An Approach to the Detection of Long-Term Trends in Upper Stratospheric Ozone from Space

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ABSTRACT

A central problem in the detection of long-term trends in upper stratospheric ozone from orbiting remote sensors involves the separation of instrument drifts from true geophysical changes. Periodic flights of a Solar Backscatter Ultraviolet radiometer (SSBUV) on the Space Shuttle will allow the detection of drifts in optically identical sensors (SBUV/2) carried on operational satellites. A detailed simulation of the SSBUV and SBUV/2 datasets defines the accuracy that can be attained by the in-orbit calibration procedure. The repeatability of the SSBUV calibration from one flight to the next is the most critical variable in the analysis. A repeatability near ±1% is essential for detection and correction of drifts in the SBUV/2 radiance measurements. The simulations show that one can infer true geophysical trends in backscattered radiance to an accuracy of approximately ±1.0% per decade when SSBUV flies approximately once per year and provides a precise calibration correction to the SBUV/2 dataset over a full decade.

1. Introduction

The detection of long-term trends in atmospheric ozone, particularly as they arise from human activity, continues to be of scientific importance. In particular, theory predicts that chlorine atoms released from industrial chlorofluorocarbons are leading to the catalytic removal of upper stratospheric ozone on a global scale. Model calculations show the largest percentage depletion in ozone near 40 km in altitude (Brasseur and De Rudder 1987; Kinnison et al. 1988) with a magnitude of 3%–4% per decade. Measurements of the ozone profile by the ground-based Umkehr method indicate changes which are generally consistent with theory, although the geographic coverage is poor and error bars on the derived trends are large (Reinsel et al. 1984, 1987).

Satellites provide the only means of obtaining global-scale information on atmospheric ozone. Unfortunately, remote sensing techniques can encounter major problems when used for the detection of changes that occur over time scales of several years and longer. The optical and electronic components of satellite-borne sensors change slowly over time, and these drifts must be accounted for if one is to distinguish instrument artifacts from true geophysical trends. A viable satellite-based ozone measurements program should be able to produce a dataset in which the remaining uncorrected trend associated with instrument drift is small compared to the trend arising from long-term ozone changes. The fundamental issue involves distinguishing a change in instrument sensitivity from a true change in atmospheric ozone.

The instruments currently in use for operational monitoring of the ozone layer are the Solar Backscatter Ultraviolet Radiometers-Model 2 (SBUV/2), being advanced versions of the SBUV instrument flown on the Nimbus 7 satellite. Heath et al. (1975) have discussed details of the instrumentation. The first of the new instruments was launched on the NOAA-9 satellite in December 1984, and a series of identical sensors will be flown through the 1990s. The quantity measured by SBUV/2 is the ratio of backscattered radiance which emerges from the atmosphere in the vertical (I_λ) to the extraterrestrial solar irradiance (F_λ) at wavelength λ. The ratio I_λ/F_λ is obtained at 12 wavelengths between 250 and 340 nm with a 1 nm spectral resolution. Vertical profiles of ozone at altitudes above approximately 30 km and total column ozone are derived by application of radiative transfer algorithms to these data. The only optical component that is not common to both the I_λ and F_λ measurements is the instrument diffuser plate, which is deployed only for solar observations. Frederick et al. (1986) have summarized these and other aspects of SBUV/2 operation. Use of the

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"backscatter ratio", defined as $A(\lambda) = I_\lambda/F_\lambda$, nullifies the effect of most instrumental drifts on the ozone derivation. However, the items identified above imply that the backscatter ratio is not necessarily stable over the lifetime of a single SBUV/2 instrument.

One approach to SBUV/2 instrument characterization involves periodic flights of an optically identical sensor on the Space Shuttle. If one adopts this shuttle SBUV (SSBUV) as the calibration standard, then a direct comparison of coincident backscatter ratio measurements with SBUV/2 provides a basis for identifying drifts in the operational sensors. Figure 1 illustrates the concept. During a period of several days the SSBUV and SBUV/2 observe the same location on the earth within one hour of the same time at the rate of about 17 coincidences per day. The low inclination of the Shuttle orbit restricts these near-coincidences to latitudes within 30 degrees of the equator. Flights of SSBUV conducted at intervals of six months to one year over an entire decade will provide a reference dataset of backscatter ratios at the same wavelengths sensed by the SBUV/2 instruments. The initial flight of SSBUV took place in October 1989.

Hilsenrath et al. (1988) have discussed the approach of using a well-calibrated sensor to identify instrument drifts in the long-term database acquired by SBUV/2. However, to assess the feasibility of the approach one must examine several issues in detail. The objectives of the work reported here are: 1) to define the variables that influence the effectiveness of SSBUV as a calibration standard, 2) to develop a methodology for bringing the SSBUV measurements to bear on the long-term SBUV/2 dataset for the purpose of seeking trends in upper stratospheric ozone, and 3) to determine the uncertainty in geophysical trends derived using the above technique. For reasons stated later in this paper, the methodology applies only to the five shortest wavelengths sensed by SSBUV and SBUV/2. These are the signals required for derivation of the ozone profile at altitudes above 30 km.

2. Issues in the detection of instrument drifts

The detection of drift in a single SBUV/2 instrument will be based on comparisons with nearly simultaneous backscatter ratio measurements made by SSBUV, taken to be the calibration standard. Let the backscatter ratio dataset obtained by SBUV/2 be $A_2(\lambda, t)$ where t is time. During the lifetime of the operational sensor there will be several flights of SSBUV, each denoted by the index $j = 1, 2, \cdots$, and during a single shuttle flight there will be N coincidences between SSBUV and SBUV/2. These will occur over a period of approximately three days. A typical value is $N = 30$. We let $A_s(\lambda, j, k)$, $k = 1, 2, \cdots, N$ and $j = 1, 2, \cdots$, indicate the SSBUV measurements where the indices j and k together specify a unique time t_{jk} during the life of a single SBUV/2 sensor. Changes in SBUV/2 sensitivity occur only over a time scale long compared to the duration of a single SSBUV flight, and we assume that SSBUV is a stable reference over a period of several days in orbit. This stability will be verified by in-flight monitoring plus pre- and post-flight calibrations.

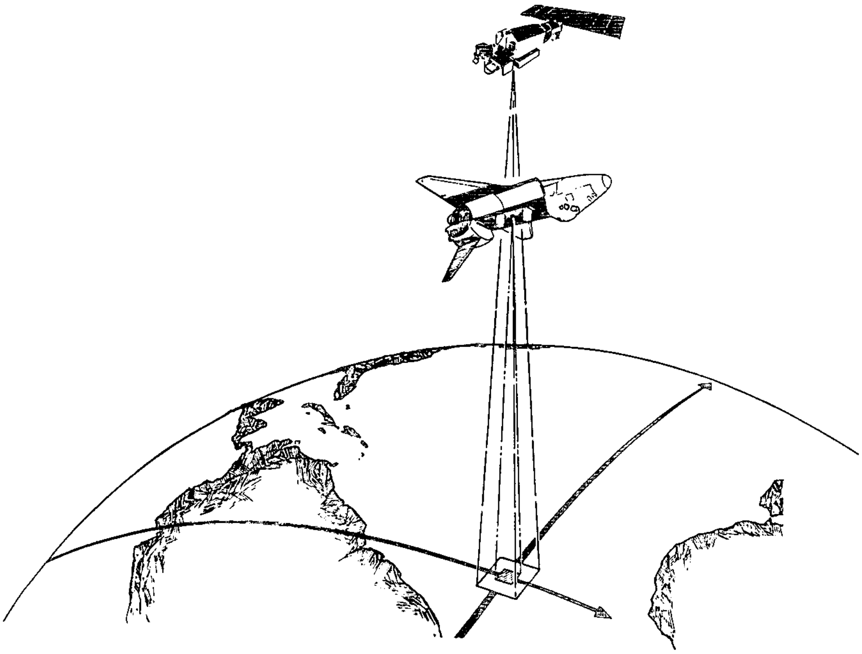

FIG. 1. Schematic of the in-orbit calibration of an operational SBUV/2 by an underflight of the shuttleborne SSBUV instrument.

A "correction factor" which normalizes A_2 to A_s during the jth shuttle mission is

$$c(\lambda, j) = \frac{1}{N} \sum_{k=1}^{N} \frac{A_s(\lambda, j, k)}{A_2(\lambda, t_{jk})}. \quad (1)$$

Several SSBUV flights during the lifetime of a single SBUV/2 instrument allow a fit to the individual $c(\lambda, j)$ to give a time dependent correction factor of the form:

$$c(\lambda, t) = c_0(\lambda) + c_1(\lambda)t \quad (2)$$

where time, t, is a continuous variable. The assumption of a linear dependence on time is not essential, and any analytic form could be chosen in place of (2). An examination of the $c(\lambda, j)$, $j = 1, 2, \cdots$, will indicate a suitable time dependence, although this can be defined only after all SSBUV flights for a given SBUV/2 sensor have been completed. The accuracy of the drift detection procedure requires only that the analytic form adopted in (2) be consistent with the behavior displayed by the ensemble of $c(\lambda, j)$ values determined in (1). Given the limited number of SSBUV flights possible during the lifetime of a single SBUV/2 instrument, the final analytic fit should include only two or three parameters. The calculations reported in this paper adopt the linear form as in (2) where the parameters c_0 and c_1 are to be determined.

We assume that long-term drifts, as manifested by c_1 being nonzero in (2), arise from changes in the radiometric calibration of the SBUV/2, as opposed to the wavelength calibration. Each SBUV/2 carries an onboard mercury lamp for performing regular updates of the wavelength calibration. If one of these lamps were to fail, then it is possible that the SSBUV and SBUV/2 measurables would refer to slightly different wavelengths and that this offset will change slowly over time. Since the ozone absorption cross section varies with wavelength, A_s and A_2 would not respond to the same degree to differences in ozone among the observations that enter the summation in (1). In this case the value of $c(\lambda, j)$ depends both on the atmosphere and on the instruments, rather than being a property of the instruments alone. This represents a new source of error, although we stress that it appears only if a calibration lamp fails. Given such an event, a detailed study of this issue would be required.

If SSBUV and SBUV/2 viewed the same scene simultaneously, then each $c(\lambda, j)$ from (1) would depend only on the properties of the instruments. Furthermore, if SSBUV were indeed a perfectly calibrated standard, then a nonzero value of c_1 in (2) would arise from a drift in SBUV/2 over a time scale of months to years. An adjustment could then be applied to the entire SBUV/2 dataset to remove the drift. This is expressed as

$$A_c(\lambda, t) = c(\lambda, t)A_2(\lambda, t) \quad (3)$$

where $A_c(\lambda, t)$ is a dataset of backscatter ratios with the instrumental trend removed. We refer to $A_c(\lambda, t)$ as the "corrected" SBUV/2 dataset which, in the ideal case, is identical to the true backscatter ratios. Since $c(\lambda, t)$ represents, in principle, a property of the SBUV/2 instrument only, the adjustment in (3) can be applied to data on a global scale, even though intercomparisons with SSBUV are restricted to low latitudes.

The procedure summarized above is straightforward, but its accuracy depends on several factors that we categorize as either geophysical or instrumental. We consider the geophysical factors first. Given two sensors with no calibration or measurement errors whatsoever, the values of A_s and A_2 in (1) are still not necessarily identical. This arises from (i) the lack of exact simultaneity between the SSBUV and SBUV/2 measurements and (ii) the differing altitudes of the two orbits combined with horizontal structure in the ozone distribution. As regards the lack of simultaneity, changes in solar zenith angle lead to a local time dependence in the backscatter ratio. Systematic differences will therefore exist between the values measured by SSBUV and SBUV/2 when the data are not simultaneous. However, it is straightforward to adjust the SBUV/2 signal to refer to the solar zenith angle of the SSBUV measurements. This can be done either with a radiative transfer model (e.g., Frederick and Serafino 1985) or by statistical regression.

Related to the differing orbital altitudes, the SSBUV field of view (FOV) intercepts a smaller area on the earth's surface, seen from a 300 km high shuttle orbit, than does SBUV/2 at an altitude near 800 km. The FOVs of SSBUV and SBUV/2, when projected onto the earth, are squares whose sides are approximately 59 km and 160 km in length, respectively. The measured radiances are implicit averages over these squares, so any variability in the backscatter ratio over length scales of several tens of kilometers will lead to a true difference between the SSBUV and SBUV/2 signals. Studies of column ozone measured by the Total Ozone Mapping Spectrometer (TOMS), whose field of view is approximately equal to that of SSBUV, indicate horizontal variations of approximately 1% over areas comparable to the SBUV/2 footprint. This number likely overestimates the horizontal variability in upper stratospheric ozone. In any case, this source of error has negligible impact on the SSBUV-SBUV/2 intercomparison since any random variations tend to average to zero in the summation of (1).

The backscatter ratio also varies because of cloudiness in the instrument FOV. Variations in tropical cloud cover over small spatial and short temporal scales pose a unique problem for the intercomparison of SSBUV and SBUV/2. To circumvent this issue, the methodology developed in this paper applies only to the five shortest wavelengths sensed by the instruments, being 252.1, 273.5, 283.0, 287.6, and 292.2 nm. Absorption by ozone at these wavelengths is sufficiently strong to prevent radiation from penetrating down to the cloud tops, backscattering, and then escaping into space. These wavelengths restrict our methodology to the detection of trends in upper stratospheric ozone. The capability to detect global scale trends in total column ozone is obviously of great importance. Instrument drifts are not so severe a problem here as in the case of ozone profile derivations, since the column ozone inference uses a ratio of backscattered radiances at different wavelengths (Klenk et al. 1982). However, differences in cloudiness between the SSBUV and SBUV/2 fields of view imply that the two instruments will sometimes sense atmospheric volumes with different radiative transfer properties. This complication merits a separate study and lies beyond the scope of the present paper.

The discussion to this point assumes that SSBUV is a perfectly calibrated standard of irradiance. In practice, factors related to instrument performance will certainly be the major source of difference between the SSBUV and SBUV/2 measurements. The two issues to consider here are (i) the scan-to-scan repeatability of SSBUV and, more importantly, (ii) the flight-to-flight repeatability in the SSBUV calibration. The simulations described below address these topics in detail.

3. Numerical simulation procedure

A test of the planned procedure for SBUV/2 drift detection requires numerical simulations that include all of the geophysical and instrumental issues described above. The first step is to generate synthetic backscatter ratios for SSBUV and SBUV/2. Let $A_T(t_{jk})$ be the true backscatter ratio at the time t_{jk} of coincident SSBUV and SBUV/2 measurements. The simulated backscatter ratio from SBUV/2 is

$$A_2(t_{jk}) = [1 + f_2(j, k)]A_T(t_{jk}) \qquad (4)$$

In this and all subsequent equations we suppress the subscript that denotes wavelength. The term $f_2(j, k)$ provides for a long-term drift in SBUV/2 response, assumed to occur on a time scale long compared to the duration of a Shuttle flight. A simple choice is

$$f_2(j, k) = \frac{f}{365} t_{jk} \qquad (5)$$

where f is the instrument drift, with $100f$ being in percent per year.

We incorporate random variations related to the geophysical and instrumental issues described above into the modeled SSBUV database. The simulated SSBUV backscatter ratios are

$$A_s(j, k) = [1 + b(j)][1 + n_s(k)]A^*(j, k) \qquad (6)$$

where $b(j)$ is the calibration bias on shuttle flight j. While it is essential that the relative calibration of SSBUV be repeatable to a high tolerance from one flight to the next, systematic offsets between SSBUV and a given SBUV/2 instrument are of no consequence for trend detection. Current procedures allow a flight-to-flight repeatability in calibration of better than ±1% in most cases (Cebula et al. 1989). Most of the calculations reported in this paper adopt ±1% as the extreme bias experienced in any one shuttle flight, although we also examine the consequences of ±2% errors.

The term $n_s(k)$ in (6) provides a noise component related to the scan-to-scan repeatability of SSBUV. Based on tests of the instrument, this repeatability is ±0.4%. For each SSBUV-SBUV/2 coincidence we simulate this by selecting $n_s(k)$ from a normal distribution whose mean is zero and whose standard deviation is 0.004. Finally, the albedo $A^*(j, k)$ incorporates an estimate of true differences in ozone between the SSBUV and SBUV/2 fields of view. Based on the TOMS analyses mentioned in the previous section, we take this variability to be random with a 2σ value equal to 1% of $A_T(j, k)$. The value of $A^*(j, k)$ is selected from a normal distribution whose mean is $A_T(j, k)$ and whose standard deviation is $0.005A_T(j, k)$.

Of the three random variables that enter (6), the flight-to-flight calibration repeatability of SSBUV has by far the greatest influence on the ability to detect drifts in SBUV/2. This is because $n_s(k)$ and the $A^*(j, k)$ take on different random values for each coincidence with SBUV/2, of which there are approximately $N = 30$ on a given SSBUV flight. This leads to a large degree of cancellation of errors. However, the SSBUV bias, $b(j)$, has a fixed value for an entire shuttle flight. Many launches of SSBUV are required to reduce the effect of the random flight-to-flight calibration bias.

There is no unique methodology for selecting the $b(j)$ for use in the simulations reported below. We proceed based on the following rationale. In view of the meticulous care to be given to the SSBUV calibration, we assume that the maximum error is bounded, and we alternately take these bounds to correspond to maximum biases of ±1% and ±2%. Given these limits, we assume that any error within this range is equally probable. Hence, for the simulations we select the $b(j)$ at random from uniform distributions whose limits are ±0.01 or ±0.02. Use of a normal distribution would have allowed the possibility for occasional very large errors. If such errors occur in practice, they would appear as anomalous values of $c(\lambda, j)$ computed in (1), and data from this shuttle flight should be omitted from the drift detection effort. By choosing the uniform distribution, we effectively assume that no unusually large biases will enter the analyses. We view this as an operational requirement on the SSBUV project.

4. Long-term simulations

The objective of the SSBUV effort is to obtain measurements that will allow the removal of instrument drifts from the SBUV/2 dataset. The corrected database will span a decade and will consist of measurements obtained by several SBUV/2 instruments flown in succession. When SSBUV provides a stable reference, drifts in the SBUV/2 instruments become irrelevant insofar as ozone trend detection is concerned.

Statistical analyses will be applied to the corrected SBUV/2 database for the purpose of detecting trends in upper stratospheric ozone. The final topic addressed in this paper involves a complete simulation of ozone trend detection based on a simulated ten-year dataset corrected for instrument drifts by comparison with a series of SSBUV flights. The first task involves simulating a ten-year dataset of true backscatter ratios, A_T, for use in (4) and (6). For this we used measurements made near the equator made by the Nimbus 7 SBUV instrument. We first detrended the dataset for the five year period 1979 through 1983 inclusive, and then repeated the time series to simulate a full decade. These backscatter ratios include all annual, interannual, and random variability, but contain no long-term trend. Figure 2 presents the five-year dataset for a wavelength of 292.2 nm. All calculations presented here utilize these values. Frederick and Serafino (1985) show that the predicted trend in upper stratospheric ozone leads to a percentage change in backscatter ratio which maximizes at 292.2 nm and that the percent change in A_T at 292.2 nm is approximately one-half the percentage change in ozone at 40 km. We next impose a known trend, presumed to be of geophysical origin, onto the dataset. The resulting time series, containing the known geophysical trend, serves as the true backscatter ratios, $A_T(t)$. The simulations then determine the accuracy with which the known trend can be recovered.

Given a ten year series of true backscatter ratios, we used (4) to construct a set of simulated data records, A_2, each presumed to be from a single SBUV/2 instrument. We then consider a case where two SBUV/2 instruments provide the ten-year data record and the more likely scenarios in which three and four operational instruments flew in succession over the period. We report results where each instrument experienced a drift of 2.0% per year, specified by $f = 0.2$ in (5). In various tests we examined cases in which the SBUV/2 drift varied from 0 to 4% per year and found that the ozone trend detection capability is insensitive to this choice. When SSBUV is the calibration standard, any accidental trend in the SSBUV calibration bias, rather than the drift in the SBUV/2s, is the major factor that controls the accuracy of geophysical trend detection.

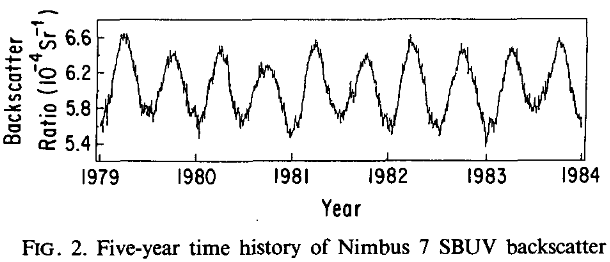

FIG. 2. Five-year time history of Nimbus 7 SBUV backscatter ratios at 292.2 nm obtained within one degree latitude of the equator. A trend of 0.75% per year has been removed from the dataset. Tick marks denote the start of each year.

Based on the latest launch schedule, we then simulated data from ten flights of SSBUV spanning the period October 1989 to September 1995 using (6). After September 1995 we conservatively assumed one SSBUV flight per year through 1999. With the simulated datasets, A_2 and A_s, the trend detection study proceeded as follows. The instrument drift in the data record from each individual SBUV/2 is removed using all SSBUV coincidences during the lifetime of the operational sensor. This procedure utilizes (1), (2), and (3) and yields the dataset $A_c(t)$. A single trend analysis is then applied to all of the corrected SBUV/2 datasets combined, which now constitute a single ten-year time series. Ideally, the deduced trend will equal the known value imposed on the dataset A_T.

We describe the corrected backscatter ratios, A_c, by a regression model of the form:

$$A_c(t) = a_0 + a_1\theta + a_2R + a_3t + \sum_{m=1}^{3} [b_m \sin(z_m) + d_m \cos(z_m)] \quad (7)$$

where t is time in days from the start of the dataset, θ is the solar zenith angle, $z_m = 2\pi mt/365$, and R is the effective surface albedo derived from radiances at 339.8 nm (Klenk et al. 1982). The term involving R provides for cloudiness in the FOV and makes little contribution at wavelengths of 292.2 nm and shorter, although we retain it here for completeness (Frederick et al. 1989). The sine and cosine terms in (7) allow for annual, semiannual, and shorter term oscillations, where the $m = 1$ and 2 components are by far the most important. The regression coefficients a_0, a_m, b_m, and d_m, $m = 1$, 2, 3, are determined by a fit to the corrected ten-year data record. The estimate of the long-term geophysical trend in percent per decade is

$$g^* = \frac{3.65 \times 10^5}{\langle A_c \rangle} a_3 \quad (8)$$

where $\langle A_c \rangle$ is the mean value of A_c over the data record. The corrected datasets derived from the series of SBUV/2 instruments and fit to the model in (7) provides the best estimate of the true backscatter ratio, A_T.

We repeated the procedure summarized above ten times each for the cases of two, three, and four separate SBUV/2 instruments flown in succession over a decade. The random variables that enter the simulated SSBUV dataset imply that the different trials yield different values of the estimated trend, g^* in (8). If we performed a very large number of trials, the estimated trends would form a distribution whose mean is the true trend g. We let σ be the standard deviation, where approximately 95% of the estimated g^* values lie in the range $g \pm 2\sigma$. We estimate σ based on the ten trials. When actual SSBUV measurements are combined with a decade of SBUV/2 data, the derived trend in backscatter albedo will represent one particular value of g^* drawn from the statistical distribution generated above. The limit $\pm 2\sigma$ is an approximate error bar to place on the derived trend.

Tables 1, 2, and 3 summarize the results for the cases of two, three, and four SBUV/2 instruments respectively. The wavelength is 292.2 nm throughout, although no significant differences exist as compared to values for other wavelengths. Results appear for geophysical trends in the backscatter ratio of $g = 0.00$, 2.00, and 4.00% per decade where the middle value is approximately that expected for a decline in ozone of 4% per decade near 40 km (Frederick and Serafino 1985). Note that a positive trend in radiance implies a decrease in ozone. The tables include the minimum and maximum estimated trends as well as the average and the two standard deviation error bars based on ten trials. Table 1, for two SBUV/2 instruments spanning a decade, shows a worst-case error in trend estimate of 1.19% (=3.19 − 2.00) per decade while the two standard deviation uncertainty range is ±0.87% per decade for all values of g. The 2σ uncertainty ranges when three and four SBUV/2 instruments are flown during a decade are ±0.56–1.00% per decade and ±0.78–1.12% per decade from Tables 2 and 3 respectively. The rather small uncertainty range of ±0.56% per decade in Table 2 may be an unrepresentative result, arising from the specific set of random numbers which entered the ten test calculations.

All values presented above assume a flight-to-flight calibration repeatability of SSBUV in the range ±1%, with the exact value for any mission selected at random from a uniform distribution. Should this not be attained, the capability to detect trends diminishes. We performed ten test cases in which trends were estimated for a true value of $g = 2.0\%$ per decade, with three SBUV/2 instruments flown over the time period, and a flight-to-flight SSBUV calibration repeatability of ±2%. The mean of the estimated trends was $g^* = 1.97\%$ per decade, but the 2σ error bar widened to 1.78% per decade. We conclude that a SSBUV calibration repeatability near ±1% is essential for unambiguous detection of trends at the 95% confidence level.

TABLE 2. Estimates of the geophysical trend in backscatter ratio at wavelength 292.2 nm based on three SBUV/2 instruments flown over a ten year period.

True trend g (%/decade)	Minimum estimated trend g^* (%/decade)	Maximum estimated trend g^* (%/decade)	Average estimated trend g^* (%/decade)	Two standard deviations (%/decade)
0.00	−0.84	0.94	0.05	1.00
2.00	1.52	2.36	1.89	0.56
4.00	3.31	4.62	4.00	0.70

Finally, it is impossible to define the schedule of SSBUV launches with absolute certainty over a time period of a decade. We have therefore examined the trend detection capability obtainable in two different scenarios, each using a flight-to-flight calibration repeatability of ±1%. In the first case we assume flights of SSBUV spaced at one-year intervals, while the second case assumes flights of SSBUV every six months. We report results for the case $g = 2.0\%$ per decade and three different SBUV/s instruments flown in the ten-year period. The mean estimated trend based on ten trials with one SSBUV flight per year is $g^* = 1.91\%$ per decade with a 2σ uncertainty of ±1.23% per decade. This error bar, while larger than desired, is adequate for unambiguous detection of a trend with the magnitude expected from theory. The trend detection capability improves substantially when the frequency of SSBUV flights increases to two per year. This case yields a mean value of $g^* = 2.15\%$ per decade with a 2σ uncertainty of only ±0.72% per decade. We conclude that SSBUV flights at a frequency of at least one per year are required for purposes of trend detection, while a somewhat higher flight frequency is desirable.

5. Conclusion

The search for long-term trends in upper stratospheric ozone must utilize a dataset that is essentially

TABLE 1. Estimates of the geophysical trend in backscatter ratio at wavelength 292.2 nm based on two SBUV/2 instruments flown over a ten year period.

True trend g (%/decade)	Minimum estimated trend g^* (%/decade)	Maximum estimated trend g^* (%/decade)	Average estimated trend g^* (%/decade)	Two standard deviations (%/decade)
0.00	−0.75	0.54	−0.15	0.86
2.00	1.55	3.19	2.16	0.88
4.00	3.29	4.92	4.02	0.86

TABLE 3. Estimates of the geophysical trend in backscatter ratio at wavelength 292.2 nm based on four SBUV/2 instruments flown over a ten year period.

True trend g (%/decade)	Minimum estimated trend g^* (%/decade)	Maximum estimated trend g^* (%/decade)	Average estimated trend g^* (%/decade)	Two standard deviations (%/decade)
0.00	−0.97	0.86	0.03	1.12
2.00	1.51	2.89	2.27	1.00
4.00	3.48	4.76	4.22	0.78

free of instrument drifts. The collection of such a data record poses several problems which arise from both geophysical and instrumental variability. Periodic flights of SSBUV will, in principle, allow detection and removal of long-term drifts in the backscatter ratio dataset being acquired by operational SBUV/2 sensors. The present flight schedule of slightly more than once per year is adequate. One flight per year is required, while a flight every six months would provide a considerable improvement in the trend detection capability. If one adopts SSBUV as a calibration standard to which the SBUV/2 results are normalized, then to a first approximation, any drifts in the SBUV/2 instruments become irrelevant. The central issue here becomes the flight-to-flight repeatability in the calibration of SSBUV. A value near ±1% is essential for unambiguous detection of the ozone trend predicted at 40 km in altitude.

The decadal trend derived from a corrected SBUV/2 database will reflect the combination of random calibration biases in SSBUV and less significant errors such as arise from different FOV sizes of the instruments. The analyses performed here show a two-sigma error bar of approximately 1.0% per decade on the derived trend. Since the expected trend in backscatter ratio is approximately 2% per decade, this uncertainty range is adequate for detection of the trend.

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