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UV spectral measurements at moderately high resolution and of OH resonance scattering resolved by polarization during the MANTRA 2002–2004 stratospheric balloon flights

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ABSTRACT

A moderately high-resolution (<0.1 nm) grating spectrometer designed to measure the solar radiation in the spectral range 295–315 nm was flown on the MANTRA stratospheric balloon payloads of 2002 and 2004. The instrument measures both the direct sunlight and the radiation scattered by the atmosphere. The latter can be observed in two orthogonal polarization directions, at 90° from the solar azimuth and at several elevations above the horizon. As the OH molecule is the principal resonant scatterer in this spectral region, this permits the inference of both ozone and OH column amounts as well as limited profile information. This paper describes the instrument and its in-flight characterization, the basic data processing and the influence of several aspects of the flight profile. The direct sun measurements are analyzed both to characterize the spectrometer responsivity to scattered radiation and to estimate the ozone abundance at the flight altitude and above. An example of a high-resolution solar spectrum at 37 km altitude is presented and compared with others in the literature. The measured OH and Rayleigh-scattered spectra are used to derive OH radiation intensity measurements (the OH airglow), which are compared with others in the literature.

1. Introduction

The hydroxyl radical is the most important oxidizing agent in the middle atmosphere, and OH chemistry dominates ozone destruction above about 40 km [1]. However, its measurement is quite challenging and for this reason there exist relatively few observations of the atmospheric concentration of this important trace species. Measurements of solar radiation scattered by OH in the $A\ ^2\mathbf{\Sigma}$–$X\ ^2\mathbf{\Pi}$ (0–0) band at 308 nm have been made in the upper stratosphere and mesosphere by rocket [2] and balloon-borne spectrometers [3,4]. The MAHRSI instrument on the space-shuttle-deployed CRISTA-SPAS satellite, also a UV spectrometer operating in the 308-nm range, produced several thousand OH profiles between about 45 and 80 km altitude, during two short periods in 1994 and 1997 [5,6]. These measurements proved difficult to reconcile with standard models of HO_x chemistry [7–9]. The $A\ ^2\mathbf{\Sigma}$–$X\ ^2\mathbf{\Pi}$ (0–0) transition is also the basis of OH measurements using balloon-borne lidar [10] and laser-induced fluorescence [11]. Measurements have also been made with balloon-borne IR interferometers, using the thermal emission of OH [12,13]. More recently the Microwave Limb Sounder (MLS) instrument on the Aura satellite, launched in 2004, has the capability to measure OH between about 20 and

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60 km altitude using thermal emission from 2.5 THz rotational lines in the ground vibrational state, and a similar instrument has been flown on a balloon [14]. These more recent measurements and analyses appear to resolve the difficulties presented by the MAHRSI measurements, although at the cost of assuming an unknown mechanism for ozone production above 40 km [15,16].

The UV spectrometer described here was designed to observe the $A\ ^2\mathbf{\Sigma}$–$X\ ^2\mathbf{\Pi}$ (0–0) scattered emission of OH from a stratospheric balloon. An early version was first flown in 1975 and 1977 on the Canadian Stratoprobe payloads launched from Yorkton, Saskatchewan and Palestine, Texas. These measurements, which very clearly identified the $A\ ^2\mathbf{\Sigma}$–$X\ ^2\mathbf{\Pi}$ radiation, have been briefly described previously [3].

The unique design of this instrument includes the capacity to significantly reduce the interference of Rayleigh-scattered light by changing the instrument's polarization. Other design features are moderately high spectral resolution (<0.1 nm), light weight, and high light-gathering power. The instrument carries an onboard data collection and control computer, and is capable of independent, automated operation as well as of remote control by telemetry.

The data presented here were obtained during the MANTRA balloon flights of September 3, 2002 and September 1, 2004.

2. Instrument design and operation

The spectrometer layout is of the most simple Ebert–Fastie type [17]. With the exception of the foreoptics, the instrument design (although larger, and having consequently higher resolution) is similar to that of the Brewer ozone spectrophotometer, also developed in our laboratory.

A unique feature of the instrument is the foreoptics, which are contained in a cylinder that can be rotated about its axis in order to change the polarization of the measurement. The first element is a 25-mm Glan–Taylor prism polarizer. When the instrument is properly pointed at 90° to the sun, by rotating the foreoptics the polarizer can be set to admit light polarized either in, or perpendicular to the scattering plane determined by the sun. The former position will greatly reduce the amount of Rayleigh-scattered light detected, since this is strongly polarized in the perpendicular direction. The Rayleigh background is much larger than the OH emission, but by this method its signal is reduced, relative to that of the OH, by as much as a factor of 16. To our knowledge this technique has not been used in other measurements of the $A\ ^2\mathbf{\Sigma}$–$X\ ^2\mathbf{\Pi}$ (0–0) OH band [2–6].

Following the polarizer, a 1/4 wave plate is set so that, in combination with the prism, it causes the light entering the spectrometer proper to be completely circularly polarized, given that the incident light has essentially no circular polarized component (Stokes parameter $V = 0$), as is the case for light from the sun or sky [18,19]. Detailed multiple scattering calculations for our viewing situation indicate a degree of circular polarization for the incident light of about 10^{-5}.

The remainder of the foreoptics consists of an aperture stop of diameter 25 mm, and a lens of focal length 200 mm, which is approximately that distance in front of the entrance slit. A small transfer lens, 15 mm in front of the entrance slit, produces an image of the aperture stop, approximately 75 mm in diameter, on the grating.

A filter wheel, located in the gap between the transfer lens and the entrance slit, allows two different neutral density filters or an opaque shutter to be rotated into the light path.

The overall instrument aperture is $f/8$, as determined by the aperture stop. At this aperture there is no significant change in focus over the 300–315 nm range. Ray-tracing analysis indicates the aberration-limited bandpass to be asymmetrical, with rms width 0.010 nm and full width at half-maximum 0.014 nm, while the astigmatism is 0.014 nm. These factors, as well as physical imperfections and focusing errors raise the actual bandpass from the 0.055 nm determined by the physical slit widths to about 0.81 nm (as measured by onboard calibration).

Attached to the foreoptics tube is a coaxial extension projecting ~220 mm outside the box containing the spectrometer. The coupling is rigid but made easily breakable so as to limit damage to the main optics during rough landings of the balloon payload. The extension, which rotates with the foreoptics, carries two pairs of photodiodes for detecting the elevation of the sun and a Teflon reflective diffuser that can be moved in front of the tube opening to diffusely reflect either light from the sun or from a mercury discharge lamp into the spectrometer. The mercury lamp is also mounted on the outside of the box and permits frequent wavelength calibration. The photodiode pairs are mounted 90° apart and aligned with the two polarizing directions defined by the Glan–Taylor prism. The fields of view of the diodes in each pair are arranged so that their exposures are equal when they point at the sun and fall off rapidly in one direction and slowly in the other, in opposite sense for each member of the pair. This allows the foreoptics rotation to be set so that the spectrometer measures either with polarization in the direction of the sun or perpendicular to it, with an accuracy of a few degrees.

The instrument is mounted on a cradle which allows it to be tilted between about 2 and 9° above the horizontal. It is designed to fly on a balloon payload with solar tracking, so it flies in a fixed orientation with respect to the solar azimuth, pointing to the sky 90° to the west of the sun and at an elevation determined by the cradle. The actual elevation of the spectrometer is monitored by an onboard clinometer with a precision of 0.02° and an estimated accuracy of 0.04°. There is, in addition, an uncertainty of 0.2° in the alignment of the spectrometer frame to its viewing direction.

The basic time unit in the operation is 8 ms, effected by a 125 Hz interrupt from the onboard computer. At each interrupt a counter that is driven by the prescaler on the photomultiplier (PMT) is read and the wavelength drive motor is commanded to take one step. All other tasks are done in the background. This includes reading signals from thermistors, LED–photodiode pairs, microswitches and potentiometers used to control the four DC motors associated with cradle