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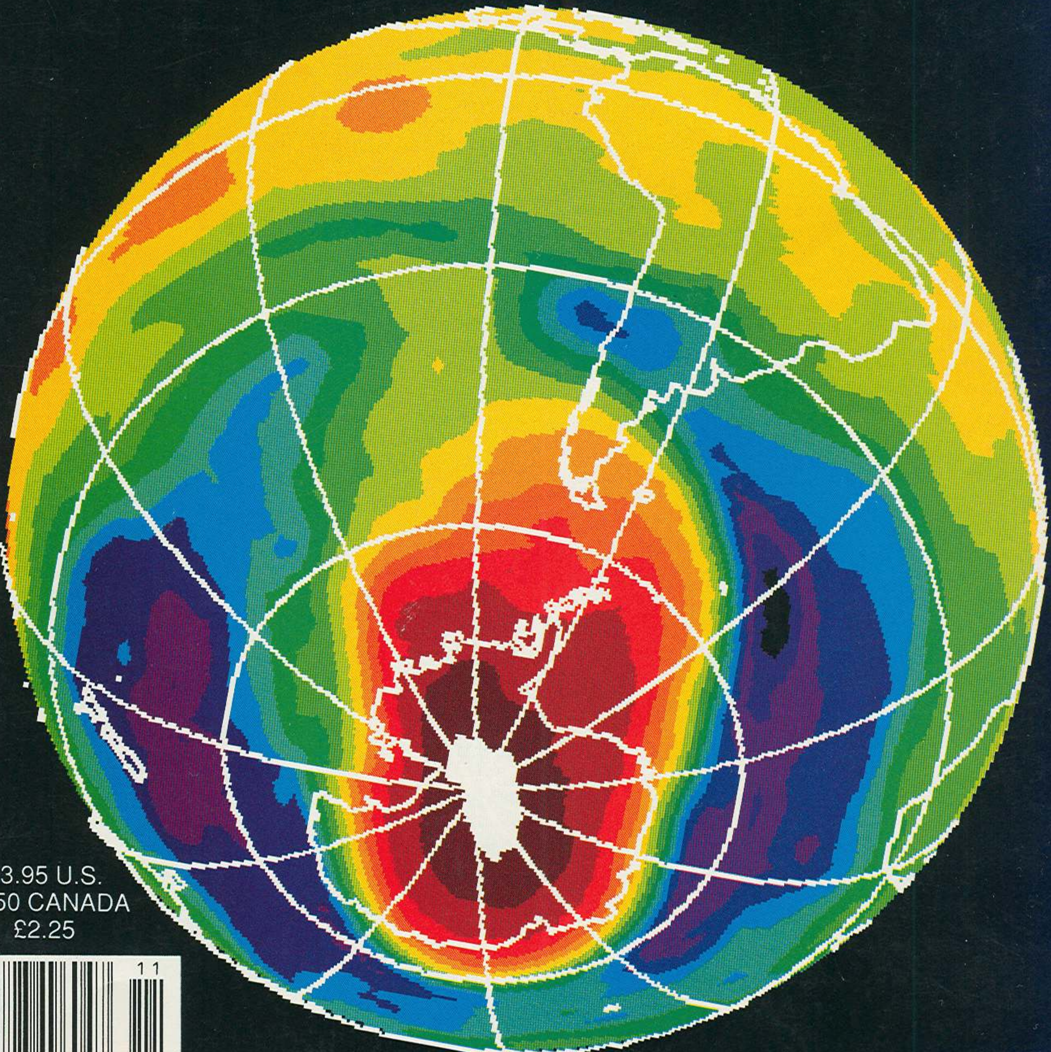
MEASURING THE OZONE LAYER



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How to Measure the Ozone Layer

By Forrest M. Mims, III, Editor

A Special Installment of "Science Experimenter"

Summary

The total amount of ozone in a column through the atmosphere can be determined by measuring two wavelengths of the ultraviolet radiation emitted by the Sun. An instrument that performs such measurements is the subject of this special installment of "Science Experimenter." Sufficient details are included for advanced experimenters to design their own ozone-monitoring instruments.

The amount of ozone between the ground and the top of the atmosphere can be measured with an instrument that is pointed at the Sun. Since 1989, I have designed and built several instruments capable of making such measurements. These instruments also provide data about direct solar ultraviolet.

For test purposes, I have assembled two nearly identical instruments called TOPS-1 and TOPS-2. (TOPS stands for **T**otal **O**zone **P**ortable **S**pectroradiometer.) Sufficient information is given here to enable advanced experimenters to assemble a TOPS instrument. Even if you do not plan to build a TOPS instrument, this article should give you considerable insight into one way the ozone layer can be accurately measured from the ground. For, as Figure 1 confirms, the TOPS instruments do indeed provide accurate data about the ozone layer.

Measuring Ozone

Ozone strongly absorbs ultraviolet (UV) radiation from the Sun with a wavelength below about 330 nanometers (nm). This absorption is so efficient that under normal conditions practically no radiation with a wavelength below 295 nm reaches the ground.

Ozone absorbs shorter wavelengths of UV much more efficiently than longer wavelengths. Therefore, the amount of ozone can be measured by a method known as *dual-*

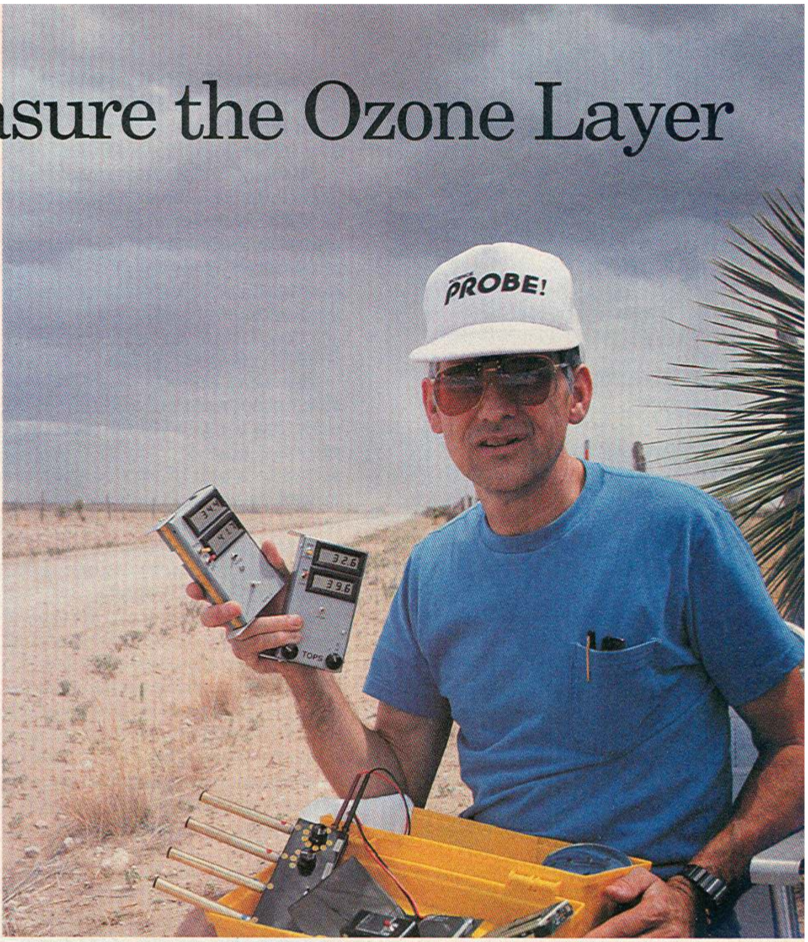
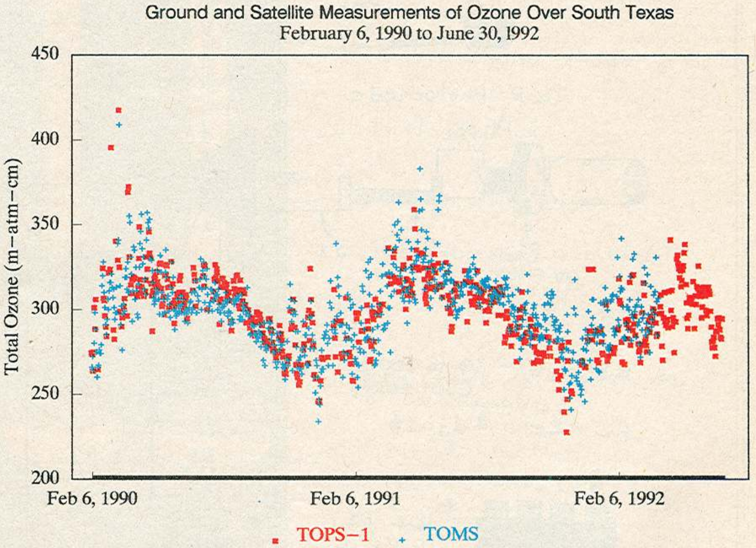


Photo by Eric R. Mims

The author measures ozone near a large thunderstorm in the New Mexico desert north of Carlsbad Caverns.



TOMS: NASA GSFC (A. Krueger et al)
TOPS−1: Forrest M. Mims, III

Figure 1. Comparison of ozone measurements made by the author using TOPS-1 in South Texas with nearly simultaneous observations by the TOMS instrument aboard the Nimbus-7 satellite.

wavelength absorption spectroscopy.

This method is, in principle, very simple. A TOPS instrument, for example, is simply a pair of UV radiometers installed in a single housing. The difficult part of measuring ozone is the various formulas that transform a pair of UV measurements into the amount of ozone. We shall discuss this topic later. First, let's examine the details of a working instrument.

The TOPS Ozonometer

In this and previous issues of *Science PROBE!*, I have referred to various measurements made with TOPS-1 and TOPS- 2. These filter ozonometers are similar in principle to the ozonometer first developed by A.L. Osherovich of the former Soviet Union and expanded on by W. Andrew Matthews and Reid E. Basher of New Zealand. The TOPS instruments are much smaller than these earlier instruments.

To make an ozone observation, a TOPS instrument is pointed directly at the Sun. UV radiation passing through the filters strikes the two detectors, which are 2-terminal photodiodes that convert light into an electrical current. The signal from each detector is amplified and sent to a miniature digital readout.

Although advanced experimenters should be able to assemble a TOPS instrument, it is important to understand that the necessary pairs of UV filters, photodiodes and high-resistance resistors are not readily available.

Selecting the Filters

The most important and expensive components of a TOPS instrument are the two UV filters. Most previous filter ozonometers respond to a pair of wavelengths separated by about 20 nm, but this means errors can be introduced by aerosols in the atmosphere. I minimize this problem by using wavelengths only 6 nm apart.

To make sure there is ample difference in the ozone absorption at two wavelengths this close together, it's necessary to use wavelengths close to the point at which all UV radiation is blocked by ozone because that's where the difference in absorption is most dramatic. I use wavelengths of 300 and 306 nm. These wavelengths work well at my latitude, 29° 35' north, but they will not work well at higher latitudes during winter and spring because of the lower Sun angle and the increased amount of ozone.

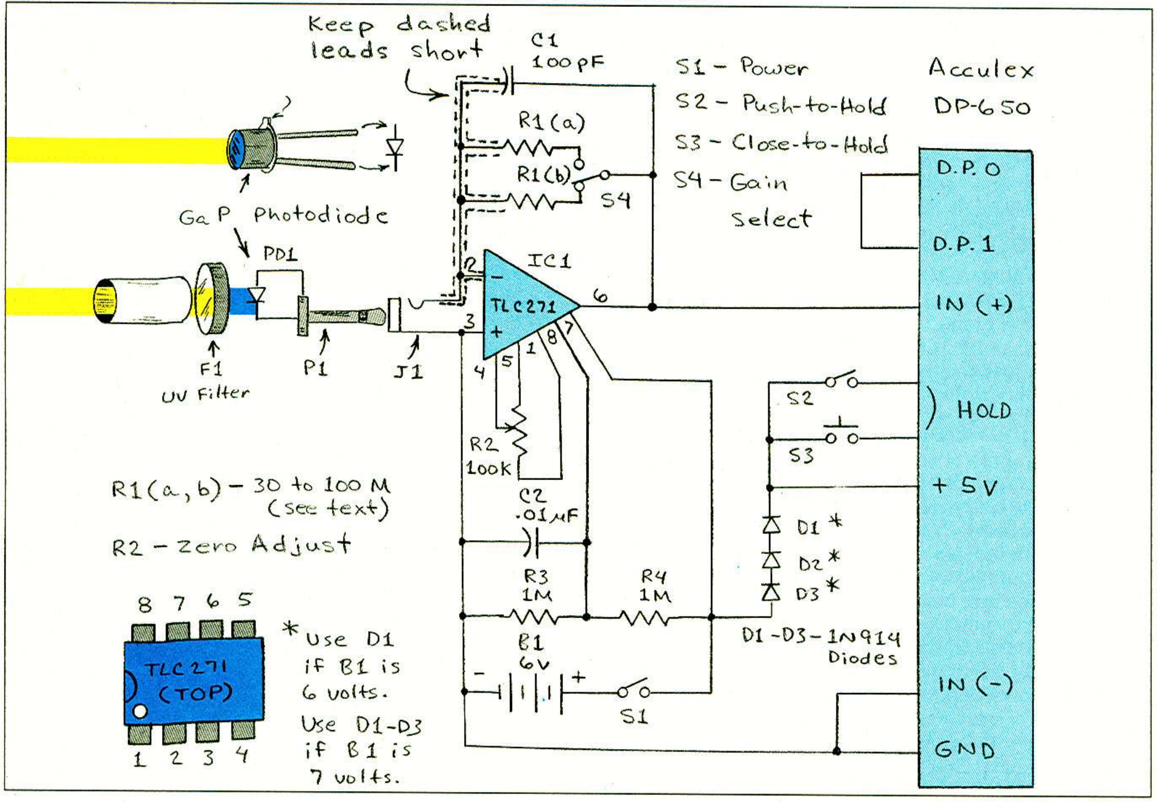
A better pair of wavelength ranges for locations above around 35° north would be 305 to 310 nm for the short wavelength and 325 to 330 nm for the long wavelength. The disadvantage of these wavelengths is that aerosols in the atmosphere may cause more error than with more closely spaced wavelengths.

For best results, the bandpass of filters used to detect ozone must be less than the 10 nm which is standard for most interference filters. The TOPS-1 and TOPS-2 filters each have a bandpass of 5 nm. If you cannot find filters with a 5 nm or less bandpass, you can reduce the bandpass of a 10 nm filter by stacking two of them.

Filters are commonly sold in diameters of 12.5 and 25 mm (0.5 and 1 in). Smaller filters are cheaper and easier to mount.

Stock UV interference filters cost $100 or more each, and custom filters are considerably more expensive. Manufacturers of stock filters include Twardy Technology, Inc.

Figure 2. Circuit diagram for one of the two channels in a TOPS ozonometer.



(P.O. Box 2221, Darien, Connecticut 06820), MicroCoatings (One Lyberty Way, Westford, Massachusetts 01886), and Andover Corporation (4 Commercial Drive, Salem, New Hampshire 03079). Additional manufacturers advertise in trade magazines for the optics and laser industries.

Building TOPS

Figure 2 is the circuit for one of the two identical UV radiometers in a complete TOPS instrument. Figure 3 shows how the various components are installed in an aluminum enclosure. If you have previous experience building miniature electronic circuits, you should be able to assemble your own instrument with these figures as a guide.

The prototype TOPS are installed in LMB CR-531 Crown Royal aluminum cases available from electronics distributors and Mouser Electronics (P.O. Box 699, Mansfield, Texas 76063; phone [800] 346-6873). Squeezing all the components into a CR-531 case requires careful planning; you can simplify assembly by using a larger cabinet. You must, however, make sure no light can leak between the filter and detector, and that the detector views a narrow cone with an angle of less than 2 degrees.

Because the signal from the photodiodes is very small, you must use a Texas Instruments TLC271CP or similar-quality operational amplifier; do not substitute a more common 741. If you substitute an even better quality amplifier, one or more of the pin connections may be different. The TLC271CP and R2 are available from various electronics distributors, including Newark Electronics. For a catalog, write Newark Electronics, 4801 North Ravenswood Avenue, Chicago, Illinois 60640-4496.

R1 is one or two very high resistance feedback resistors that are not widely available and whose values can be specified only approximately because of variations in signal transmitted by different filters at various wavelengths. I use two resistors to give two gain levels. Only one is needed if you plan to make measurements near noon throughout the year.

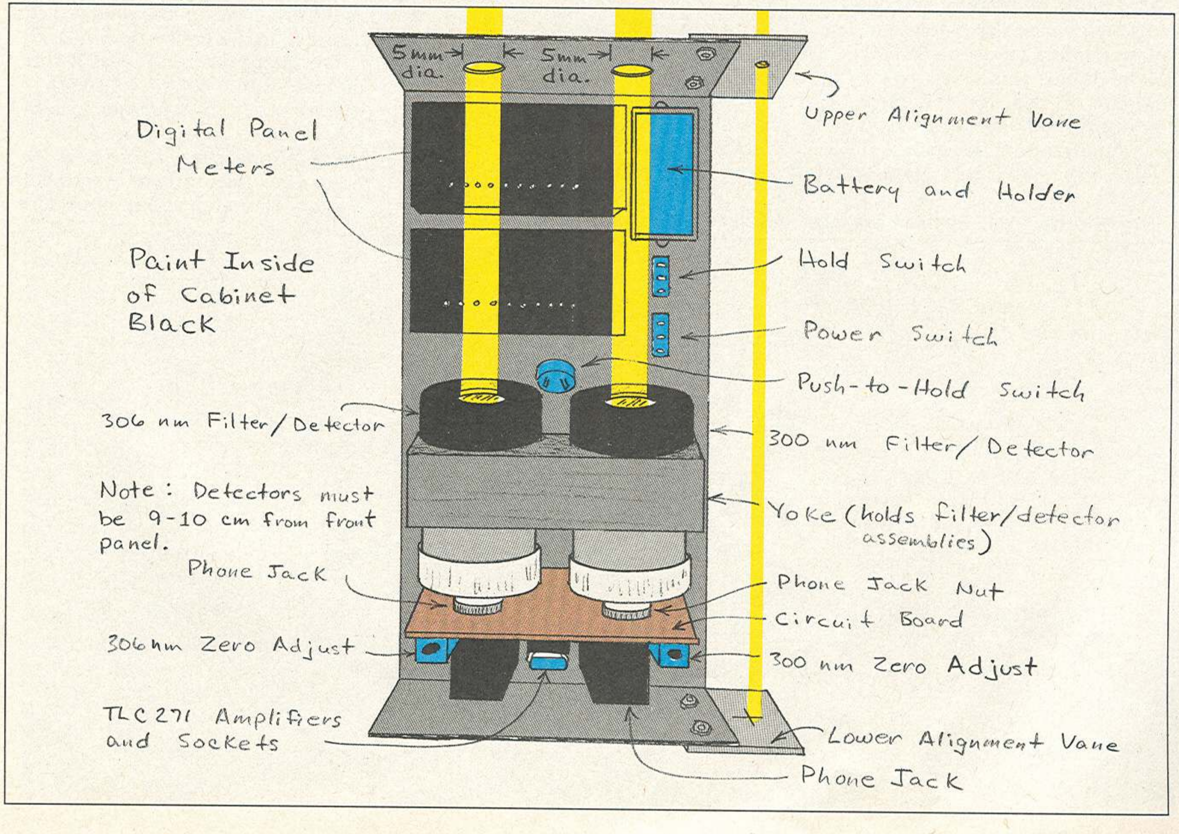
The optimum resistance will probably be between 30 and 100 megohms. The exact value is not critical; if 44 megohms works, then 32 megohms will work but with reduced gain.

Special Construction Note: The construction portion of this article requires intricate assembly procedures (including careful component positioning and soldering). It should be attempted only by readers with considerable electronics construction expertise. If you are seriously interested in measuring ozone and are unable to assemble your own instrument, see "SPAN Ultraviolet Filters" at the end of this article.

I select the best value by inserting each of several resistors into the circuit temporarily while monitoring the readout, with the filtered detector pointed at the Sun. The selected resistance should cause the readout to display perhaps 80% or so of its full range for bright, noon Sun with low ozone conditions.

Resistors of more than 22 megohms are hard to find and expensive. You can make your own by soldering together a string of several 10 and 22 megohm resistors available from electronics parts stores. Use the smallest possible resistors (e.g. 0.1 watt), place them

Figure 3. Assembly details for a TOPS ozonometer.



side by side, and keep the soldered leads as short as possible.

It's important to use gallium phosphide (GaP) photodiodes because they do not respond to the near-infrared radiation that leaks through most UV filters. UV-sensitive silicon photodiodes are cheaper, but they are very sensitive to near-infrared. Special blocking filters can solve this problem, but they are expensive.

Gallium phosphide photodiodes are made by Hamamatsu Corporation (P.O. Box 6910, Bridgewater, New Jersey 08807). The G1961 ($34.23 plus shipping) is housed in a TO-18 package and has an effective surface area of 1.0 square mm. The G1962 ($43.98) is housed in a TO-5 package and has a surface area of 5.2 square mm. The G1962 is a better choice for low signal levels at northerly latitudes and for wavelengths near 300 nm. (The G1962 will not fit the filter holder shown in Figure 4.)

The size of the UV filters and the digital readouts determines the size of the instrument. The prototype TOPS use large 25-mm filters and compact DP-650 ±200 millivolt digital panel meters from Acculex (440 Myles Standish Boulevard, Taunton, Massachusetts 02780; $60 each plus shipping). If your budget is limited, you can use a pair of external voltmeters. However, an important advantage of the DP-650 units is that the data in the display can be saved simply by pressing a push-button switch that connects Pin 11 to Pin 1 (+5 volts). A new reading can be made when the switch is opened.

The DP-650 readout must be powered by no more than 5.5 volts. Diodes D1-D3 in Figure 2 reduce the battery voltage to this level. If you use a 6-volt battery, only one diode is needed. Use all three diodes if you use a 7-volt battery.

You will need to make two light-tight mounts for the filters and detectors. Light can leak through the back of the detector, so it must be entirely installed inside the mount or its back must be coated with a non-conductive black paint.

If you have access to a machine shop, you can make filter holders from aluminum. Or you can do as I have done, and improvise. Figure 4, for example, shows an improvised mount for a G1961 photodiode and a 12.5 mm filter. The 25-mm filters in the prototype TOPS are installed in the improvised mount shown in Figure 5. The phone plug in both mounts provides a means for isolating the photodiode from external light. These plugs are inserted into phone jacks installed in the circuit board.

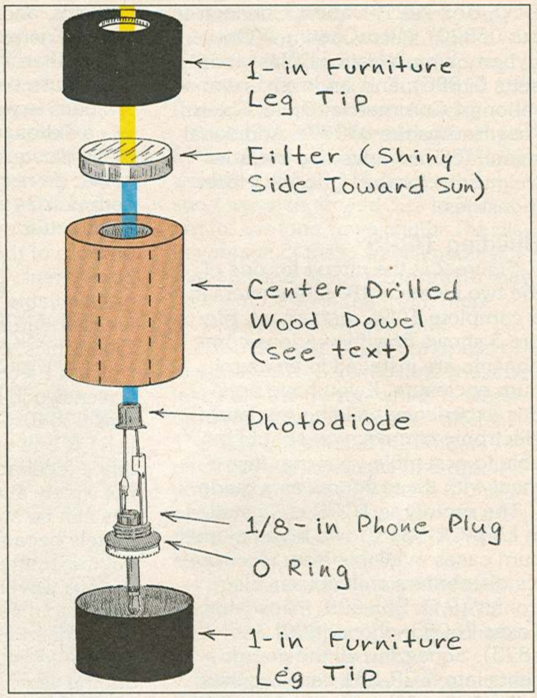
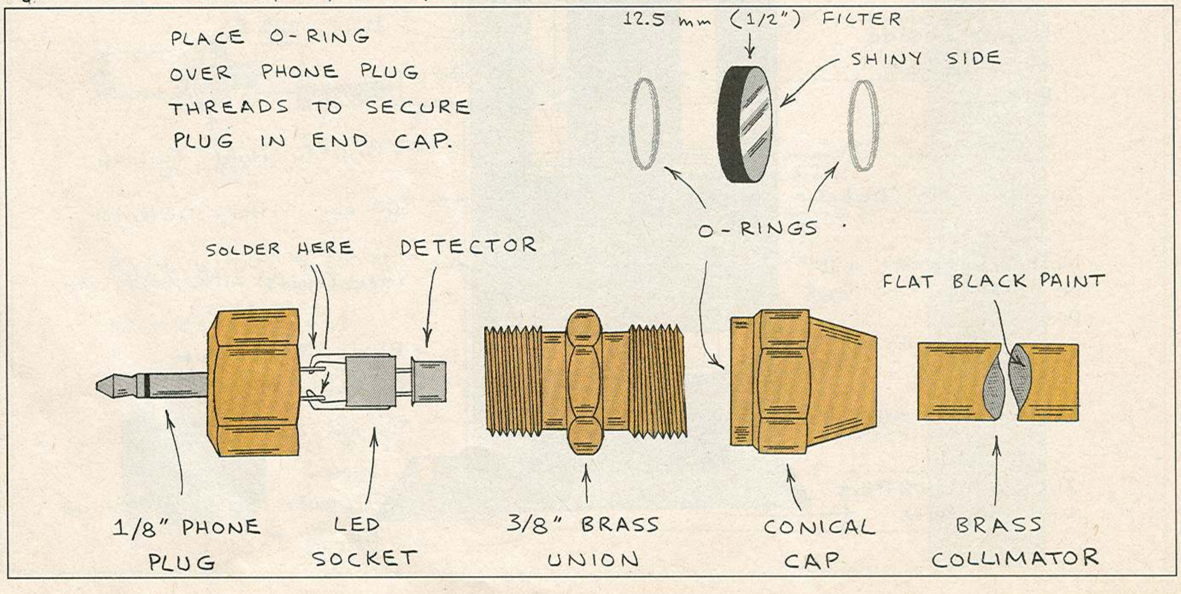


Figure 5. Holder for 25-mm (1.0-in) filter and photodiode made from two plastic furniture tips and a wood dowel.

The filter holder in Figure 4 can be fitted with a collimator tube made from 0.25-in aluminum tubing. An alternative collimator, which also works with the filter holder in Figure 5, is to mount both holders at one end of an enclosure

Figure 4. Holder for 12.5-mm (0.5-in) filter and photodiode made from a brass union.



and form a pair of matching apertures in the opposite end (see Figure 3). Carefully measure the distance between the two detectors before forming the holes, because both detectors must be perfectly centered in the circle of sunlight projected through the holes.

Testing and Aligning TOPS

After you assemble the instrument circuit, carefully check the wiring. It's especially important that the battery connections to the digital readouts and the amplifier be correct. If everything is in order, install a battery in the battery holder and switch on the instrument. Both readouts should display digits. Block both photodiodes and adjust the trimmer potentiometers (R2) until the two readouts read 0 volts.

A pair of aluminum vanes (see Figure 3) provides a means for optically aligning TOPS. Bore a small (1-2 mm) hole near the center of the upper vane. With the cabinet open, point the instrument at the Sun and align it until sunlight strikes both filters. Then place a small mark where sunlight from the upper vane strikes the lower vane.

If your filters are recessed, you can see when sunlight is striking them by placing a glass micro-

Computing the Ozone Amount

Determining the amount of ozone over your head requires several steps. Although complicated at first, they will become easy if you begin a regular measurements program.

Finding Local Mean Time

Solar noon for your location is not necessarily when your watch shows 12:00, especially if daylight-saving time is in effect. Complete details about how to determine the local time for your location are given in various books and magazines about astronomy and sundial making.

Briefly, the Earth rotates 360° in 24 hours. This is equivalent to 1° in 4 minutes, or 15° in 1 hour. The standard time longitudes or meridians range from 45° to 165° west in increments of 15°. Therefore, the time at each meridian is 1 hour earlier than the previous meridian.

To find your local time, first find the number of degrees between your longitude and your time meridian. Multiply the number of degrees by four to obtain the correction for your location. If you are east of the time meridian, add the correction to the standard time for your area; if you are west of the meridian, subtract the correction from the standard time. The result is known as your *local mean time*.

For example, the longitude for Omaha, Nebraska, is 96°, 6° west of the standard time meridian of 90°. This means the time correction is 6 x 4 or 24 minutes. Because Omaha is west of the meridian, 24 minutes must be subtracted from Central Standard Time to arrive at the local mean time for Omaha.

Over the course of a year, the Earth's orbit causes the Sun to run either ahead of or behind local mean time by as much as 16 minutes. The actual difference between local mean time and the actual or apparent time is called *the equation of time*. Computer programs that compute the Sun's angle (see next page) automatically determine the equation of time. For additional information, see "Further Reading."

Determining the Sun Angle

You will need to know the angle of the Sun above the horizon to compute the air mass and thus the ozone amount overhead. You can determine this angle manually or by formulas that require the date and the exact time.

If you measure the angle manually, be sure to do so immediately after making the observations. You can do as I have done and install a bubble level on your TOPS instrument to facilitate this measurement. Hold the unit on its side with the upper alignment vane pointed toward the Sun. When the bubble is centered, measure the length of the shadow cast by the upper vane.

The tangent of the Sun's angle above the horizon is the length of the upper vane divided by the length of the vane's shadow. If you are careful, you should be able to measure the Sun's angle to within a degree or so.

Whether or not you measure the Sun angle directly, it's very important to record the date and the exact time of your observations. The time information will permit you to calculate the Sun angle electronically at a later date should you elect to do so.

Various computer programs are available that give the angle of the Sun for any time on any day of the year for any location on Earth. Two such programs that I have often used are AstroCalc™ and AstroCalc Plus™ (Zephyr Services, 1900 Murray Avenue, Pittsburgh, Pennsylvania 15217).

My son, Eric, and I have devised a Lotus 1-2-3® (versions 2.1 or 3) spreadsheet program that permits a computer to calculate the angle of the Sun. This program is given in Table 1 on the next page. It should work with or be adaptable to other spreadsheet programs that include the necessary trigonometry functions.

The Total Ozone Equation

Various equations for computing the amount of ozone use Beer's law. A simplified version for two wavelengths, without taking aerosol scattering into effect, is

$$O_3 = \frac{\log (L_1{}^\wedge/L_2{}^\wedge) - \log (L_1/L_2) - (b_1-b_2) \times (p \times m/1013)}{(a_1 - a_2) \times m}$$

where, $L_1{}^\wedge$ and $L_2{}^\wedge$ are the intensities of the two wavelengths outside the atmosphere;

L_1 and L_2 are the intensities of the two wavelengths during an observation;

a_1 and a_2 are the absorption coefficients for ozone at the two wavelengths;

b_1 and b_2 are the Rayleigh scattering coefficients for air at the two wavelengths;

m is the air mass (approximately 1/sin c where c is the angle of the Sun above the horizon); and

p is the mean barometric pressure of the observation site in millibars (inches of mercury times 33.864 gives pressure in millibars).

$L_1{}^\wedge/L_2{}^\wedge$, the ratio of the signal at the two wavelengths above the Earth's atmosphere, is known as the *extraterrestrial constant*. Unless you are a space shuttle astronaut, you'll need to measure this value from the ground by making a Langley graph on a very clear, dry day when the ozone amount remains fairly constant.

Record L1 and L2 (see below) and the time as often as possible for a few hours ending or beginning at solar noon. Plot the log of the ratio L1/L2 against air mass (m, the reciprocal of the sine of the Sun's angle above the horizon) on a graph. If you extend the plot to 0 air mass, as shown in Figure 6, you will find the approximate extraterrestrial constant.

The problem with the Langley graph method is that the effective center wavelength of a UV filter changes as the Sun's angle changes. Therefore, the line of points on the graph will begin to curve beyond some air mass. For very short wavelength filters, the line will begin to curve as early as m = 1.2 or so.

Since this problem is caused by the filter's bandwidth, narrow bandpass (< 3 nm) filters work much better than ordinary filters with a bandpass of 10 nm. In any event, when you extend the line formed by the dots to m = 0, ignore dots that curve.

An alternative way to find $L_1{}^\wedge/L_2{}^\wedge$ is to use satellite measurements of sunlight (see a recent edition of *Handbook of Chemistry and Physics*, CRC Press). Although I have had good results using this method, the bandpass of a UV filter limits its accuracy.

L_1/L_2 can be the ratio of the UV measurements in watts per square meter or simply the numbers read from the readouts. Because the ratio of the two signals is being measured, it's not necessary to know the calibration of the photodiodes.

The ozone absorption and Rayleigh scattering coefficients can be found in published tables. For ozone, see "Absolute Absorption Cross Sections of Ozone in the 185-to 350-nm Wavelength Range" by L.T. Molina and M.J. Molina in *Journal of Geophysical Research* (vol. 91, no. D13, Dec. 20, 1986, pp. 14,501-14,508). For Rayleigh scattering, see the second column of Table III in "Tables of the Refractive Index for Standard Air and the Rayleigh Scattering Coefficient" by Rudolf Penndorf in *Journal of the Optical Society of America* (vol. 47, no. 2, Feb. 1957, pp. 176-181).

scope slide over them. If you then tilt the slide at a 45° angle, you will see the filters reflected in the slide.

Using TOPS

Before using the instrument, be sure the cabinet is closed and that no light leaks through any openings. If necessary, use black paper to shield the detectors from light leaks. You can also insert tubes over the detector/filter assemblies. In either case, be sure that nothing blocks the sunlight reaching the detector.

To use the instrument, first make sure both amplifiers are zeroed by switching on the power in subdued light or by blocking the apertures. If either readout indicates more than 0, open the case and adjust the appropriate zero potentiometer (R2).

Go outdoors and point the instrument toward the Sun while watching the shadow the upper alignment vane casts on the lower vane. When you see the spot of sunlight on the lower vane, align the instrument until the spot of sunlight is centered over the alignment mark. Hold the instrument securely and, assuming the instrument incorporates readouts with a hold feature, press the readout "Hold" button to save the data.

Operators of Dobson spectrophotometers usually make ozone observations at mid-morning, solar noon and mid-afternoon. Noon measurements are important because that's when the level of solar UV is highest. Also, since the Nimbus-7 satellite is in a Sun-synchronous orbit, it will pass within range of your location within half an hour or so of noon every day.

Make at least three observations per session. Record them in a notebook or read them into a tape recorder and transcribe them later. Be sure to record the standard time. Later, you can use the standard time to determine the correct local apparent time.

After a measurement session, store the instrument in a clean, dust-free spot because dust and deposits from cooking fumes will block UV. **Never store the instrument inside a closed car or car trunk on a sunny day because high temperatures may alter the wavelength response of the filters.**

The photodiode window and both faces of both filters must be kept meticulously clean. Dust must be blown away with clean compressed air. Especially dirty filters can be cleaned with a drop of camera lens cleaner fluid and lens cleaning tis-

Table 1. Lotus 1-2-3® Program for Computing Air Mass

```
A7: (D4) 33687 [DATE]
B7: (D8) (B:B7) [TIME]
C7: 84 [DAY NUMBER]
D7: [TOPS LOW WAVELENGTH]
E7: [TOPS HIGH WAVELENGTH]
F7: +D7/E7 [TOPS WAVELENGTH RATIO]
G7: [OZONE EQUATION]
H7: @HOUR(B7)+(@MINUTE(B7)/60)+(@SECOND(B7)/3600) [DECIMAL HOUR]
I7: (@PI/180)*(360*C7/365.25) [DAY ANGLE]
J7: @ASIN(0.3978*@SIN(I7-1.39975+0.03351*@SIN(I7-0.04887))) [SUN DECLINATION]
K7: (@PI/180)*15*(H7+((time meridian-site longitude)/15)+N7-12) [HOUR ANGLE]
L7: (@PI/180)*(latitude) [SITE LATITUDE IN RADIANS]
M7: @ASIN(@SIN(L7)*@SIN(J7)+@COS(K7)*@COS(L7)*@COS(J7)) [SUN ANGLE]
N7: -0.128*@SIN(I7-0.0489)-0.165*@SIN(2*I7+0.3438) [EQUATION OF TIME]
O7: (F4) 1/@SIN(M7) [AIR MASS]
```

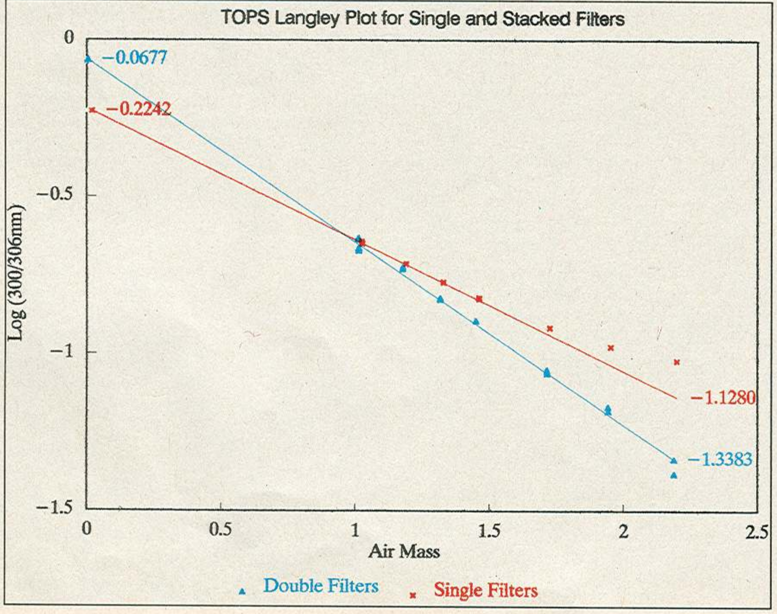
Calibrating TOPS

Several methods can be used to calibrate ozone instruments. The simplest is to compare your observations with those made by a nearby instrument. In the United States, Dobson spectrophotometers are located at Mauna Loa, Hawaii; Fresno, California; Boulder, Colorado; Bismarck, North Dakota; Nashville, Tennessee; Caribou, Maine; and Wallops Island, Virginia. In Canada, ozone instruments are located at Edmonton, Alberta; Churchill, Manitoba; Toronto, Ontario; and Goose Bay, Labrador. You can obtain the daily readings from these and other ozone stations from the World Ozone Data Center. (Address will be sent to SPAN participants; see next page.)

If you are not near a Dobson station, perhaps you can visit a nearby area while on vacation, preferably in June or July when the Sun is highest in the sky. If the ozone is relatively stable, you can make measurements over half a day to simulate a range of Sun angles for different times of the year.

Another method is to compare your readings with those made by satellite. NASA operates a computer bulletin board that gives worldwide measurements of ozone observed by the TOMS instrument aboard Nimbus-7. However, this satellite is rapidly reaching the end of its useful life. Also, various computer problems and calibration difficulties often cause delays of many months in the placement of ozone data on the bulletin board. New ozone monitoring satellites would solve this problem. Meanwhile, for information about obtaining the TOMS data, write the National Space Science Data Center (Goddard Space Flight Center, Code 933.4, Greenbelt, Maryland 20771).

Figure 6. Determining the extraterrestrial constant by means of a Langley plot.



sue. The film left behind should then be removed with a drop of methyl alcohol and lens cleaning tissue.

Modifying TOPS

There are many ways to modify the basic TOPS design. One is to save money by using only one digital readout; a selector switch would permit the signal from each detector to be sampled sequentially. However, this method is not satisfactory when making observations through thin clouds or cloud haze and especially when the Sun peeks out from behind clouds for only a second or so.

Another modification is to eliminate the readouts and connect the amplifier outputs to a computer by means of an analog-to-digital (A/D) conversion board, as Eric and I have done. Many A/D boards come with software that will permit you to select how often the computer samples the detectors. Or you can do as we did and write your own software. See ads in electronics and computer magazines.

An advantage of a computer is that you can insert a program that automatically computes the ozone amount within milliseconds of each observation. Both channels of UV data and the ozone measurements can then be displayed or printed out and saved on a disk. In any case, it is very important that the instrument be properly pointed at the Sun when the computer is taking data. ✳

PARTS LIST

(One of two channels)

B1 —	Miniature 6-volt (23-469) or 7-volt (23-601) battery
C1 —	100 pF capacitor (272-123)
C2 —	0.01 uF (272-131)
D1-D3 —	1N914 diode (276-1122)
DPM —	Digital Panel Meter (see text)
F1 —	Ultraviolet filter (see text)
IC1 —	TLC271CP (Texas Instruments; see text)
J1 —	1/8" phone jack (274-249, 274-250 or 274-248)
P1 —	1/8" phone plug (274-286 or 274-287)
PD1 —	Photodiode (see text)
R1 —	See text
R2 —	100K trimmer potentiometer (see text)
R3,R4 —	1M resistor (271-059)
S1,S2 —	SPST miniature toggle switch (275-624)
S3 —	Normally open push-button switch (275-1571)
S4 —	SPDT miniature toggle switch (275-625)

Miscellaneous — Perforated or etched circuit board, enclosure and alignment vanes (see text), battery holder (270-405), filter holder, wire and solder.

(Numbers in parentheses are Radio Shack 1992 catalog numbers.)

SPAN Ultraviolet Filters

The Science Probe Atmospheric Network (SPAN) is looking for dedicated ozone and UV-B observers. However, ozone and UV-B measurements by different instruments are not always consistent. The best way to provide consistent measurements is for all instruments in the network to use filters from the same manufacturing run.

SPAN is now working with a major filter manufacturer to determine the best specifications for filters suitable for use with TOPS instruments.

If you are seriously interested in purchasing one or more pairs of such filters together with suitable high-resistance feedback resistors, send a self-addressed, stamped business-size envelope to SPAN, P.O. Box 11250, Fort Worth, Texas 76110. Include a typed or neatly printed letter with your name, affiliation, address and phone number, and state your level of interest. **Do not send money.**

If sufficient inquiries are received, SPAN will arrange for a production run of identical filters. Depending on the number of participants, the cost of a pair of filters and resistors should be under $150, including shipping, handling and a nominal registration fee.

SPAN is also looking into the possibility of manufacturing ozone- and UV-monitoring instruments. If you are SERIOUSLY interested in more information on obtaining a pre-built, calibrated instrument, please note this in your letter.

FURTHER READING

For additional information about the design of filter instruments for measuring solar UV, see "How to Monitor Ultraviolet Radiation from the Sun" by Forrest M. Mims, III in "The Amateur Scientist" department of *Scientific American* (August 1990, pp. 106-109). Basic electronic construction tips can be found in *Getting Started in Electronics* by Forrest M. Mims, III (Radio Shack, 1983).

Among the scientific papers on filter ozonometers that proved helpful in the development of the TOPS instruments are these:

"Agreement Between Dobson Spectrophotometer and Filter Ozonometer Measurements of Total Ozone" by W.A. Matthews in *Journal of Applied Meteorology* (vol. 11, Feb. 1972, pp. 239-241).

"Problems in the Use of Interference Filters for Spectrophotometric Determination of Total Ozone" by R.E. Basher and W.A. Matthews in *Journal of Applied Meteorology* (vol. 16, Aug. 1977, pp. 795-802).

"The Effect of Bandwidth on Filter Instrument Total Ozone Accuracy" by R.E. Basher in *Journal of Applied Meteorology* (vol. 16, Aug. 1977, pp. 803-811).

For information about determining local apparent time and the equation of time, see *Sundials and Their Construction* by Albert E. Waugh (Dover, 1973) and various books about astronomy.

Acknowledgments

Development of the TOPS instruments would not have been possible without the advice and encouragement of Arlin J. Krueger of NASA's Goddard Space Flight Center. Dr. Krueger provided ozone data from the TOMS instrument aboard the Nimbus-7 satellite that made possible early verification of the accuracy of the TOPS instruments. I am also indebted to Walter Komhyr and John DeLuisi of NOAA for helpful advice and to Robert Grass of NOAA for spending two days comparing TOPS-1 and TOPS-2 with Dobson-65, the World Secondary Standard Dobson Spectrophotometer. The filters for the TOPS ozonometers were provided by Barr Associates.

Shown here in the back of his pickup truck during a field trip are some of the instruments Forrest Mims has designed to measure the ozone, water vapor and oxygen in a column through the atmosphere. The two light blue instruments with dual digital readouts are the TOPS ozonometers described in this article.