The direct effect of this attitude error on derived ozone is expected to be negligible except at very high latitudes. Figure 2b contains a plot of the 360 nm solar signal using the same prelaunch angular correction plus the yaw angle adjustment. While the working data are more realistic, there are clearly some systematic deviations which can be attributed to incorrect prelaunch characterization of high incidence angles. The discontinuity seen in mid 1993 was caused by an instrument change described in section 3.2.

Given these apparent errors, the working diffuser data are still considered unreliable for single-wavelength solar signal characterization. Rather, reference diffuser data, which were always obtained at normal incidence, were used in a simple polynomial regression for the 360 nm spectrometer throughput. This characterization, which is close to that of version 6, is overplotted in Figure 2b. Other wavelengths were determined as ratios to the 360 nm channel. Working diffuser measurements were used in the time dependence characterization of these ratios because there is little evidence of spectral dependence in the prelaunch angular characterization errors. As an example, the solar signal time dependence for the 312/360 nm ratio is shown in Figure 2c along with the time dependence characterization.

3.2. Data Problems Due to Chopper Wheel Synchronization

As reported previously [Jaross et al., 1995], the M3/TOMS instrument began to experience chopper wheel synchronization problems in mid May 1993. By the beginning of June, the loss of synchronization, as measured by a detector on the chopper wheel, had reached 100%. Two different levels of synchronization loss were seen in the data. First, during some

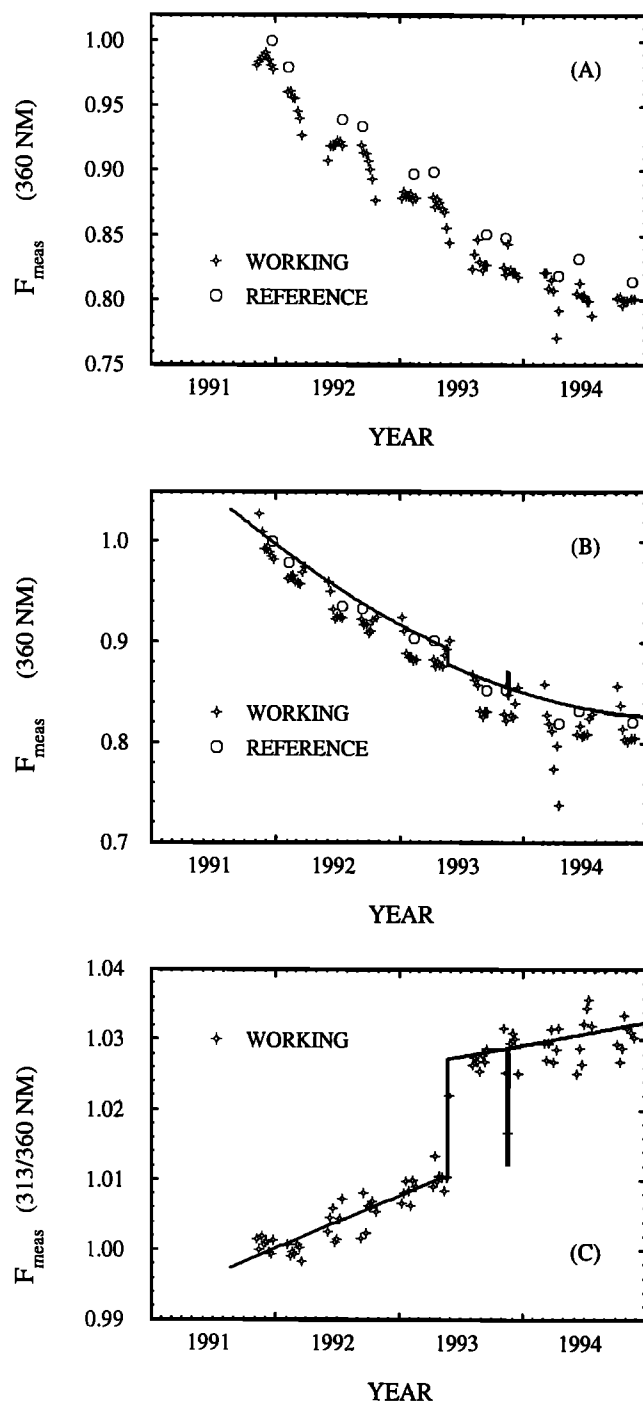


Figure 2. Time dependence of the Meteor 3/TOMS measured solar flux normalized to 1 at the first reference measurement. The version 7 characterization is overplotted. (a) Measurements using prelaunch angular corrections. (b) Measurements using prelaunch angular corrections with a 1.4° yaw adjustment. (c) Measurements and characterization of the 312/360 nm solar flux. The May 1993 discontinuity seen in Figures 2b and 2c was caused by the onset of chopper wheel synchronization problems.

brief periods of time the chopper wheel synchronization had become unstable enough to make the science data unreliable. It was straightforward to detect these occurrences and to reject the data taken during them because certain wavelength ratios were very sensitive to chopper wheel changes. This problem

was particularly acute during early June 1993, with all of the data being rejected for June 8, most of the data being rejected for June 6, 7, 9, and 10, and some of the data being rejected for June 2, 3, 4, and 5. Less severe periods of data rejection occur throughout the rest of the M3/TOMS data record.

For most of the data, however, the 100% loss of synchronization could be handled as a transition in the state of the instrument and, therefore, as a change in the instrument's spectral sensitivity [Jaross *et al.*, 1995]. Little degradation in data quality was seen.

During a 10 day period after the onset of the chopper wheel problems (May 20 through May 30), the instrument calibration was in transition. Because solar measurements could not be used to accurately track instrument changes during this particular period, the transition was characterized as a step change occurring on May 21. This simplified assumption could lead to a maximum of 2% error in retrieved ozone during the 10 day period in question.

3.3. Normalization

The procedure of normalizing M3/TOMS to N7/TOMS used a limited sample of both Meteor 3 and Nimbus 7 data in which measurements were taken as close to the same time as possible. The procedure was broken into three steps. Since the determination of ozone depends on the calculation of scene reflectivity, the normalized radiance measured from the 380 nm channel, which determines reflectivity, was first externally adjusted to agree with the one from N7/TOMS. The Meteor 3 data contained in the sample data set were then reprocessed. In the second step the normalized radiances of the other two wavelengths that constitute the A triplet (312 and 331 nm) were adjusted to agree with those from Nimbus 7, and the data were once again reprocessed. Finally, the normalized radiances from the 317, 340, and 360 nm wavelengths were adjusted for internal consistency; in this way, ozone values determined from the different sets of triplets were made to be consistent in regions where they provide accurate measurements.

Although there is almost a 2 year overlap between the Meteor 3 and Nimbus 7 data sets, the precessing orbit of the Meteor 3 satellite limited matchups in which the two instruments measured normalized radiances of the same scene at nearly the same time to five periods. These periods correspond to ones in which the LECT of either the ascending node or descending node of Meteor 3's orbit was close to that of the LECT of Nimbus 7.

The LECT of Nimbus 7 during this period was between 1000 and 1100 LT. The comparison data set was formed from the five matchup periods by selecting Meteor 3 data which consisted of days in which its LECT was between 1000 and 1100. The data from both satellites were then binned into 1° by 1° grids. Only near-nadir (scan angle less than or equal to 6°) data were used, which helped to minimize differences in scattering angle between the two instruments. Also, only one measurement from each satellite was selected for each grid point. The data selected corresponded to those with the smallest value of the optical path for a given grid point. To further minimize differences in viewing conditions and scattering angles between the two instruments, four more constraints were then placed on these data:

1. In order to stay away from confounding factors such as sea glint, the solar zenith angle for both instruments was required to be above 20°. Similarly, in order to stay away from high solar zenith angles, both instruments were required to have solar zenith angles less than 40°.

2. The solar zenith angles of measurements from both instruments were required to be within 2° of each other.

3. Although the LECTs of both satellites were within 30 min of each other, for a given scene the time difference between measurements taken by each satellite could be much more (particularly near the poles). The data set was therefore further limited to those areas of the grid in which both satellites measured ozone within 1 hour of each other.

4. The stability of a given scene was checked by comparing its 380 nm radiance to the 380 nm radiances of neighboring scenes. If the radiance change was too rapid (greater than 10%) in either the cross-track or the along-track direction, the measurement was rejected.

Despite the constraints described above, atmospheric differences precluded direct comparison of normalized radiances measured by the two instruments. These differences are taken into account using residues calculated in version 7 of the TOMS total ozone algorithm.

In the application of the TOMS algorithm, normalized radiances are expressed as N values:

$$N = -100 \log_{10} (I/F). \quad (4)$$

In determining ozone, the measured N values are compared with theoretical ones calculated using a radiative transfer model that includes Rayleigh scattering and ozone absorption. In order to compute theoretical N values, it is necessary to characterize the reflecting properties of the surface. Thus the TOMS algorithm determines an effective surface reflectivity as well as a total ozone amount. Broadly speaking, the longer wavelength channels are used to determine reflectivity, and the shorter wavelength channels are used to determine ozone. Once these quantities are derived, an algorithmic residue r is defined:

$$r = N_{\text{meas}} - N_{\text{calc}}, \quad (5)$$

where N_{meas} is the measured N value and N_{calc} is the theoretical N value calculated using the solution ozone and effective surface reflectivity. The residue is therefore a measure of atmospheric effects not included in the radiative transfer model as well as calibration errors not accounted for. A complete description of the TOMS version 7 algorithm can be found in the work by *McPeters et al.* [1996b].

Since a direct comparison of the residues between the two instruments, rather than N values, is independent of small wavelength or viewing geometry differences, they are used both to normalize Meteor 3 ozone measurements to Nimbus 7 and to internally adjust the remaining three wavelengths.

In terms of the residues defined above, the difference in N value between measurements made at similar wavelengths by M3/TOMS and N7/TOMS can be written as

$$\Delta N = (r_{\text{M3}} - r_{\text{N7}}) + (\Omega_{\text{M3}} - \Omega_{\text{N7}}) \left(\frac{\partial N}{\partial \Omega} \right)_{\text{M3}} + (R_{\text{M3}} - R_{\text{N7}}) \left(\frac{\partial N}{\partial R} \right)_{\text{M3}} \quad (6)$$

where

- r_{M3} Meteor 3 residue;
- r_{N7} Nimbus 7 residue;
- Ω_{M3} ozone measured from Meteor 3;
- Ω_{N7} ozone measured from Nimbus 7;
- $(\partial N / \partial \Omega)_{\text{M3}}$ ozone sensitivity for Meteor 3;
- R_{M3} reflectivity measured from Meteor 3;

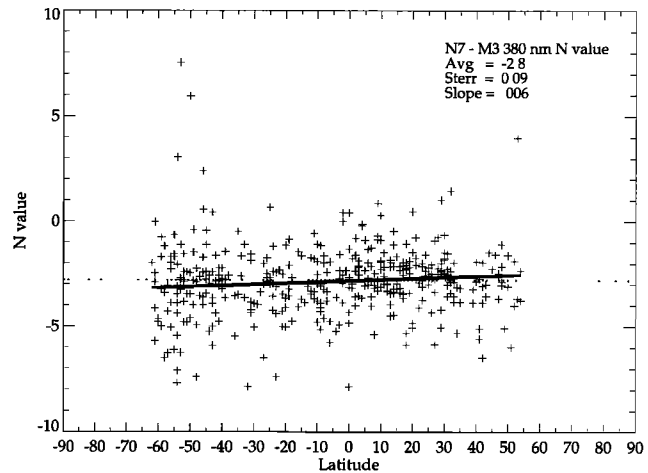


Figure 3. Comparison of the 380 nm normalized radiances from Meteor 3 and Nimbus 7 TOMS for the matchup data set as a function of latitude. The offset of $-2.8 N$ value units seen here was later applied to the data. A linear regression is also overplotted on the data, but is shown only for informational purposes and was not applied.

R_{N7} reflectivity measured from Nimbus 7;
 $(\partial N / \partial R)_{\text{M3}}$ reflectivity sensitivity for Meteor 3.

The second and third terms in the above equation are needed to account for actual differences in the measurements between the two instruments.

Figure 3 shows the results of applying the third term of (6) to the 380 nm channel (since the 380 nm channel residues are zero, the first term drops out; since this channel is also insensitive to ozone, the second term also drops out). The data are plotted as a function of the latitude. The offset of $+2.8 N$ value units (± 0.08) indicates that the effective reflectivity of M3/TOMS is approximately 6% higher than N7/TOMS at high reflectivities and 2% higher at low reflectivities. To account for this offset and the resulting reflectivity differences, a $2.8 N$ value adjustment was made to each of the Meteor 3 wavelengths, and the matchup data were reprocessed.

A similar analysis was performed for the 312 and 331 nm wavelengths. On top of the $2.8 N$ value adjustment above, the calculated means and standard errors indicate an added offset of $-0.2 N$ value units (± 0.06) for the 312 nm channel and 0.31 (± 0.06) N value units for the 331 nm channel. These offsets result in an approximate 2% difference between the M3/TOMS and N7/TOMS A triplet (with the M3/TOMS A triplet being lower, see Figure 1). These added adjustments were made to the wavelength channels, and once again, the matchup data were reprocessed in preparation for internally calibrating the remaining channels.

All comparisons between matchup data appear to have a latitude dependence as exhibited by a regression overplotted in Figure 3. This slope represents a sensitivity change of 2.5% from pole to pole in one or both instruments. While the slope obtained from this regression is not statistically significant and has not been applied in the normalization, other evidence suggests this latitude dependence is real. Comparison of instrument sensitivities over Greenland and Antarctica using an ice radiance calibration technique [*Jaross and Krueger*, 1993] revealed a 3% spread in relative sensitivities between the two continents. The mean Meteor 3/Nimbus 7 sensitivity ratio of

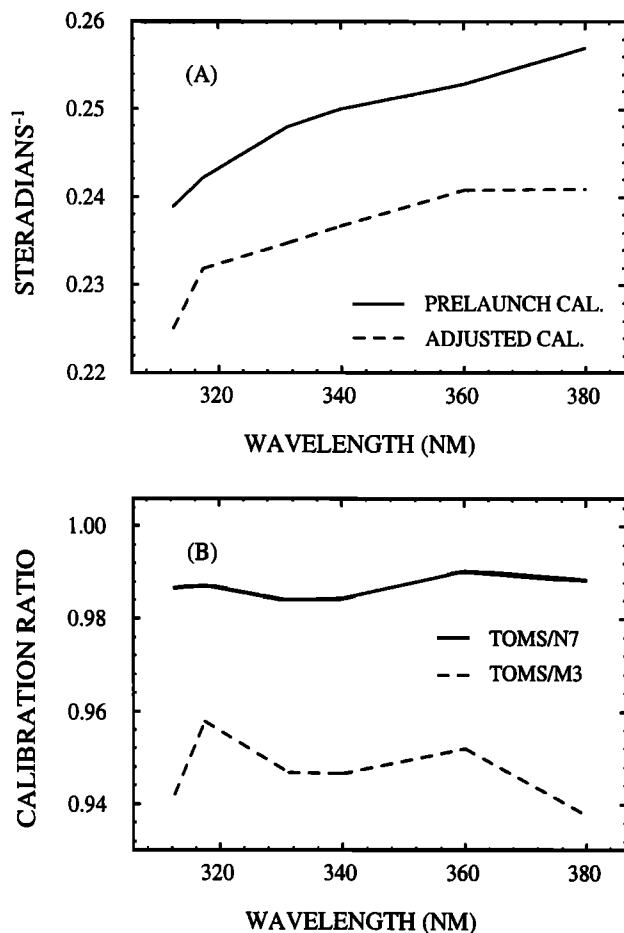


Figure 4. The albedo calibration as a function of Meteor 3 wavelength: (a) prelaunch and after normalization; (b) adjusted to prelaunch ratios for Meteor 3 and Nimbus 7 calibrations (those of Nimbus 7/TOMS are shown for reference).

Figure 3 falls midway between the Greenland and Antarctic results. A latitude dependence observed in the N7/TOMS radiance response [Wellmeyer *et al.*, 1996] is a likely explanation for the effect. The resulting systematic uncertainty of $\pm 1\%$ in the 380 nm normalization is well within the overall statistical uncertainty of $\pm 3\%$ observed in single-wavelength comparisons.

The main motivation for internally adjusting the remaining three wavelengths is algorithmic. Since different wavelengths are used to determine total ozone in different solar zenith angle regimes, it is imperative that the spectral dependence of the initial calibration be consistent with the theoretical radiances of the forward model used in the retrieval. Any inconsistencies can be identified through analysis of the residues. In cases where the A triplet (312 nm, 331 nm, 380 nm) wavelengths are used to determine total ozone and effective reflectivity, residues can be computed for the other wavelengths (317 nm, 340 nm, 360 nm). These specifically characterize the inconsistency of these measured radiances with the total ozone and reflectivity derived using the A triplet. Since these residues were previously adjusted for N7/TOMS, modal residues from the M3/TOMS A triplet retrievals from the overlap data set were used to estimate the necessary adjustments.

Figure 4 contains plots of the albedo calibration $A(t = 0)$ as a function of wavelength, both the prelaunch calibration and the adjusted calibration resulting from the normalization pro-

cedure described above. Though the internal Meteor TOMS adjustments result in agreement between the A triplet and B triplet total ozone and therefore a self-consistent global map, they also result in a less continuous set of calibration coefficients, particularly at 317 nm. Smooth spectral dependence is expected because A is proportional to diffuser reflectivity. This result may imply some inconsistency between the instrument calibration and the forward model used in the retrieval. The 312/317 nm discontinuity, seen more clearly in the ratio plot of Figure 4b, represents roughly 2% in total ozone. A similar analysis of the N7/TOMS calibration adjustments did not indicate a discontinuity of this magnitude.

4. Results

Figure 5 shows the difference between ozone values determined from M3/TOMS and N7/TOMS for the match-up data set after all of the adjustments to the Meteor 3 normalized radiances have been made. Since the adjustments were made only to within 0.1 N value, a systematic error of approximately ± 0.8 Dobson units (DU) is possible. The results shown in Figure 5 therefore indicate that the normalization procedure produced a M3/TOMS data set in agreement with N7/TOMS within the known error.

The Meteor 3 TOMS data set was then processed, and a level 3 gridded product was produced. A histogram of the total ozone difference between M3/TOMS and N7/TOMS for March 20, 1992, was again made and is shown in Figure 6. The peak is much more Gaussian in shape and narrower when compared to Figure 1. A Gaussian fit to the distribution, also shown in Figure 6, is centered at -0.6% with a sigma of 1.8%. At least half of the -0.6% offset in the peak of the Gaussian is due to the 0.8 DU (approximately 0.3%) offset shown in Figure 5. The remaining 0.3% difference is well within the uncertainty of ozone determination. Sources of uncertainty include small algorithmic errors resulting from differences in scattering angles between the two instruments in the presence of aerosols and differences in scan bias between the two instruments. These differences are not fully characterized by the radiative transfer model used in the retrieval. The uncertainty

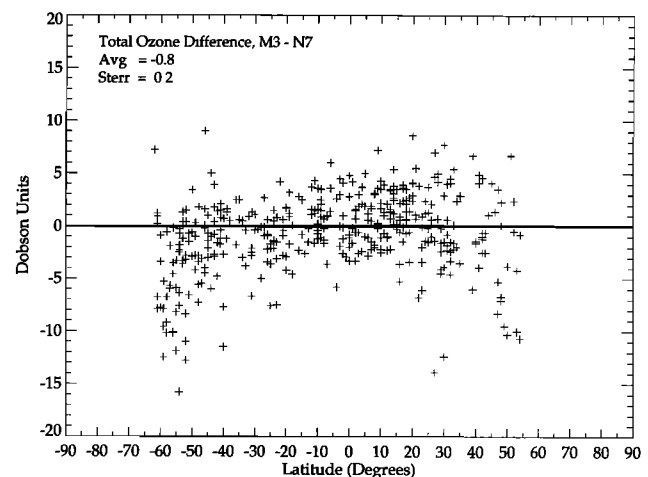


Figure 5. The difference in ozone between Meteor 3 and Nimbus 7 TOMS for the matchup data set after normalization. An offset of -0.8 Dobson units is indicated, which is within the known errors.

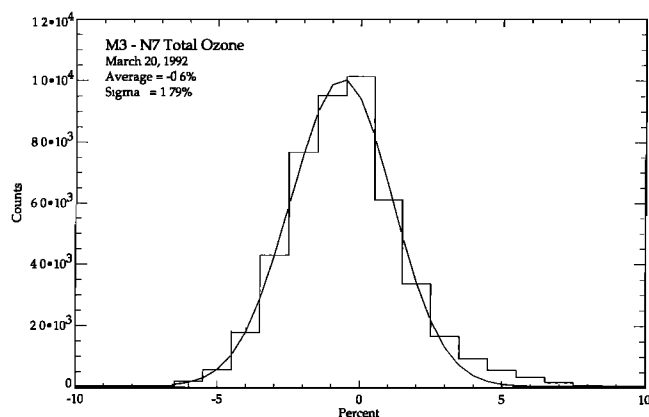


Figure 6. A histogram of the difference in ozone between Meteor 3 and Nimbus 7 TOMS for March 20, 1992, after normalization. The histogram includes all points in the 1.25° longitude by 1° latitude level 3 grid. A Gaussian fit of the histogram indicates an offset of -0.6% .

due to residual calibration errors is approximately 0.5% for each instrument.

Mean total ozone values from the level 3 data product were calculated for 10° latitude bands and compared to those from the level 3 N7/TOMS data set for each day when the two instruments were taking data. Figure 7 shows the difference of the zonal mean values for four of the latitude bands. The plots clearly indicate large periodic discrepancies between the two instruments, particularly during the first year of overlap when aerosols from Mount Pinatubo were abundant. As described in section 2, the discrepancy occurs due to calibration and radiative transfer modeling problems as the orbit of Meteor 3 drifts toward the terminator.

The relationship between the LECT of Meteor 3 and differences in ozone measured by the two instruments is clearly indicated in Figure 8, which shows the zonal mean ozone difference as a function of the LECT of Meteor 3 (0000–1200 and 1200–0000 hours are superimposed) for the same four latitude bands as in Figure 7.

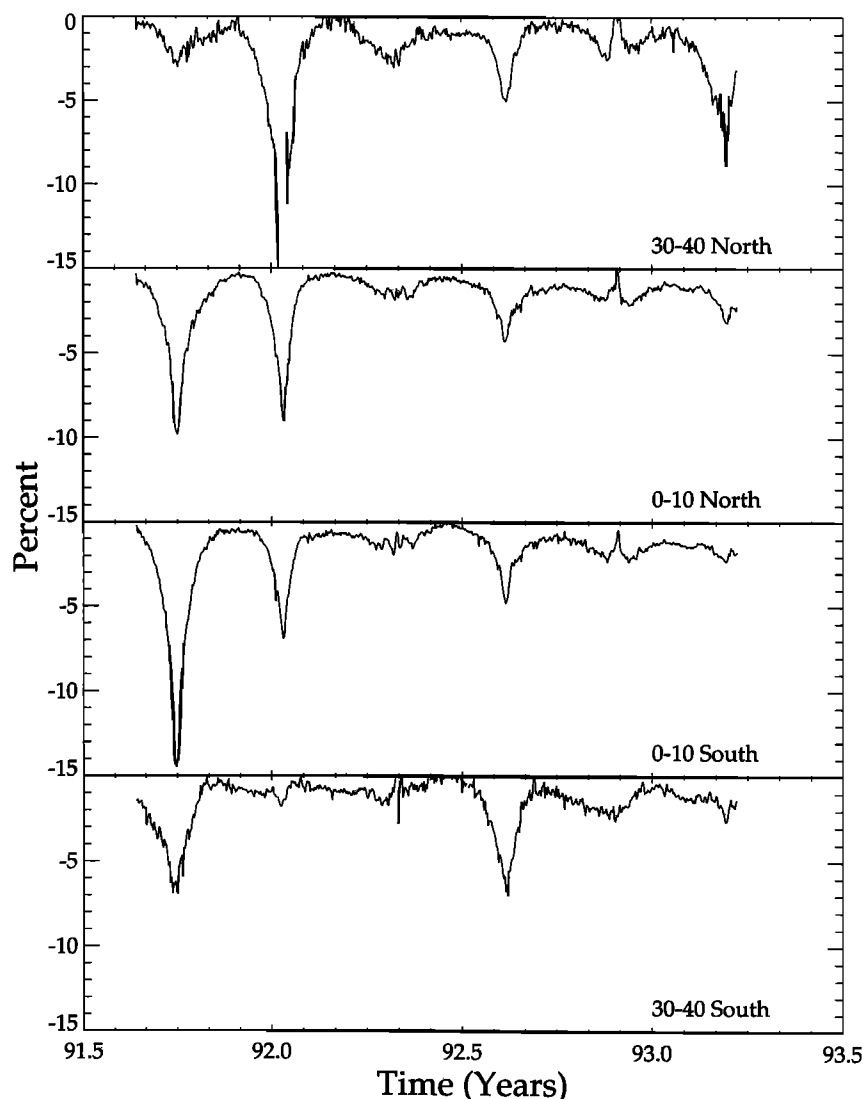


Figure 7. A time series of the day-to-day difference in total ozone between Meteor 3 and Nimbus 7 TOMS for four zonal mean latitude bands. Large periodic discrepancies can be seen that correspond to Meteor 3 orbits that are near the terminator.

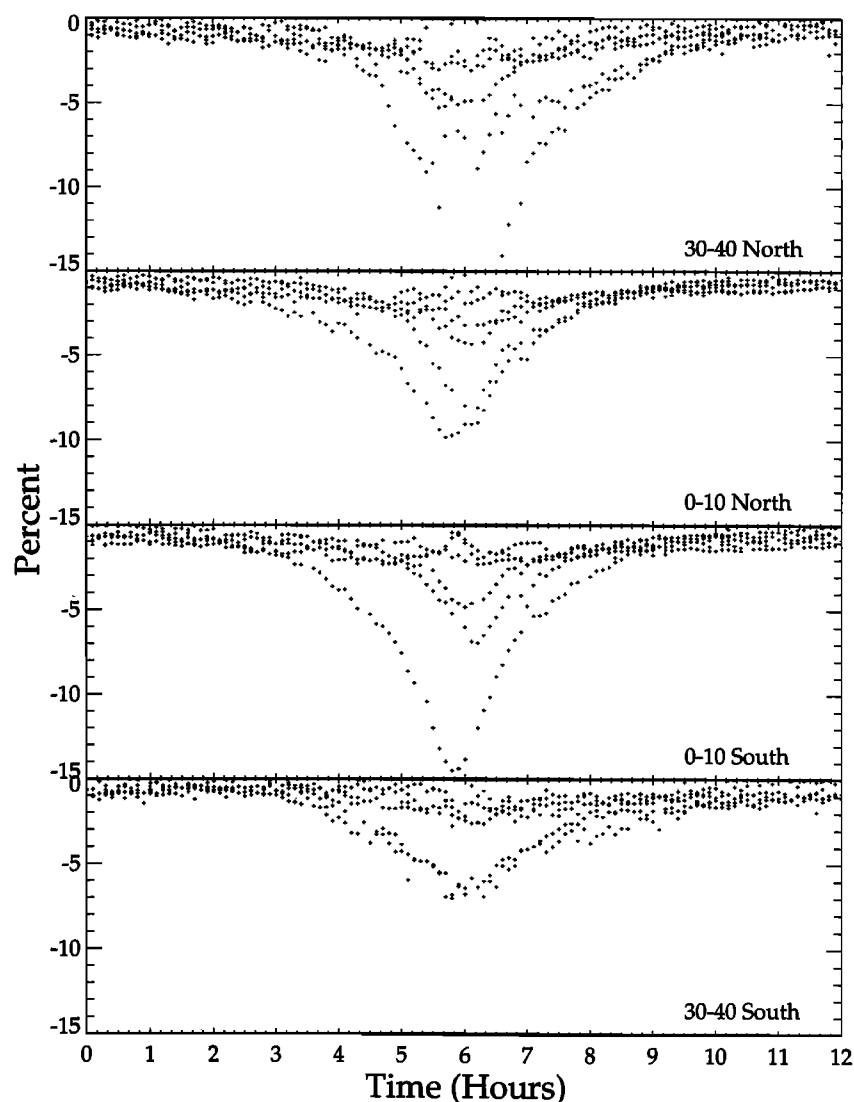


Figure 8. The difference in total ozone between Meteor 3 and Nimbus 7 TOMS for the same four latitude bands as Figure 7 plotted as a function of Meteor 3 local equator crossing time (0000–1200 and 1200–0000 hours are superimposed).

Because of these problems, only data taken when the orbit of Meteor 3 was well away from the terminator have been archived and made available for use. In particular, data taken when the sunlit portion of the first orbit of the day had a LECT between 0900 and 1500 have been made available during the first data year (August 1991 through August 1992) and those taken when the sunlit portion of the first orbit of the day had a LECT between 0800 and 1600 have been made available for the remaining $2\frac{1}{2}$ years. The tighter limitations in the first data year are applied because of the strong impact of aerosols from Mount Pinatubo during that period. It should be noted that a small dependence on LECT remains in the constrained data set.

Figure 9 shows zonal mean comparisons for data constrained between these LECTs for 10 of the 18 latitude bands. In general, the ozone agreement between M3/TOMS and N7/TOMS is within 1%. This difference can be more clearly seen in Figure 10, in which the mean difference between M3/TOMS and N7/TOMS for each of the 18 latitude bands is plotted as a function of latitude band.

5. Conclusions

The M3/TOMS data set was reprocessed through version 7 of the TOMS retrieval algorithm with an updated calibration. Part of the calibration procedure was an overall adjustment of the normalized radiances of M3/TOMS to agree with those from N7/TOMS for measurements in which time and viewing conditions were closely matched between the two instruments.

Subsequent ozone comparisons made between the full M3/TOMS data set and the N7/TOMS data set indicate agreement within 1% when the orbit of the Meteor 3 satellite was away from the terminator. When the Meteor 3 satellite orbited near the terminator, problems due to both the calibration of the instrument and the radiative transfer model used in the algorithm lead to unreliable ozone retrievals. During the first data year the problems were exacerbated by stratospheric aerosols from Mount Pinatubo. As a result, only data taken when Meteor 3's orbit was away from the terminator (i.e., when either the ascending or descending LECT of the orbit is between

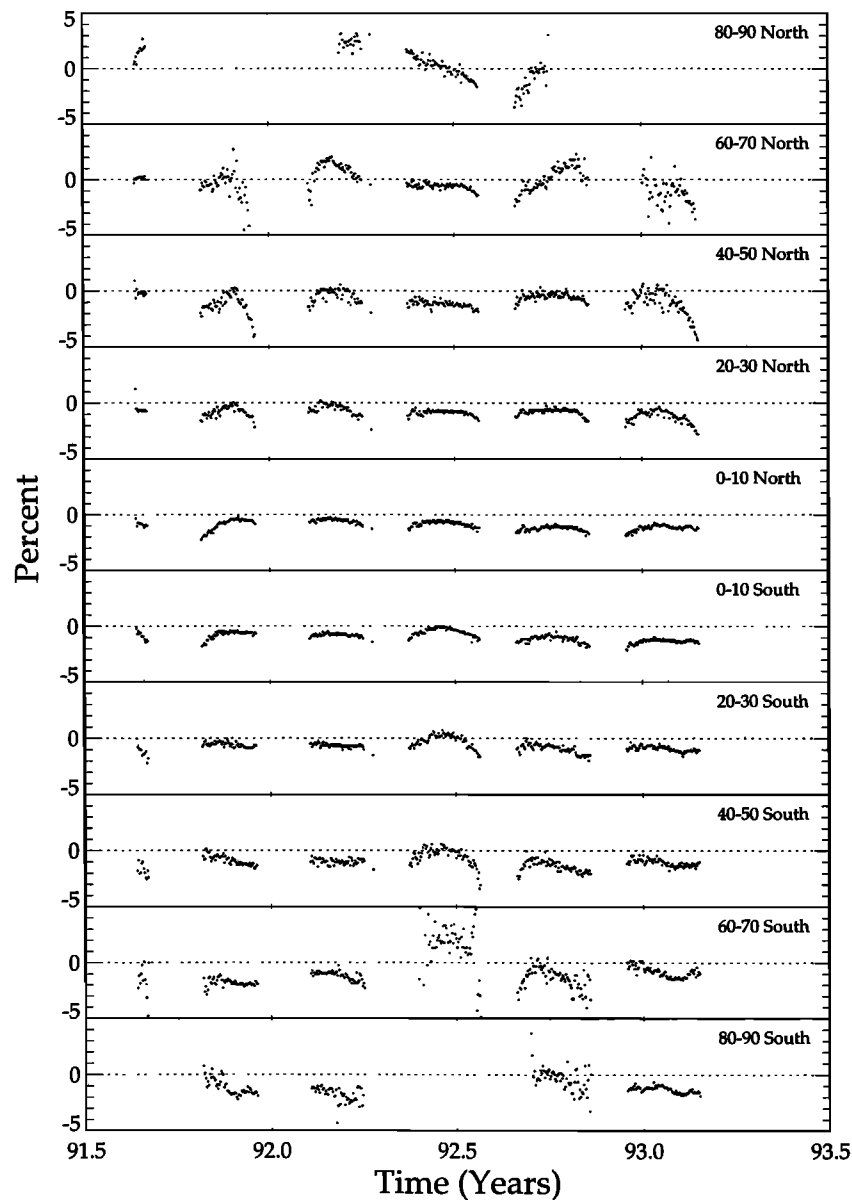


Figure 9. The time series of the difference in total ozone between Meteor 3 and Nimbus 7 TOMS for 10° latitude bands.

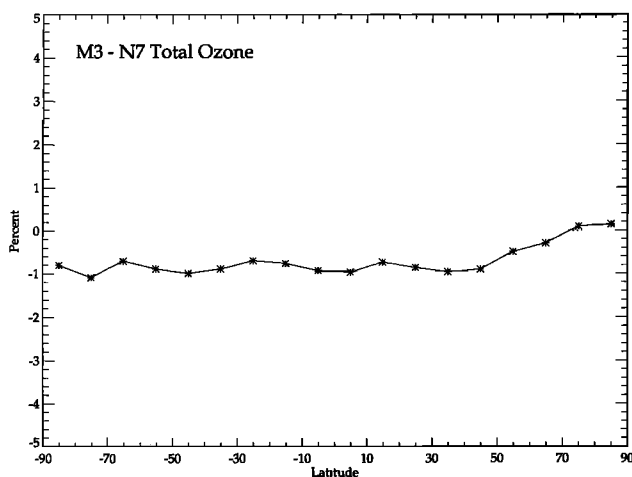


Figure 10. The mean difference in total ozone between Meteor 3 and Nimbus 7 TOMS as a function of latitude band. The agreement between the two instruments is within 1% almost everywhere.

0900 and 1500 for the first data year, 0800 and 1600 later) are being released and archived. Furthermore, the onset of chopper wheel synchronization problems in May 1993 led to periods of large-scale data rejection through to the end of the M3/TOMS data set.

Acknowledgments. The authors would like to thank other members of the OPT for their help in producing and providing both M3/TOMS and N7/TOMS data. The authors would especially like to thank Omar Torres for many helpful discussions regarding the radiative transfer model and ozone retrieval under both aerosol-contaminated and extreme viewing angle conditions.

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(Received October 4, 1996; revised February 21, 1997; accepted February 21, 1997.)