WOUDC Data Sponsorship Statement Document – NASA Goddard Space Flight Center (GSFC)

Date:	2016-07-16
Author:	Arlin Krueger
Agency:	NASA Goddard Space Flight Center
Measured Quantities:	Upper Stratospheric Ozone Profiles

Data and DSS Document versions – WOUDC archive of ROCOZ Ozone profiles

Data Version:	1
DSS Document Version:	1

Personnel

Name	Agency	Role	Comments
Arlin Krueger	NASA (GSFC)	Principal Investigator	Retired

Contact Information

Arlin Krueger
1610 Briggs Chaney Rd
Silver Spring, MD 20905
USA

Introduction

ROCOZ UV filter rocket ozonesondes were developed at the US Naval Ordnance Test Station, China Lake, CA for launch on Arcas meteorological rockets and deployment on a parachute at apogee (Krueger and McBride, 1968). The instruments were capable of measuring ozone densities and mixing ratios from 20 to 60 km. Seventeen Arcas-ROCOZ ozone profiles were acquired by the Navy on a NASA shipboard expedition (4°N - 58° S) and from four Meteorological Rocket Network (MRN) stations (9°N – 64°N).

In 1969 the ROCOZ program was transferred to NASA Goddard Space Flight Center (Heath, et al., 1972) where fifteen more Arcas-ROCOZ ozone profiles were acquired from eight platforms (9°N – 64°N) (Krueger, 1973). A total of thirty-two Arcas-ROCOZ ozone profiles were collected between 1965 and 1975.

In 1975 ROCOZ instruments were redesigned for improved performance and ruggedness as well as to fit on the smaller Super Loki-Dart vehicles that replaced Arcas rockets at MRN stations. SL-Dart – ROCOZ instruments were used by NASA in over 250 launches at eight platforms from 12°S to 63°N in 20 years (Krueger, 1984; Barnes et al., 1986). Of these launches 131 profiles have been recovered for archival.

ROCOZ data campaigns were designed to survey latitude and seasonal changes in ozone densities in the stratosphere and lower mesosphere. A monthly sounding program at Wallops Island, VA produced a mid-latitude seasonal climatology (Krueger, 1984). The 1976 US Standard Atmosphere mid-latitude ozone model was constructed in part with ROCOZ data (Krueger and Minzner, 1976). The program included sets of repeatability evaluation flights and intercomparisons with chemical and other optical rocket ozonesondes at middle- and high-latitudes.

As satellite techniques were developed the rocket data were initially used to calibrate a new satellite experiment (OGO-4 UV spectrometer) and later to validate new techniques that included backscatter UV instruments (BUV, SBUV, SBUV/2), infrared limb emission instruments (LIMS), and solar occultation instruments (SAGE, SME) (McCormick, et al., 1984). The NASA Stratospheric Ozone Intercomparison Campaign in 1989 included ROCOZ flights to compare with ground-based ozone lidar and microwave techniques (Margitan, et al., 1995).

The format of the archival rocket data is the extended comma-separated value (CSV) format described in the WOUDC User's Guide.

<u>Platforms (Sites) and Description</u>

WOUDC Platform ID	Site	Rocket & Instrument	Latitude	Longitude	Dates
	Antigua, West Indies	Arcas-ROCOZ	17.17	-61.82	5/16/1972 - 1/31/1974
		SL-Dart-ROCOZ			2/3/1976 - 12/6/1976
	Barking Sands, HI (PMRF)	Arcas-ROCOZ	22.04	-159.79	9/17/1967 - 3/3/1971
	Ft. Greely, AK	Arcas-ROCOZ	63.96	-145.7	8/14/1971
STN 77	Ft. Churchill (CRR)	Arcas-ROCOZ	58.75	-94.07	7/19/1968
		SL-Dart-ROCOZ			2/16/1977 - 3/15/1979
STN 203	Ft. Sherman, Panama Canal Zone	Arcas-ROCOZ	9.37	-79.95	11/6/1970 - 11/13/1970
STN 219	Natal, Brazil	SL-Dart-ROCOZ	-5.92	-35.16	11/19/1978 - 7/17/1980
	Point Mugu, CA (PMR)	Arcas-ROCOZ	34.1	-119.1	10/8/1964 - 6/18/1970
STN 217	Poker Flat, AK (PFRR)	SL-Dart-ROCOZ	65.12	-147.49	9/28/1976 - 7/25/1980
	Pucusana, Peru	Arcas-ROCOZ	-12.46	-76.78	5/24/1975 - 5/25/1975
	Primrose Lake (PRL)	SL-Dart-ROCOZ	54.75	-110	4/5/1979 - 8/20/1980
	USS Croatan	Arcas-ROCOZ	4N - 58S	78 - 82W	3/7/1965 - 4/12/1965
STN 107	Wallops Island, VA(WFC)	Arcas-ROCOZ	37.84	-75.48	9/16/1968 – 2/6/1969
		SL-Dart-ROCOZ			2/21/1975 - 7/6/1994
STN 155	White Sands, NM (WSMR)	Arcas-ROCOZ	23.38	-106.48	5/5/1974

Payload and Operations

Meteorological rockets and a Meterorological Rocket Network (MRN) of launch stations were developed after the IGY for low cost, synoptic measurements of air temperature and winds in the upper stratosphere and lower mesosphere. These stations contained a rocket launcher, radar, and a GMD meteorological tracking receiver that is also used for balloon radiosondes.

Arcas rockets were the first to be developed for meteorological soundings. Thermistor-equipped datasondes were launched and deployed on metallized silk parachutes that were tracked by radar for altitude and wind velocity data. The solid-propellant Arcas rocket slowly burns for 28 seconds. After 100 seconds the rocket reaches apogee near 60 km where the parachute and instrument are ejected.

Super Loki-Dart vehicles replaced Arcas rockets in 1975 for lower cost and better reliability. The Super Loki motor accelerates the Dart to 1600 m/s in 2.1 seconds. The Dart then separates and coasts to 70 km where a charge ejects the payload and its parachute.

The ROCOZ program used the MRN launch ranges to measure ozone density profiles over a range of latitudes. Ozone mixing ratio distributions were then computed using air density derived using the hydrostatic equation and air temperature profiles from supporting Datasondes and Radiosondes. Ozone density and mixing ratio on both geometric height and air pressure scales made the rocket data useful for validation of all satellite ozone sounding techniques.

Instruments

Optical ozonesondes measure the absorption per unit height of UV sunlight in the Hartley and Huggins Bands of ozone. Ozone density is computed given the absorption coefficient and solar geometry. Several wavelength bands are required to measure the 500-fold range of ozone densities between 25 and 60 km. The ROCOZ instrument is a filter wheel photometer with 305 and 320 nm filters for ozone measurements up to 30 km, similar to optical balloon ozonesondes (Kulcke and Paetzold, 1957), and 285 and 260 nm filters to measure ozone densities from 30 to 60 km (Krueger and McBride, 1968). With smaller solar irradiance at the shorter wavelengths a special broad UV band filter with high optical density across the visible wavelengths was designed to prevent light leaks. Especially the shorter wavelength filters required blocking of the more intense visible solar wavelengths. Narrow band interference filters defined the narrow bandwidth ROCOZ bands within the broadband blocking filter.

In the original Arcas version of ROCOZ instruments sunlight was collected with a transmitting integrating sphere. This eliminates the need for attitude control during the descent on a parachute. Diffuse sunlight from the integrating sphere passes through a visible light-blocking filter and sequentially through each of the four filters mounted in a rotating filter wheel. Light intensity was measured with a UV sensitive photomultiplier tube. The analog photometer data were sent to the ground using a standard meteorological transmitter. In data processing the signals from the three shorter wavelength filters are divided by the non-absorbed 320 nm signal to compensate for low frequency noise due to irregularities in angular response.

The Arcas ROCOZ instruments were designed to fit in a 10 cm diameter nose cone. The instrument was attached to a parachute in a vehicle section below the nose cone using an adaptor that contained a 15-meter nylon rope for separation from the parachute to reduce shadowing. A yoyo despinner mechanism was designed to reduce the deployment dynamics after separation from the vehicle that spins at 1200 rpm for stability. The instrument was potted in Styrofoam for shock and vibration protection and for thermal stability.

When Super Loki - Dart vehicles replaced Arcas rockets, the ROCOZ instruments were completely redesigned to fit inside a 4.5 cm diameter Dart. The filter wheel and four filters were reduced in size and a UV-enhanced silicon photodiode replaced the photomultiplier (Krueger, 1984, Barnes and Simeth, 1986). The most significant change was to replace the integrating sphere with a flat diffuser plate with a cosine law response to incident sunlight. To compensate for signal changes due to the varying angle of incidence a fraction of the transmitted diffuse light was monitored by a second, blue-filtered photometer. The blue photometer and the UV filter signals were sampled as each filter was aligned with the diffuser. The ratio of the two signals removed the modulation due to pendulation under the parachute. This compensation greatly reduced the sampling and orientation noise over that from the Arcas ROCOZ integrating sphere. In addition, a new Starute parachute was more stable during descent. Launch times were limited to solar zenith angles greater than 15° and less than 60° to avoid shadowing by the parachute near noon and low signals near sunrise or sunset.

In 1982 the ROCOZ program was transferred to the Wallops Flight Center (WFC) where filter wavelengths were revised to optimize channel overlaps (Barnes and Simeth, 1986). The shortest wavelength filter bandpass was increased and the electronics were updated to improve the signal-to-noise ratio at the higher altitudes (Holland, et al., 1985). The WFC modified instruments, designated ROCOZ-A were used in thirty-six flights in 1983 - 1985.

Calibration

ROCOZ instruments measure ozone density differentially so that no absolute radiometric calibration is required. However, the individual channel sensitivities are adjusted for optimum dynamic range using a Xe arc solar simulator in preflight laboratory adjustments.

The change in irradiance with height is converted to ozone density using effective ozone absorption coefficients that are calculated using Cary spectrophotometer measurements of the filter spectral response curves. These effective absorption coefficients are functions of ozone optical depth due to changes in the spectrum of sunlight across the finite bandpasses of the filters (3 nm for 320, 305, and 285 nm filters, 10 nm for the 260 nm filter). As the overhead ozone increases during payload descent ozone absorbs shorter wavelengths more than longer wavelengths. Thus, the effective mean wavelength of a filter shifts to the red where the ozone cross sections are lower.

The narrow band interference filters were generally stable based on repeated lab calibrations and evaluation of interchannel agreement at crossover altitudes in flight data. One batch of unstable interference filters used in soundings in 1978-1979 was detected by poor interchannel agreement.

Data Analysis

Ozone densities are computed using Beer's Law of absorption. The goal is to measure the irradiance and its uncertainty in each of the four channels at uniform altitude intervals (1 or 2 km). However, data collection is not uniform with altitude because the parachute descent rate slows exponentially with time. The sampling rate is one sample per UV channel per second while the descent rate decreases by a factor of two for each 10 km from a maximum of 170 m/sec at 60 km. This yields about 11 samples/km at 50 km and 50 samples/km at 30 km.

Even though the SL-Dart instruments had lower noise than Arcas instruments smoothing is required to estimate the irradiance at the top and bottom of each layer. Because of the non-constant sampling density polynomial curve fitting produced periodic artifacts in the ozone profiles and manual smoothing of the data plotted vs. altitude was used on ROCOZ data until 1978. Subsequently a new smoothing algorithm fitted a low order polynomial to the 100 data points in the vicinity of each height level. Outliers are detected by their deviation from the fitted curve and the curve is refit to the remaining data points. The value of the polynomial and its confidence interval are evaluated at the central point. The ozone density is calculated from the logarithmic difference of the irradiances at the top and bottom of each layer. The statistical uncertainty then is calculated from the confidence intervals. After 1982, new Wallops Island data processing algorithms changed the smoothing interval from the nearest 100 data points to a four-kilometer interval centered on the chosen heights (Barnes et al., 1986).

Under most conditions, the random errors in the data due to angle compensation errors are on the order of 0.4%. Common mode errors and drift in the UV photometer are removed by taking the ratio of the three short wave UV channels to the 320 nm reference channel. This also removes any low frequency changes in the compensation photometer from the UV data.

The ozone densities are computed independently for each of the three active channels over an optical depth range from 0.1 to 2. To produce a single ozone profile the results are merged using the uncertainties as weighting factors in the regions of overlap. Biases between results in the overlap regions provide an internal test for validity of the filter calibration and instrument performance. Significant deviations provide clear evidence of errors and are grounds for rejection of the data.

Ozone mixing ratio is computed from the ozone density using independent air density measurements. Whenever possible Arcas or SL-Dart datasonde flights were made to acquire the temperature distribution vs. height. Using the hydrostatic equation air pressure and density profiles are derived from the rocket and balloon temperature data.

Ozone data accuracy

The precision of ozone density data from ROCOZ soundings is limited primarily by random errors in sampling of solar irradiance. The random irradiance errors are calculated from uncertainties of piecemeal curve fits centered on a given altitude level. These errors, propagated through the retrieval algorithm, vary with ozone optical depth. They are large at low optical depths where the change in signal with height is small, and at high optical depths where the signal to noise ratio is small. These uncertainties are then used to compute a weighted average ozone density in the overlap region between filters. The combined uncertainties are provided in the flight data tabulations for use in comparisons and in averaging of datasets. The uncertainty varies from <1% at optimum optical depths to >100% at small and large optical depths.

Other sources of random errors are digitization errors (<0.3%), horizon skylight contribution (<0.1% at short wavelength bands, <0.5% at longest wavelength band), and quantization errors during calibration of leakage in the wings of the filters (0.1 – 0.4%). Radars that have uncertainties of about 10 meters measure the payload altitude.

Biases in the ozone densities come mostly from errors in the ozone cross sections and their temperature coefficients. Prior to 1980, room temperature Inn and Tanaka cross sections for < 272 nm, +18°C Vigroux cross sections from 272 to 289.5 nm, and -44°C Vigroux cross sections for wavelengths > 289.5 nm were used to approximately represent air temperatures at the heights where each filter collected data. The errors due to air temperature deviations are on the order of 1% at high (260 nm filter) and low (305 nm filter) altitudes and could be as large as 7% for data collected by the 285 nm filter at intermediate altitudes. In 1980 standardized ozone cross sections were adopted for the International Ozone Rocket Intercomparison (IORI) campaign.

Over the life of the ROCOZ program dual launches and repeatability tests are available to support the random error estimates. Two Arcas ROCOZ instruments were launched within 3 hours on May 5, 1974 at White Sands Missile Range. The profiles had a 6.1% mean difference in ozone mixing ratios. The Super Loki-Dart instruments were compared on several occasions. Two flights on November 17, 1976, launched 12 minutes apart, showed a mean difference of 3.5% between mixing ratio profiles. On July 21, 1977 five instruments launched throughout one day at Wallops Island had a relative standard deviation of 10.6%. Dual launches were also made in August and September 1978. Three flights made on October 21, 1979 had a relative standard deviation of 4.2%. Three repeatability tests in 1983 and 1984, each using four ROCOZ-A instruments, found a 3.2% relative standard deviation in ozone density (Barnes, et al., 1986). Based on the repeatability tests the data precision is better than 10% and has generally improved with instrument and algorithm changes to better than 5%.

Data Use Policy

Data can be used without restriction as to author's nationality or institution. It is requested that NASA be acknowledged as the data source and that publications, as listed below and appropriate, be referenced. Notifying us that these rocket data are being used, and if they result in a publication, sending a copy, would be appreciated.

References: Publications and Reports

Barnes, R.A. and P.G. Simeth, (1986), Design of a rocketborne radiometer for stratospheric ozone measurements, Rev. Sci. Instr. 57, 544 (1986); doi: 10.1063/1.1139209.

Barnes, R. A., A. C. Holland, and H. S. Lee, (1986), An improved rocket ozonesonde (ROCOZ-A), 2, Preparation of stratospheric ozone profiles, J. Geophys.Res. 91, 14,521-14,531.

Heath, D. F., E. Hilsenrath, A. J. Krueger, W. Nordberg, C. Prabhakara, and J. S. Theon, (1972) Observations of the Global Structure of the Stratosphere and Mesosphere with Sounding Rockets and with Remote Sensing Techniques from Satellites, NASA Technical Memorandum, X-651-72-279/TMX-66044, NASA GSFC, Maryland, USA, 1972.

Holland, A. C., R. A. Barnes, and H. S. Lee, (1985), Improved rocket ozonesonde (ROCOZ-A), 1, Demonstration of precision, Appl. Opt. 24, 3286-3295.

Johnson, F. S., J. D. Purcell, and R. Tousey (1951), Measurements of The Vertical Distribution of Atmospheric Ozone from Rockets, J. Geophys. Res., 56(4), 583-594.

Krueger, A. J., (1973), The mean ozone distribution from several series of rocket soundings to 52 km at latitudes from 58°S to 64°N, Pure Appl. Geophys. 81, 1272-1280.

Krueger, A. J. and W. R. McBride, (1968), Rocket ozonesonde (ROCOZ) - Design and development, NWC TP4512, Naval Weapons Center, China Lake, California. DOI: 10.13140/2.1.2379.8080

Krueger, A. J. and R. A. Minzner, (1976), A mid-latitude ozone model for the 1976 U. S. Standard Atmosphere, J. Geophys. Res., 81, 4477-4481.

Krueger, A. J. (1984). Inference of photochemical trace gas variations from direct measurements of ozone in the middle atmosphere, PhD Dissertation, Colorado State University. (Available from author and ResearchGate).

Kulke, W. and H.K. Paetzold, (1957), Uber eine Radiosonde zuer Bestimmung der vertikalen Ozonverteilung. Ann. Meteorol. 8, 47-53.

McCormick, M. P., T. J. Swissler, E. Hilsenrath, A. J. Krueger, and M. T. Osborn (1984), Satellite and Correlative Measurements of Stratospheric Ozone: Comparison of Measurements Made By SAGE, ECC Balloons, Chemiluminescent, and Optical Rocketsondes, J. Geophys. Res., 89(D4), 5315-5320.