Nightsky Imaging Tomography Experiment to measure Ozone with Starlight

NITEOWL

A proposal to the Small Payloads Program
of the Canadian Space Agency

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Part One

Summary (Abstract)

1 Description of the research program

1.1 General introduction

Since its inception in the 1920s, major advances in the study of atmospheric ozone have been made, progressing from ground based observations to balloon, aircraft, rocket and satellite platforms. Observations from the ground are convenient and provide long term data but cover only a small area of Earth and cannot provide a global picture of the ozone distribution and its complex dynamical variations. Satellite instruments are capable of remotely sensing total ozone levels and height distributions, providing comprehensive current data over most of the Earth. Over the last three decades many satellite missions have involved ozone measurements [1], and several other missions are now operating or in preparation [2]. Significant progress has been achieved in understanding the major processes involved in ozone dynamics. Despite this, no comprehensive model capable of predicting long term trends of the ozone layer exists. Recent satellite missions are directed toward obtaining comprehensive data which will support the development of such models.

Over the last two decades, ozone chemistry has ceased to be a purely scientific problem, as major ozone depletions have taken place, both in the polar regions and elsewhere. The associated potential for human health problems and disruption of plant life, including effects on the agriculture, forestry, and fisheries industries, have made this subject one of intense public interest and concern. In light of the potentially disastrous consequences of ozone depletion both for key sectors of the national economy and for public health, it is imperative to provide an effective, low cost means of global ozone monitoring which can provide data on ozone levels both to the Canadian public and to the scientific community. It is worth noting that recent specialized ozone satellite missions are not able to meet this requirement fully because of their extreme complexity and high scientific specialization. Due to the extremely high costs associated with these missions they are normally conducted with broad international cooperation.

We propose to develop an instrument to measure the vertical and horizontal distribution of ozone at altitudes of 10 - 50 km. The technique involves measuring ozone concentrations using an imaging spectrograph suspended from a parachute deployed from a sounding rocket at apogee near 80 km altitude. Data from a number of such instruments flown simultaneously along a baseline of several hundred kilometers are processed on the ground using tomographic analysis to yield vertical and horizontal ozone profiles. This type of instrument and analysis could lead to a relatively low-cost microsatellite-based system for global ozone monitoring, drawing upon the national capabilities of Canadian universities and industry.

The goal of the proposed project is to develop and validate an instrument for parachute deployed from a sounding rocket. The ultimate goal is to create within the Canadian space science community and Canadian industry a capability for construction and deployment of a microsaellite-

based system for global ozone monitoring. Such a system would be an efficient low-cost alternative to the presently contemplated systems (TOMS, SBUV, GOMOS), and would provide important and timely information about the ozone layer to both the Canadian public and the atmospheric science community

1.2 Global ozone distributions in the polar winter

Churchill ozonesonde data from the fall and winter of 1965 showed peak ozone partial pressures between 0.16 and 0.25 μbar at altitudes from 18 to 25 km, with negligible ozone above 40 km altitude. The temperature fell from 260 K at ground level to about 215 K at 10 km altitude but was roughly constant up to 30 km.

1.2.1 Other Species Targets

The availability of other species in the atmosphere will be determined by the spectral region that the detector will target and the resolution of measurement. The visible region of interest (400-800 nm) contains such possible targets as H_2O, O_2, NO_2 and NO_3, according to HITRAN 1992. Specific wavelengths used in the detection of a particular species are usually contaminated by other atmospheric constituents. A full spectral range allows better separation amongst atmospheric constituents, including aerosols, and does not necessarily rely on unique spectral signatures.

Simultaneous in situ measurements of radicals and other representatives from the important chemical family, NO_x, will provide valuable information to aid in the interpretation of the ozone trend in this region. The source of stratospheric NO_2 is mainly N_2O, which has seen significant increase in recent years from industrial pollutants. Determining the NO_2 trend will help to develop more insight into the effects of its source.

Several species undergo large diurnal variations. The conversion from NO to NO_2 at night is a rapid process, while the photolysis rate of NO_3 is large enough that NO_3 is nearly immeasurable during the day. The object of our stellar occultation method is to determine vertical profiles of these nighttime species. Both NO_2 and NO_3 have strong absorption features within the spectral range of 400-700 nm. From studies at the tangent altitude of 24 km, NO_2 suffers at least an estimate 7% loss in transmission at 431 nm (without scattering). The resolution of our instrument will be assessed, and the availability of other species which are available for retrieval will be determined.

1.3 Absorption and scattering of starlight in the visible spectrum

Ozone column concentrations will be determined by measuring the absorption of starlight by atmospheric ozone in the Chappuis bands between 450 and 750 nm. The method is self-calibrating and is based on a comparison of stellar spectra measured above and within the stratospheric ozone layer. The three-dimensional position of the instrument will be measured using GPS technology, and the sight lines to the stars will be determined by identifying the stars using a simultaneous video record of the star field observed.

1.3.1 Scattering

Rayleigh scattering involves particles which are much smaller than the incident wavelength. The cross-section is well known, and the effect of this transmission loss process will be included in our retrieval technique. Mie scattering involves particles which are comparable or larger than the incident wavelength. The size, shape and density of the scattering molecule all contribute to the effect. A simple Mie scattering model will be included in our analysis. A substantial increase to the aerosol layer at 10-15 km may be detrimental to our results below this altitude. Times of major volcanic eruption should be avoided, which is possible since our mission is of such short duration. The effects of polar stratospheric clouds (PSCs) will be analyzed further. It is as yet unclear whether some science is attainable from a PSC event.

1.4 Imaging spectroscopy of stars

1.4.1 Stellar Absorption Lines as Wavelength Markers for Spectra

It is well known that the spectra of many stars, i.e., those of certain spectral classes, on or not too far off the main sequence, resembles that of a blackbody. In addition to the Planck curve, there are a number of spectral features caused by absorption due to the stellar constituents. The absorption lines are often called Fraunhofer lines.

In looking at the spectra of stars from various spectral classes over a large wavelength range "short lists" of absorption lines can be made. As an example, the spectral features of a solar type star (spectral class G68V) are given. Clearly evident by inspection in this spectrum are Calcium II H and K lines around 390 nm, the G-band which originates from CH absorption around 430nm, Magnesium I at 515nm and Sodium D near 580nm. The exact values of these quantities can be found in the literature.

The biggest difficulty will be the selection of lines. Ideally, suitable lines will be both strong and isolated. However, the currently proposed resolution of the instrument (about 5nm/pixel on the CCD) will limit the number of usable lines. Fortunately, at least for solar type stars, those listed above should prove strong and "wide" enough to be detectable on at least two to three pixels of the CCD.

In order to use an absorption line as a wavelength marker, it will be necessary to determine the spectral type of the star from which the light came. This will require the matching of a measured spectrum to that of a well known spectrum. Traditionally, this has been done manually, however, recent advances in artificial neural networks has made automated spectral classification possible. This must be investigated in the future. Also to be determined is an appropriate "short list" of usable absorption lines for different spectral types.

In conclusion, it is appears that it will be possible to use absorption lines for wavelength markers. Adequate features exist that are of appropriate strength and width in the required wavelength range. Still, more precise work has yet to be done to determine exactly which lines will be detectable.

1.4.2 Airglow/Auroral contribution:

A launch from Churchill automatically involves an auroral contribution because Churchill is located right in the auroral zone: 68 degrees north (AACGM model). Therefore an increased intensity at 557.7 nm and 630.0 nm is expected. The following approaches to the problem were discussed:

1) Only use the wavelength between 557.7 and 630.0 nm. Problems: we limit ourselves to a quite narrow wavelength band, and we cannot use the whole Chappuis absorption band.

2) Use notch filters to minimize the intensity at these wavelengths. Problems: The characteristic of notch filters includes higher harmonics that absorb up to 30% at wavelengths different from the ones we want to exclude. They also have a 'large' halfwidth. Therefore we exclude a whole range of wavelengths from our spectrum.

3) Include the whole spectrum and don't bother about the increased intensity. Problem: Background noise on CCD: Actual dark areas are recognized as being green (and/or red). The pixel that recognizes the auroral wavelengths can not necessarily be used because the intensity of aurora can change. Solution: One can use a single pixel as a kind of notch filter: always exclude the pixel that registers the auroral wavelength(s). Therefore a high resolution would be better.

We decided to go with 3) because we want to use the whole feature of the Chappuis band and we want to keep our option open to detect other species.

1.5 Vertical and tomographic profile inversion of ozone distribution

1.5.1 Required/achievable accuracy of measurements - TBD

1.5.2 Ground-based Data Handling Issues

From the perspective of the Ground-Based Data Handling team, there are numerous tasks to be grappled with.

1.5.2.1 Data Decompression from Telemetry (picture reconstitution)

Compression algorithm; Decompression algorithm; Associated data losses

1.5.2.2 Spectral Inversion (from picture to ozone column amounts)

1.5.2.2.1 Error Sources

The reconstituted images captured by the CCD will be the result of more than just O_3 absorption. Other absorption phenomena attenuating the starlight reaching the CCD will include Rayleigh scattering, NO_2 absorption, and aerosol scattering. In addition, instrumental noise and dark current phenomena will be present to some extent. Each of these are addressed below.

- Rayleigh scattering

Rayleigh scattering, caused by the presence of molecules between the star and our instrument, will be present to some extent in our 'unocculted' views above the ozone layer, and will increase as the instrument descends. This phenomenon varies as ...

(formulae, variables, etc.)
(estimate of significance in CCD images)
(removability from the data)

- NO_3 absorption

NO_3 is also present in significant amounts above 20km altitude.

(concentration by altitude, citations)
(absorption levels expected)
(estimate of significance in CCD images)
(removability from data?)

- aerosol scattering

Probably the least predictable influence on the CCD images is the effect of airborne particles in all levels of the atmosphere.

(determining variables)
(variation by altitude)
(expected significance)

- Instrumental sources of error

In addition, instrumental optical phenomena, noise from the intensifier and CCD readout electronics, and dark currents will all be present to some extent.

(expected optical phenomena and significance)
(expected noise sources and levels)
(expected dark currents and significance)

- Cumulative estimate of non-removable error

(transfer function magnitude, character, etc.)

1.5.2.2.2 Spectral Inversion Method

- Algorithm
- Effectiveness
- Speed estimate

1.5.2.3 Tomographic Inversion (from ozone column amounts to O_3 distribution reconstruction)

There are a variety of criteria and approaches to consider in designing the reconstruction process once spectral inversion has been completed. To understand the process, we will make some simplifying assumptions, and assess the validity of each of these assumptions.

1.5.2.3.1 Simplifying assumptions

- vertical linear instrument trajectory (true as long as terminal velocity > expected horizontal wind speeds.)
- an appropriate distribution of stars of appropriate brightness and constancy (validity determined with statistical analysis of the stellar sphere; optimizable by choosing best zeniths and therefore dates and times.)
- stationary globe with respect to the stellar sphere (not true but completely predictable; can be added later.)

1.5.2.3.2 First level of processing

The most rudimentary information available from the occultation data is a one dimesional variation in the ozone column concentrations within the plane defined by the trajectory of the instrument and each star viewed by the instrument. Each star viewed by the instrument both above the ozone and through some part of the ozone provides this data in its own instrument-trajectory—star-position plane. The collection of the data in these planes can then be reconstructed into 3-D ozone distributions using other techniques.

- A 2-D Reconstruction option

If a purely vertical variation of ozone concentration were assumed with each star plane, Abel's equation could be used and a lower triangular matrix generated in order to find calculate what that vertical ozone variation is. This vertical variation would be different for each star plane. The vertical ozone variations could then be interpolated between adjacent star planes to give the variation in vertical ozone distributions with respect to azimuth.

- 3-D Reconstruction options:

- Fourier reconstruction

The collection of star planes for which 1-D ozone variations are known might yield a crude three dimensional reconstruction by finding the Fourier coefficients best approximating the variation in ozone concentration around a circle of a given altitude and radius centered on the instrument trajectory.

- Moving Sector reconstruction

If we pick a small angle and assume that the variation in the ozone distribution within a sector of that size does not vary significantly across its width, then we can treat stars falling within an azimuthal sector of that width as though they were all in the same plane. This permits us to get two or more look-directions within the plane affording a significant foundation for reconstruction of the ozone as it varies with distance from the instrument. Doing this repeatedly, moving the sector boundaries a few degrees each time around the domain should enable us to reconstruct the entire domain in three dimensions.

- Other reconstruction techniques

2 Relevance of ODIN aeronomy and other projects

TBD

3 Theoretical studies, data analysis and dissemination of the scientific results

TBD

4 Composition of the science team and personnel responsibilities

TBD