NIGHTSKY IMAGING TOMOGRAPHY EXPERIMENT TO MEASURE OZONE WITH STARLIGHT

NiteOwl

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

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NiteOwl

Part One

Executive Summary

The Nightsky Imaging Tomography Experiment to Measure Ozone with Starlight (NiteOwl) has as its primary objective to develop and validate an instrument capable of providing high resolution data on spatial variations of atmospheric ozone. The NiteOwl project is a joint venture of the University of Saskatchewan and SCI-TEC Instruments Inc. of Saskatoon. A compact slitless imaging spectrograph will be developed for stellar occultation measurements with 3 - 5 nm spectral resolution at wavelengths from 400 to 780 nm. It will be used to measure column ozone concentrations during an Arctic winter night. Using visible wavelength absorption in the Chappuis bands provides ozone measurement capabilities in the scientifically important height range of the upper troposphere and lower stratosphere. Ozone observations in this region will provide data needed for both the analysis of global ozone trends and studies of local ozone transport and ozone production at tropospheric altitudes.

The NiteOwl mission will be carried out from SpacePort Canada at Churchill, MB. The parachute-borne imaging spectrograph will be deployed from a rocket at apogee near 80 km, and will return to the ground while spinning slowly to scan the horizon. Global Positioning System technology will fix the payload position and an attitude video camera will provide accurate pointing information with high time resolution. Observations of unocculted stellar spectra will first be acquired above 60 km, and used to normalize occulted spectra subsequently observed from within the ozone layer. In this way the NiteOwl instrument will be self-calibrating. The normalized wavelength profiles of absorption depth will be inverted to yield column concentrations of ozone, total molecular density, and possibly NO_2 and NO_3. Vertical and horizontal distributions of ozone at altitudes from 10 to 50 km will be determined from column ozone concentrations by tomographic reconstruction, with expected resolutions of 3 km vertically and 100 - 200 km horizontally.

The NiteOwl project will provide an excellent training ground for young Canadian scientists and engineers, by virtue of the important ozone science objectives, and the unique opportunities provided by a multidisciplinary project team working closely with an industrial partner. The synergy that has been developed between SCI-TEC Instruments Inc. and several units of the University of Saskatchewan in preparing this proposal will lead to a successful project

The NiteOwl project is intended to pave the way for a Canadian microsatellite-based system for global ozone monitoring. Such a system would be an efficient low-cost national initiative with key advantages over currently operating and proposed systems (*e.g.*, TOMS, GOMOS). It would provide important and timely information about the ozone layer to the Canadian public and the atmospheric science community, and could lead to the development of new industrial capabilities and wealth generation for SCI-TEC Instruments, Inc.

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1. NiteOwl Mission Science

1.1 Introduction

Over the last two decades, major ozone depletions have taken place both globally and particularly in the polar regions. The associated potential for human health problems and disruption of plant life, including effects on the agriculture, forestry, and fishery industries, have made this subject one of intense public 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 that there be 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.

From their ground-based beginnings in the 1920's, atmospheric ozone observations have expanded to encompass measurements from balloon, aircraft, rocket and satellite platforms. While observations from the ground are convenient and provide long term data they can cover only a small geographic area and cannot provide a global picture of the ozone distribution and its complex chemical and dynamical variations. The current generation of satellite instruments is capable of remotely sensing total column ozone [ ] and stratospheric height profiles [ ]. During the last three decades many satellite missions have made ozone measurements [ ], and several other missions are now operating or are in preparation [ ]. Significant progress has been achieved in understanding the major processes involved in ozone dynamics and chemistry [ ]. However, despite this no comprehensive model exists that is capable of predicting long term trends of the ozone layer. *(Check this statement - STROBE?)*

Recent and current satellite missions have aimed at obtaining comprehensive data which will support the development of ozone trends models. By virtue of the complexity of ozone chemistry, these experiments are often required to measure simultaneously several atmospheric constituents including aerosols, as well as cloud coverage and temperature distributions [ ]. Such facilities-class missions require major resources, entail very long lead times, and are often conducted with broad international cooperation. It is worth noting that the methodology of the instrumental techniques developed for such experiments is often unsuitable for a monitoring type system, either because of high cost or high specialization. In addition, these major experimental programs are not well suited for the training of highly qualified personnel.

The proposed NiteOwl mission follows a different paradigm for the development of Canadian space science and technology. First, we propose to validate working principles for an instrument which can provide a basis for a relatively low cost microsatellite-based system for global ozone monitoring. Such an instrument should be able to measure ozone with high spatial resolution in both the horizontal and the vertical, including the upper troposphere and lower stratosphere between 10 and 25 km altitude. High spatial resolution ozone data for this region, such as those obtained during the NiteOwl mission, are of great importance both for current theoretical models of global ozone trends and for studies of local ozone transport between the stratosphere and troposphere. Secondly, the scientific and technological objectives of the proposed experiment are formulated to foster within Canadian industry an interest and capability for space science missions with potential commercial spin-offs in the area of environmental monitoring. Finally, the project time frame, project team composition, management philosophy and financial strategy for supplementary funding, were all designed to maximize the training potential for a new generation of Canadian space scientists and

engineers. This last element also includes the enhancement of public awareness of Canadian space science missions in general, and those specifically related to ozone science, in particular.

1.2 Mission Objectives

1.2.1 Science objectives

Our specific goal is to look for local signatures in ozone concentrations which may indicate increased ozone transport between the upper troposphere and the lower stratosphere (UTLS). These high resolution data (3 km vertical, 200 km horizontal) will be used to clarify the mechanisms for ozone formation and transport in the UTLS. These data complement and will be used in collaboration with existing Canadian and international ozone observation missions [ ]. Such data are also required by existing theoretical models of global ozone trends, in particular the Canadian Middle Atmosphere Model (MAM) General Circulation Model (GCM) [Beagley *et al.* 1995].

1.2.2 National Space Science and Technology Objectives

All stages of the NiteOwl project implementation are designed to maximize the training potential for students and young researchers by providing them with wide opportunities for professional development within the environment of a multidisciplinary team comprising academic and industrial partners. It is intended that a number of supplementary studies and analyses required by the NiteOwl project be conducted by a multidisciplinary group from different Departments and Colleges of the University of Saskatchewan. It is expected that an NSERC grant application will be prepared during Phase A. New forms of student involvement are planned and have already been implemented in the proposal submission stage. Contract overhead amounts paid to the University of Saskatchewan will be used, where possible, as an additional source of financial support for graduate students involved in the NiteOwl project.

The NiteOwl project will be carried out in close collaboration with the industrial partner, SCI-TEC Instruments, Inc. (SCI-TEC), as it began with the preparation of this submission. The goals of this collaboration are: to establish a precedent for economically beneficial collaboration between Canadian university space scientists and technology-based small-to-medium enterprises (SMEs); to explore the feasibility of an idea for ozone monitoring with the potential to lead to a space mission that provides scientific, social, and economic benefits to Canadians; to increase the interest and ability in Canadian industry to conduct space science missions in environmental monitoring with potential commercial spin-off; and to provide graduate students in science and engineering at the University of Saskatchewan with direct hands-on experience in space payload design and development, while learning how to work in an industrial environment. It is believed that the instrument and analysis proposed for the NiteOwl mission can lead to a relatively low-cost national microsatellite-based system for global ozone monitoring that draws upon, and enhances, the expertise of Canadian universities and industry.

1.2.3 International Collaboration Objectives

High resolution data on ozone spatial distributions in the upper troposphere and lower stratosphere region provided by the NiteOwl mission will augment current Canadian involvement in the international efforts to understand and predict global ozone trends.

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1.2.4 Public Service and Educational Outreach Objectives

The NiteOwl project provides an opportunity to increase public awareness of Canadian space science activities by means of wide communication of the goals, progress and results of the NiteOwl project. The long-term goal of the NiteOwl project is to pave the way for the deployment of a national system for monitoring global ozone distributions in the atmosphere. Such a system can provide timely and important information to Canadian citizens about potential health risks stemming from reduced ozone protection, as well as harmful effects on plant and animal life. This benefit to the Canadian public is seen as a high priority goal for the NiteOwl project since it will be supported by public funding. Communication of the potential benefits of the project has already begun locally with front-page coverage in the University of Saskatchewan "On Campus News", a seminar highlighting the innovative development of the proposal, and a World Wide Web home page devoted to the project.

1.3 Ozone in the Atmosphere and Ozone Measurements

There are two main regions where the presence of ozone directly affects life on Earth: stratospheric ozone at altitudes of 15 - 50 km, and tropospheric ozone below 15 km. The stratospheric portion includes about 90% of the ozone, and is commonly referred to as the “ozone layer.” This layer is responsible for the absorption of biologically damaging ultraviolet sunlight known as UV-B. The absorbed sunlight dissociates ozone molecules, heats the stratosphere, and is ultimately responsible for the temperature structure of the stratosphere.

The ozone concentration in the stratosphere is controlled by a number of minor constituents, such as oxides of hydrogen, nitrogen, chlorine, and bromine, which catalytically destroy ozone. Total column ozone abundances from 1979 to the present show a general downward trend [*e.g.*, Ozone Trends Panel Report 1988]. From both ground-based and satellite measurements, a 4-5% decrease per decade has been observed in both hemispheres at mid-latitudes [XVIII Quadrennial Ozone Symposium 1996]. The theory of Rowland and Molina [ ] predicts the catalytic destruction of ozone by chlorine radicals from chlorofluorocarbons (CFC's), with most of the ozone loss occurring in the upper stratosphere. The most dramatic examples of such destruction are the annual variations in ozone concentration with significant destruction of ozone occurring during the winter - spring transition in both hemispheres. This destruction is most significant over the Antarctic where it has been dubbed the “ozone hole.” Smaller variations are observed in the Arctic and elsewhere [XVIII Quadrennial Ozone Symposium 1996]. The larger ozone depletion over the Antartic is explained by the vortex circulation pattern which is stronger, colder and lasts longer in that region than elsewhere. These conditions facilitate the formation of polar stratospheric clouds (PSCs) which may significantly increase ozone destruction through a number of mechanisms associated with chemical reactions occurring on surfaces of ice, nitrate, sulfate and other particles. Some examples include the conversion of inert chlorine, such as HCl, into its reactive chlorine monoxide form, and the bonding of nitrogen dioxide, which becomes unavailable to stop the destruction of ozone. The main cause of Antarctic ozone depletion is heterogeneous chemistry occurring on PSCs which form more readily in the extreme cold. In the Arctic, the stratosphere is warmer and PSC formation is less likely. However, chlorine and other reactive species have similar concentrations in both hemispheres. Were the Arctic stratosphere to cool significantly, similar destruction of the ozone layer could be expected.

The stratospheric ozone concentration decreases above and below the maximum near 25 km, but increases again in the upper troposphere below 10 km (Figure 1-1). Unlike stratospheric ozone,

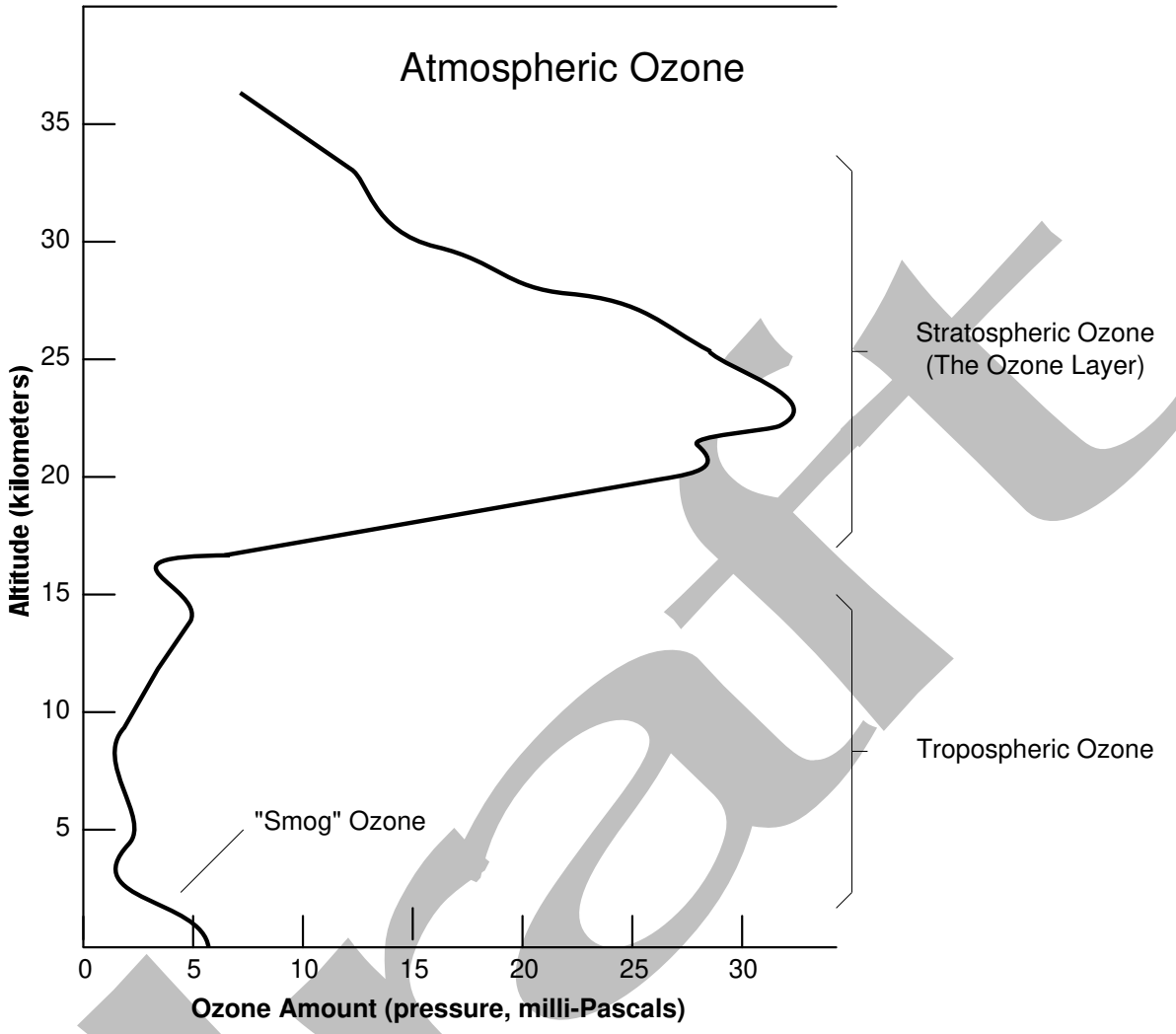

Fig. 1-1. Typical distribution of ozone in the troposphere and stratosphere (after a figure from NOAA Aeronomy Laboratory, 1996).

ozone in the troposphere is a pollutant and acts as a greenhouse gas, causing a warming of the same order of magnitude as that expected from the anticipated increase in CO_2 concentration [Fishman 1991]. The ozone concentration in this region is determined by the balance of ozone transport and exchange between the stratosphere and troposphere, and local ozone production due to both natural (lightning) and anthropogenic factors such as industrial pollution. The role played by tropospheric ozone in the overall ozone balance and in the depletion of stratospheric ozone is not well understood. Global ozone measurements in the UTLS would facilitate investigation of the effects of transport processes in this region on stratospheric ozone, and could indicate possible pollution events. Ozone's relatively weak absorption at visible wavelengths in the Chappuis bands lends itself to tangent path measurements in the UTLS region, below the peak of the ozone layer.

The NiteOwl experiment uses a self-calibrating stellar occultation technique. Stars as light sources offer many advantages for such measurements: ubiquity, spectral distribution, and collimated light. The ability of this technique to conduct measurements during the Arctic polar night is an

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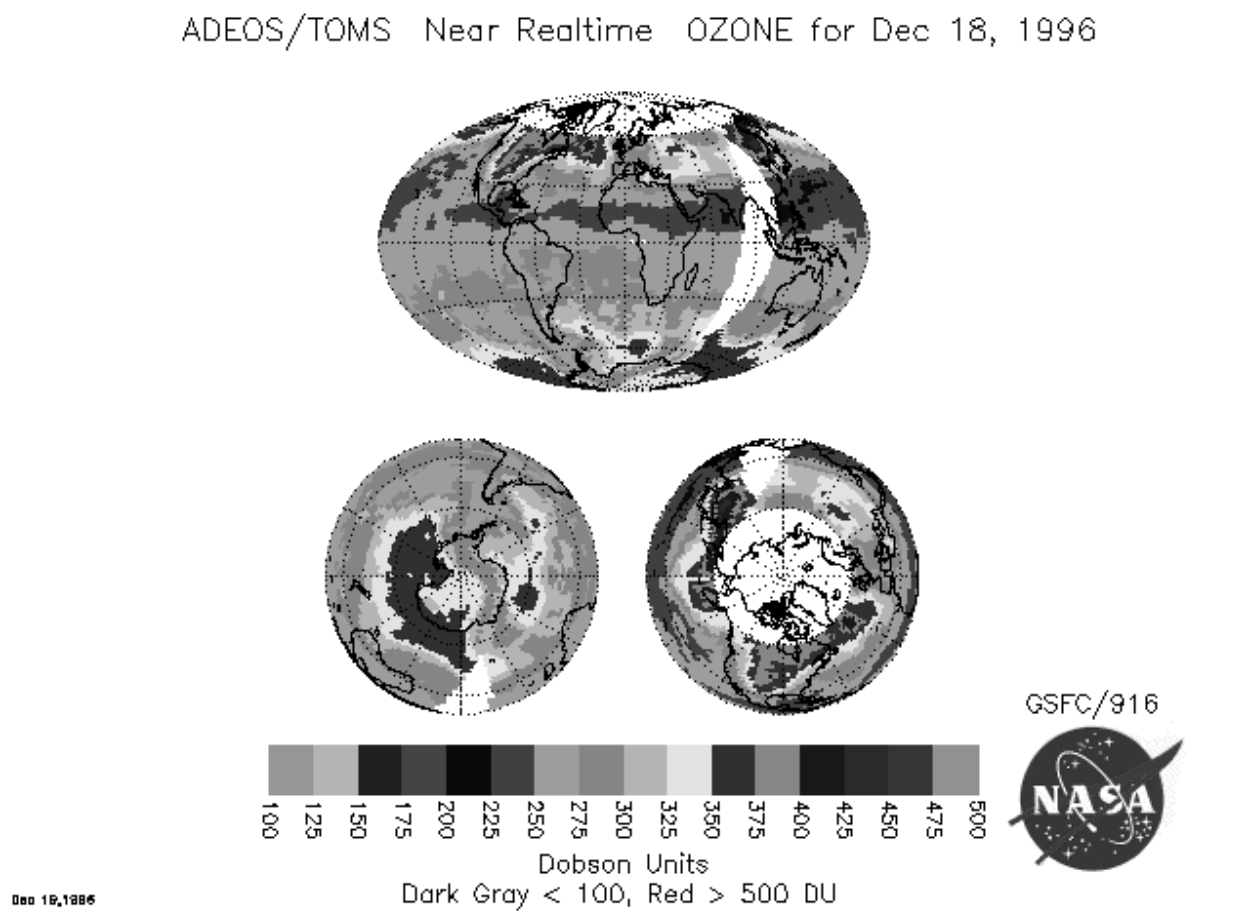

Fig. 1-2. Recent ADEOS/TOMS global ozone maps showing a winter data gap at high Northern latitudes. (Courtesy NASA Goddard Space Flight Center.)

important consideration as large areas of Canada cannot be monitored by other means (note the gap in TOMS data at high Northern latitudes in Figure 1-2).

Despite a wealth of experimental data on ozone distribution currently there are no global altitude resolved measurements of ozone. TOMS is producing outstanding maps of total tropospheric ozone [ ] but they are of low accuracy (of the order of 50%) and provide little detail on altitude distributions. Currently existing models of ozone dynamics predict large vertical (2-3 km) and horizontal (100-500 km) variations of ozone distributions [ ]. They also predict an importance of low amplitude (of the order of 10%) variations of ozone concentrations in the lower stratosphere. Further validation and constraint of theoretical and computational models of global ozone trends requires experimental data with horizontal resolution of a few hundred km and vertical resolution of 2-3 km with an overall precision better than 10%. The NiteOwl project aims at developing techniques that can provide such data.

While the primary objective of the NiteOwl mission is to measure ozone, it may also be possible to map PSC formations if any are encountered. Preliminary analysis with the current model

of the imaging spectrograph indicates that PSC formations should be detectable. This possibility will be investigated in detail during Phase A.

A nighttime experiment using stars as light sources also offers unique opportunities to make measurements of other species which are undetectable during the daytime. The nitrogen oxides are an important class of such species, which undergo large diurnal variations. The conversion of NO to NO_2 at night is a rapid process, while the photolysis rate of NO_3 is large, such that NO_3 is nearly absent during the day. A secondary objective of the NiteOwl experiment is to determine vertical profiles of these nighttime species. Such measurements may provide valuable information on ozone chemistry and will enhance the interpretation of the ozone results. Both NO_2 and NO_3 have absorption features within the spectral range from 400 to 700 nm. Preliminary calculations for a tangent altitude of 24 km indicate 7% absorption at 431 nm by NO_2. This should be detectable with the target resolution and sensitivity of the NiteOwl instrument. The wide spectral range of the instrument (400-780 nm) also allows more accurate determination of the column concentrations of the absorbing and scattering species, including aerosols. We will also conduct a detailed investigation of the possibility of NO_x measurements during Phase A.

2 The NiteOwl Experiment

The NiteOwl instrument will be launched from SpacePort Canada (Churchill, MB) aboard an Orion rocket. This rocket will take the payload to an altitude of 80km. From apogee the payload will descend using a parachute specially designed to provide a low spin rate. Measurements of stellar spectra attenuated by atmospheric absorption will be taken using an imaging spectrograph (ISG) viewing horizontally. As the payload rotates the ISG will scan the full horizon. The position of the payload will be monitored using an onboard Global Positioning System (GPS) receiver, which will also facilitate post-flight recovery. An attitude video camera (AVC) in the payload will image the star field to determine the look direction of the ISG. Data transmitted to the ground will include measurements made by the ISG and the GPS receiver, an attitude video camera (AVC), a temperature sensor, and possibly a chemiluminescent ozonesonde to measure ozone *in situ*. A block diagram of the payload is shown in Figure 1-3.

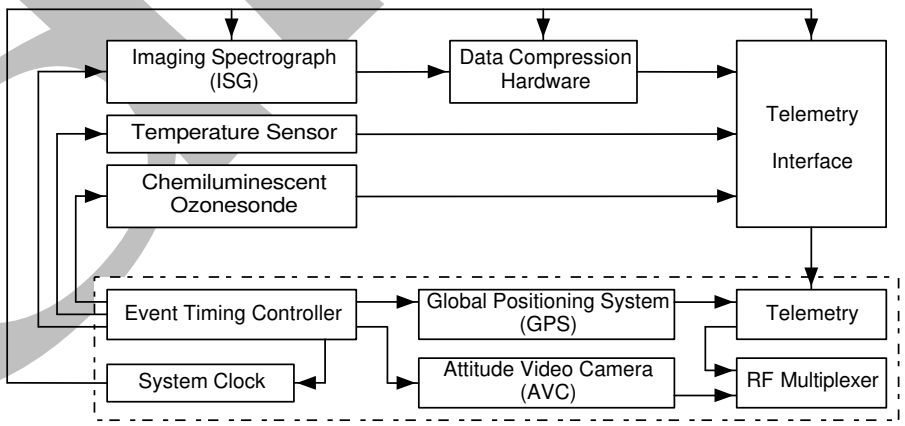

Fig. 1-3. Block diagram of the NiteOwl payload showing the flow of control and data.

The ISG will disperse incident starlight using a transmission diffraction grating and focus the light onto a charge coupled device (CCD) detector which will measure the spectral irradiance reaching the instrument. The planned spectral resolution of the measurements is 3 - 5 nm, and the wavelength range from 400 to 780 nm will span the Chappuis bands of ozone, as well as absorption bands of NO_2 at shorter wavelengths and NO_3 at longer wavelengths. The CCD detector readout will undergo lossless compression and will be transmitted, together with the data from the GPS receiver and the other sensors, via an interface to the telemetry system, which will transmit the data to a receiving system on the ground over an S-band PCM-FM link.

2.1 Description of Experimental Methods

The NiteOwl experiment will measure ozone concentrations using a stellar occultation technique. The rotation of the payload during its descent through the atmosphere allows observations of stars all around the horizon, and measurements of ozone column concentrations at all azimuths where sufficiently bright stars are seen. The technique allows measurements to be made at any local time during the night, as it does not depend on tracking any particular star. The sun and moon need only be far enough below the horizon that scattered light may be neglected. Several stars will be visible in each 1-s image from the ISG; however, the signal-to-noise ratio (SNR) of 100:1 required for accurate spectral and tomographic inversion will only be achieved for stars of magnitude 3.0 or brighter (Part Two, §3.1.3). Repeated observations of each star from successively lower altitudes provide an array of lines of sight through the atmosphere. The combination of all sight lines through the region to be reconstructed provides the raw data on which tomographic analysis will be performed. Figure 1-4 illustrates the change with altitude of the spectrum of a third-magnitude G-type star when viewed tangent to the atmosphere. Ozone absorbs most strongly at 550 - 620 nm, while Rayleigh scattering reddens the transmitted light.

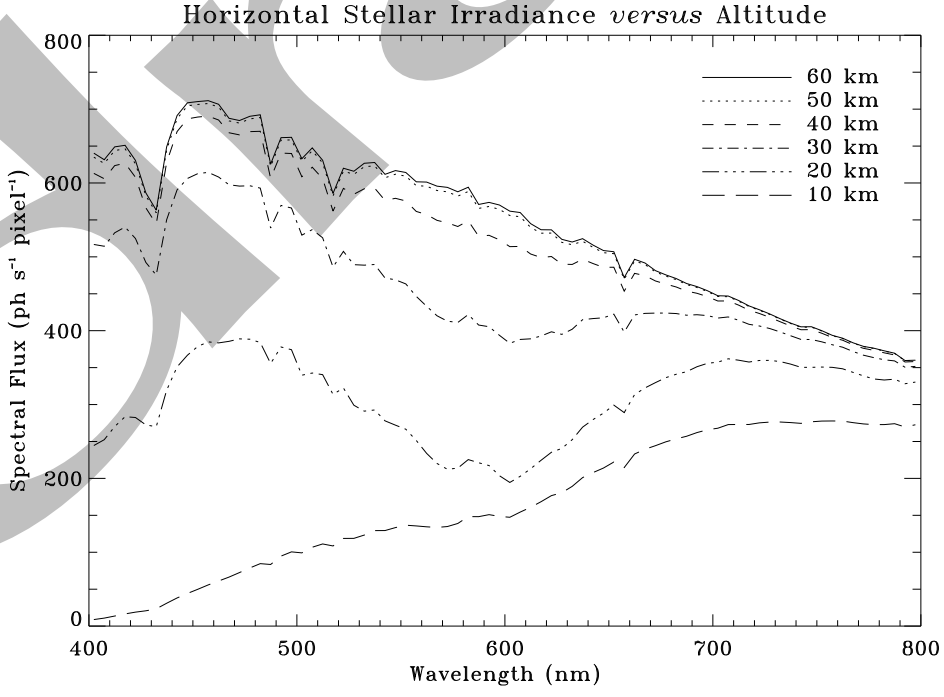

Fig. 1-4. Spectrum of a 3rd-magnitude G-type star viewed horizontally through the atmosphere at various altitudes.

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The initial measurement of each stellar spectrum from above the stratospheric ozone layer provides a reference spectrum for all subsequent observations of that star.Subsequent measurements of a star's spectrum from within the stratospheric ozone layer are divided by the initial (unabsorbed) spectrum to yield fractional transmissions, from which column concentrations of O_3 (and possibly NO_2, NO_3, and M) may be derived. In this way the ISG is self-calibrating, as there is no dependence on absolute sensitivity of the instrument.

The occultation technique to be used for the NiteOwl mission is based on taking the ratio of the spectral irradiance $I(\lambda)$ from a particular star when seen through the atmosphere, to the unattenuated spectral irradiance from the same star when seen above the atmosphere $I_0(\lambda)$ (Eq. 1-1):

$$\frac{I(\lambda)}{I_0(\lambda)} = \exp(-\sigma(\lambda)\ N) \qquad (1\text{-}1)$$

where $\sigma(\lambda)$ is the absorption cross section per molecule and N is the column number density of the absorbing species (cm^{-2}). If the atmospheric attenuation is due solely to ozone, the column density of ozone in the path may be calculated from Eq. 1-1. If other species absorb significant amounts of radiation at the wavelength of interest then additional terms must be added (Eq. 1-2):

$$\frac{I(\lambda)}{I_0(\lambda)} = \exp(-\Sigma_j\ (\sigma_j(\lambda)N_j)) \qquad (1\text{-}2)$$

As starlight passes through an absorbing atmosphere, the irradiance decays exponentially, with the amounts of ozone and other absorbing/scattering species along the light path determining the degree of attenuation. Working with the logarithm of the ratio of spectral irradiances transforms the governing equation to a linear one, permitting a tomographic solution process.

The tomographic reconstruction of the ozone distribution presents a number of challenges. These arise from the slenderness and curvature of the domain, the dominance of the vertical component of the ozone density gradients, the very weak absorption cross section in the Chappuis bands necessitating large column lengths, and the requirement to reconstruct geographic variations using a small range of source elevation angles. These factors conspire to make the problem ill- posed.

Because each potential source star must be viewed at least once above the stratosphere, the 80 km apogee limits data gathering to stars which are no lower than 4.5° below the horizon, *i.e.*, the set of all points 90° from the local zenith. Assuming such a star is present and bright enough and is observed by the instrument, the lowest of its rays that clear the aerosol contaminated region below 10 km altitude will provide data on ozone no further away than 1000 km from the instrument and then only at 60 km altitude. Above the horizon, elevation angles greater than 6° pass through too little atmosphere for attenuation to be clearly different from noise.

If ozone varied only with altitude, the tomographical problem would be governed by Abel's integral equation [Vest 1979] which is only moderately ill-posed. Preliminary simulations, however,

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show that if ozone varies horizontally, a purely vertical inversion yields poor results. To incorporate the horizontal variation in ozone, a technique other than Abel inversion must be used.

2.2 Instruments

The ISG will image starlight from a field of view subtending 15° horizontally and about 12° vertically. Collimated light from each star in the field of view is dispersed by a low-resolution transmission grating, and then focused onto the CCD detector by a fast, large-aperture objective lens. The pitch of the grating and the focal length of the objective lens will be chosen to provide a spectral resolution of 3-5 nm per CCD pixel.

A GPS receiver, to be provided by Bristol Aerospace Ltd. (BAL), will allow real-time determination of the experiment position and velocity in three dimensions with 100-m accuracy. Simultaneous operation of a second GPS receiver on the ground will enable inverted differential GPS post-processing to reduce the positional uncertainty

A Xybion intensified video camera identical to that flown on the OEDIPUS-C mission will be provided by BAL as an AVC to determine the pointing direction of the ISG. The knowledge base required for attitude determination from the video signal was developed for the GEMINI mission and resides at the University of Saskatchewan [Moorhouse 1994].

Subject to availability and payload mass and power restrictions, it would be useful to fly a chemiluminescent ozonesonde [Hilsenrath and Kirschner 1980], to provide *in situ* validation of the optically determined ozone profiles. This instrument is the only technique available for routine nighttime *in situ* ozone measurements above balloon altitudes.

In order to determine other trace species concentrations, it is required that temperature or pressure be measured. Although the inversion technique could also provide some measure of these parameters, several species are extremely sensitive to photolysis rate dependent on the temperature. With this requirement on the precision of the temperature survey, it is best to provide a definite means of measurement. A standard thermistor, such as that used in the Super Loki datasonde [Schmidlin 1986], will allow the measurement of temperature in a simple, effective and reliable way that would not place significant burden on the cost or payload weight of the mission.

2.3 Expected Performance

2.3.1 NiteOwl Instruments

Falling from an apogee of 80 km, the NiteOwl instrument will scan the horizon, building a database of reference stellar spectra as it falls through the mesosphere. The instrument will image unocculted stars of magnitude 3.0 or brighter with a minimum SNR of 100:1 while rotating at a rate of 6° per second or less. The spectral resolution will be 3 - 5 nm, and the angular resolution will be 1 arcmin in elevation.

The chemiluminescent ozonesonde provides ozone profiles over the altitude range from 65 to 20 km, with about 12% accuracy and 6% precision. The thermistor temperature accuracy is better than 1 K up to 53 km altitude when used on the Super Loki datasonde. Slightly lower accuracy will be achieved on the NiteOwl payload, which is expected to fall faster than the datasonde.

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2.3.2 Tomographic Reconstruction

The distribution of stars around the horizon depends on the latitude of the launch site and the local sidereal time (LST) during the flight. For a launch from SpacePort Canada (Churchill, MB) during a dark-moon period in the winter of 1998-99, LST windows exist for which the horizon distributions of stars brighter than 3rd magnitude contain no gaps wider than 40° of azimuth (12% of the horizon), and sectors of azimuth where suitable stars occur at azimuth spacings of 5 - 10° (Part Two, §7.2).

To provide estimates of the reconstruction error, a preliminary code was developed to generate synthetic noisy tomographic data using the vertical ozone density profile from the GOMOS model [Kyrölä *et al* 1993] with a gentle geographic variation superimposed. An attempt was made to reconstruct the ozone density distribution within the domain from the noisy data.

A classical tomographical approach was used, *i.e.*, starlight paths were tracked through the domain to generate line integrals, the field was discretized spatially (thus reducing the governing integral transform to a system of linear equations), and random noise corresponding to an RMS SNR of 100:1 was added to the data before applying solution techniques. Simplifying assumptions included no earth rotation during the experiment and no lateral payload drift, though this will clearly not be the case in practice.

The domain reconstructed lay between 10 and 40 km altitude and between a hypothetical vertical line of instrument trajectory and another locally vertical line 1200 km away. These boundaries defined an annular sector. The domain was defined by sweeping this sector between two planes, each of constant azimuth, about the instrument trajectory line. These planes were close enough together that ozone did not vary significantly between them, but far enough apart to include two stars near the horizon at +1° and -3° elevation angles. From an analysis of the star horizons available at Churchill and current estimates of geographic ozone variations, 5° was a reasonable width.

Two approaches to solving the linear systems yielded very encouraging results; both used regularization [Craig and Brown 1986; Dubovikova and Dubovikov 1987] to stabilize the systems. One approach modelled the gentle geographic distribution using an assumed form with one degree of freedom. The second approach used a full domain discretization.

The simulations provide confidence that for a S/N ratio of 100:1, the average vertical ozone density profile may be determined to within 12% of true values with a resolution of 3 km.

The ultimate accuracy in reconstructing the geographic distribution will depend on many factors including the nature of the actual geographic distribution (for which little is known *a priori*), the type of regularization used, and the model upon which inversion is based. Alternatives to regularization, such as the maximum probability method [McDade and Llewellyn 1993], are available as well. The determination of the optimum model and form of inversion, taking expected payload drift and star rising and setting into account, will be made during Phase A.

2.4 Data Acquisition and Processing

Data will be telemetered from the payload on two frequencies. Losslessly compressed data from the imaging spectrograph (ISG) will be merged with data from the GPS receiver, the temperature sensor, and possibly the chemiluminescent ozonesonde, and transmitted to the ground using bi-phase PCM-FM telemetry at an S-band frequency. In addition, the 2-MHz bandwidth analog

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video signal from the AVC, carried on a different S-band frequency, may be RF-multiplexed onto the same antenna or transmitted to the ground from another antenna. The raw telemetry data will be recorded on tape as well as being decommutated in real time.

The time-stamped AVC data will determine the look direction of the ISG at each moment. This technique was used successfully in the GEMINI project. The combination of the GPS-determined position-velocity data and the AVC attitudes defines precisely the atmospheric column along which the total ozone concentration is measured, as well as the rate of change of the column.

The ISG images must be decompressed and spectrally inverted to determine the optically absorbing species and their corresponding column densities. The first step is to remove the blurring caused by payload spin during the 1-s exposure time. This blurring will be primarily horizontal, and thus perpendicular to the vertical wavelength dispersion caused by the horizontal orientation of the grating rulings. Therefore, adjacent spectra can be shifted and summed to compensate for the motion of the ISG. This is accomplished by referring to the angular deflections obtained over time from the AVC results. This summation will simultaneously intensify the measured spectra and tend to cancel the readout noise present on each measured spectrum.

3 NiteOwl in the Canadian and International Context

Ozone monitoring in Canada is currently carried out using a network of ground-based Brewer ozone spectrophotometers, part of the Global Ozone Observation Network, together with balloon-borne ozonesondes, and lidars at Toronto and Eureka, NWT. Brewer instruments routinely use both the sun and moon as sources, and the development of a stellar Brewer is nearing completion. Canada is developing the OSIRIS and MOPITT space experiments to address the need for global measurements of ozone and other key trace gases in the UTLS region.

Much of our current knowledge of global ozone trends has come from the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7, which provided nearly fifteen years of accurate global ozone maps using solar backscattered ultraviolet (SBUV) observations. Successor instruments on the Japanese Advanced Earth Observing Satellite (ADEOS) and NASA Earth Probe continue to monitor total column ozone. The Global Ozone Monitoring Experiment (GOME) on the European Space Agency (ESA) Remote Sensing 2 (ERS-2) platform also provides global ozone column and profile data in the nadir using differential optical absorption spectroscopy (DOAS) at wavelengths from the UV to the near infrared (IR).

Several satellite experiments use solar occultations to derive altitude profiles of ozone and other species. The Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite (UARS) and the Stratospheric Aerosol and Gas Experiment (SAGE) II on the Earth Radiation Budget Satellite (ERBS) are currently operational in orbits which allow only seasonal coverage of the polar regions. The Polar Ozone and Aerosol Monitor (POAM) II experiment, which provided excellent coverage of high-latitude ozone, is no longer operational as the French Satellite pour l'Observation de la Terre (SPOT)-3 platform which hosts POAM II began to tumble in mid-November 1996. An Improved Limb Atmospheric Spectrometer (ILAS) in a polar orbit on ADEOS has begun to acquire ozone profiles. As well, the Microwave Limb Sounder on UARS is currently providing ozone profiles with 6 km vertical resolution, and experiments operating on similar principles at microwave (AMAS) and IR (MIPAS) wavelengths are planned.

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The ESA Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on the ENVISAT platform has been in preparation for over five years, and is scheduled for launch in late 1998. GOMOS will measure ozone and numerous other minor constituents using a stellar occultation technique, as does NiteOwl. The large number of target species necessitates much higher spectral resolution and coverage than are proposed for NiteOwl, and increases the cost and complexity of the instrument. As well, observations are restricted to the relatively few first-magnitude stars, thus hindering both spatial resolution and the possibility of tomographic analysis. A smaller instrument (Calibration for Ozone by Atmospheric Limb Acquisitions - COALA) using stellar occultation has been proposed as a payload complement to an ozone sensor operating on other principles.

This submission proposes a conceptually simple and elegant experiment to measure ozone at night by using visible-wavelength stellar occultation. Measuring column ozone concentrations along multiple lines of sight through the observed volume allows a tomographic reconstruction of the volume ozone distribution, with the spatial resolution required by current predictive ozone models. The moderate spectral resolution proposed for the NiteOwl experiment is sufficient to measure ozone absorption in the Chappuis band; it also allows higher instrumental sensitivity, thus expanding the range of useful stars and improving the resolution of the derived ozone distribution.

It should be noted that an opportunity exists to fly the NiteOwl experiment as part of a microsatellite mission. The Niteowl Submission Team has learned that payloads will be solicited for the ESA PROBA technology demonstration microsatellite, to be launched in early 1999. ESA plans to bear payload integration costs for all selected payloads, so CSA costs for the NiteOwl payload, if it is selected by ESA, would be limited to those for instrument development. It is believed that the NiteOwl instrument could be ready to take advantage of this opportunity.

4 Required Theoretical and Modelling Support

During the Phase A study, simulations of the spectral inversion technique and the tomographic inversion technique will provide important support to the mission and have the potential to substantially improve the quality of the measurements. Funding for these studies will come from existing sources such as NSERC.

4.1 Spectral Inversion Modelling

For the purposes of this proposal, stellar spectra have been generated for locally tangent viewing, using nominal O_3, NO_2, NO_3 and total molecular concentration profiles, and current absorption and scattering cross sections. During Phase A this modelling will be extended to nominal angles above and below the horizontal, with the addition of noise to the modelled spectra, and the spectral inversion will be performed to analyze the sensitivity of the process to random and systematic noise. In addition, aerosol scattering cross sections will be assessed to determine the expected impact of various aerosols, including PSCs, on the NiteOwl measurements.

(NOTE: This could be cast as a fundable trade-off study needed to determine the optimum spin rate ⇒ spectral blur ⇒ SNR ⇒ spectral inversion accuracy. Should we go for it?)

4.2 Tomographic Inversion Modelling

There are a variety of tomographic inversion algorithms available for reconstruction of the ozone distribution from the column density data. Specific to this inversion problem is the difficulty

in bridging the gaps in the horizontal star distribution to permit finer azimuthal resolution. Also, the spherical shell geometry of the region to be reconstructed and the extremely limited viewing angles over which data are obtained make the selection of specific reconstruction algorithms very important.

(NOTE: This could be cast as a fundable trade-off study needed to determine the required data rate ...)

The method used to establish the accuracy and resolution specifications stated in this proposal is based on regularization techniques [Dubovikova and Dubovikov 1987] and has involved only small sectors of the horizon having more than one star in them. Several other algorithms are available in the literature. In parallel with the Phase A activity of this project, all relevant inversion techniques will be compared to identify the most appropriate for this reconstruction problem. This study would use the actual star distribution during the launch window and include changes in the star positions during descent. In addition to existing algorithms, development of new or modified reconstruction algorithms will be considered.

5 Required Support Measurements

It is desirable to obtain independent measurements of both total column ozone and ozone profiles for comparison with the results from the NiteOwl experiment. SCI-TEC Instruments Inc. will provide a Mk III Brewer ozone spectrophotometer to measure total column ozone, using solar observations on the days before and after the NiteOwl launch, night-time lunar observations before or after launch, or a combination of solar and lunar observations. In order to use the Mark III Brewer during the same night as the mission, the moon must be at least 20° above the horizon for at least one hour. Satellite-borne total column ozone measurements from GOME or TOMS would also provide useful support, if the launch occurs late enough in the winter that the SBUV technique can be used at the latitude of Churchill (cf. Fig. 1-2). Weather permitting, the Mk III Brewer ozone spectrophotometer will be used to measure the ozone profile in Umkehr mode.

Meteorological data are also required for launch support and to aid in both the spectral and tomographic inversions. Akjuit Aerospace Inc. will provide regular data on both surface weather and stratospheric winds, the latter at 12-hour intervals. Altitude profiles of temperature and pressure to the stratospause would be useful, and may be obtained from a combination of balloon sounding and satellite-borne sensors. Regional cloud/aerosol data from weather and other operational satellites will also be required to confirm the scattering cross-section in the upper troposphere.

6 Data Analysis and Publication Plan

Before the NiteOwl launch, a number of preliminary studies must be carried out, as described in §§4.1 and 4.2 above. These will **(support the optimization of the experiment design, and)** evaluate and optimize the choice of techniques to be used in interpreting both synthetic data before the launch, and real data obtained from the mission itself. The results will be publishable.

The optical configuration to be used with this project is not a common one. Innovative optical design used in this project may form an important part of the larger paper to be prepared on the NiteOwl project. This paper, to be submitted after launch, will include an overview of our mission, its design and execution, and the data gathered, along with some preliminary results of the data

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interpretation. It is believed that the lessons learned will support the successful design and launch of a Canadian ozone monitoring microsatellite.

Subsequent to the general mission paper, detailed column density and tomography results will be published along with comparisons with contemporary results obtained by others monitoring the problem of polar stratospheric ozone depletion.

In addition to these results, the data gained from the GPS receiver and the AVC will enable the analysis and publication of the payload dynamics accompanying a high-altitude deployment of a low-spin parachute. This will be a useful advance on the current state of the art.

7 Science Team

7.1 Members of the Science Team

Dr. D.P. Steele (Professional Research Associate and Adjunct Professor of Physics and Engineering Physics, University of Saskatchewan) is the Principal Investigator of the NiteOwl Team. His areas of specialization and expertise are upper atmospheric physics and optical imaging of atmospheric emissions to derive atmospheric state parameters.

Dr. H.S. Caplan (Professor and Head of Physics and Engineering Physics, University of Saskatchewan) has extensive experience in science administration and project management.

Dr. A.V. Koustov (Assistant Professor of Physics and Engineering Physics, University of Saskatchewan) has expertise in geophysical application of ground-based and satellite measurements to study the structure of the Earth's atmosphere and ionosphere.

Dr. A.I. Smolyakov (Assistant Professor of Physics and Engineering Physics, University of Saskatchewan) has extensive theoretical expertise in the analysis of random processes in plasma environments including neutral turbulence and dynamics of non-linear processes in fluid-like media.

Dr. R.J. Bolton (Professor of Electrical Engineering and Associate Member in Computer Science, University of Saskatchewan) has expertise in VLSI circuit design, pattern recognition techniques, digital circuit design, computer systems and electrical systems integration. He also has experience in the analysis of attitude video camera and on-board CCD data.

Dr. H.C. Wood (Professor and Head of Electrical Engineering and Associate Member in Agricultural and Bioresource Engineering, University of Saskatchewan) has extensive expertise in the development of instrumentation for optical atmospheric studies.

Dr. J.D. Bugg (Associate Professor of Mechanical Engineering, University of Saskatchewan) has expertise in numerical modelling and experimental investigations of thermal/fluid systems.

Dr. A.T. Dolovich (Associate Professor of Mechanical Engineering, University of Saskatchewan) has expertise in the development of tomographic methods for optical measurement and non-destructive testing.

Dr. C.E. Soteros (Associate Professor of Mathematics and Statistics, University of Saskatchewan) has expertise in computer simulation.

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Dr. R. Srinivasan (Associate Professor of Mathematics and Statistics, University of Saskatchewan; consultant with AT&T Bell Laboratories) has extensive expertise in noise modeling, data compression techniques, and inversion algorithms.

Mr. E.V. Ivanov (Senior Research Engineer, SCI-TEC Instruments Inc., Saskatoon) has expertise in optical system design and construction, and balloon-borne optical measurements of stratospheric ozone.

Dr. J.E. Johnston (Senior Research Scientist, SCI-TEC Instruments Inc., Saskatoon) has expertise in both ground-based and space-borne spectroscopy and interferometry applied to chemical composition measurements of the troposphere, stratosphere, and mesosphere.

Mr. D.J. Sniezek (Vice President of Research, Development, and Engineering, SCI-TEC Instruments Inc., Saskatoon) has extensive experience in project management and the development and engineering of optical equipment for atmospheric ozone monitoring.

Dr. M.J. Painter (Assistant Professor of Accounting, College of Commerce) has experience in project management and the supervision of graduate management students.

7.2 Responsibility and Level of Effort

Table 2-1 details the members of the NiteOwl Science Team and their respective areas of responsibility and levels of effort. It should be noted that the proposed Science Team, consisting of faculty members of five departments and three colleges of the University of Saskatchewan as well as senior science and engineering personnel of SCI-TEC Instruments, Inc, bring to the project a very wide range of professional experience and complementary expertise. All members of the Science Team worked closely with each other and with the student members of the Submission Team during the preparation of this proposal, and have developed a cohesive unit capable of carrying out the complex, multifaceted project described in this proposal.

Table 2-1. The NiteOwl Science Team

Team Member	Responsibility	Level of Effort
D.P. Steele	Project co-ordination, mission planning and science	160 hr/month
H.S. Caplan	Project management	5 hr/month
A.V. Koustov	Instrument calibration and data storage	20 hr/month
A.I. Smolyakov	Mission simulation	20 hr/month
R.J. Bolton	Electrical/electronics design, risk analysis	25 hr/month
H.C. Wood	Design consultation	5 hr/month
J.D. Bugg	Mechanical and thermal design	15 hr/month
A.T. Dolovich	Development of tomographic analysis technique	15 hr/month
C.E. Soteros	Inverse problem	15 hr/month
R. Srinivasan	Data compression, image reconstruction	15 hr/month
E.V. Ivanov	Optical instrument fabrication and testing	15 hr/month
J.E. Johnston	Optical instrument specification and design	30 hr/month
D.J. Sniezek	Management of instrument development	5 hr/month
M.J. Painter	Supervision of graduate financial management students	5 hr/month

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7.3 Graduate Student Members of the Submission Team

Among the objectives of the Small Payloads Program are the training of (primarily) graduate students, and increasing synergy among university disciplines and between university and industry. The preparation of this proposal met these objectives in several innovative ways. The major part of the work required to develop the instrument concept, and to meet the requirements of the Announcement of Opportunity, was carried out by eight graduate students in four departments of three Colleges at the University of Saskatchewan, as course work for special-topics graduate courses in Physics & Engineering Physics and the Master of Business Administration Program in the College of Commerce. These students, all of whom have strong technical backgrounds and other applicable skills and experience as shown below, worked directly with each other under the supervision of Science Team members to identify the key questions in their areas of responsibility, to locate or develop the resources needed to answer the questions, and to integrate their work with that of the other groups to optimize the overall design of the NiteOwl experiment. The students responsible for the management plan worked directly with D.J. Sniezek, SCI-TEC Vice-President of Research, Development, and Engineering, as well as with University personnel to cost the mission elements, develop the work breakdown structure and schedule, and formulate the management plan.

Table 2-2. Graduate Student Members of the NiteOwl Submission Team

Graduate Team Member	College/Department	Responsibilities
J.K. Chan	Commerce	Work breakdown, budget, management plan
J.E. Giesbrecht	Electrical Engineering	Electronics, detectors, GPS, telemetry
D.P. Harris	Commerce	Work breakdown, budget, management plan
M. Huber	Physics & Engineering Physics	Optical filters and lenses, ozone
E.B. McDougall	Physics & Engineering Physics	Gratings, electronics
J.J. Offiong	Physics & Engineering Physics	Stellar spectra, risk and reliability
J.A. Steele	Mechanical Engineering	Stellar distribution, tomography
M.M. White	Physics & Engineering Physics	Cross-sections, refraction, other species

J.K. Chan holds a B.E. in Electrical Engineering and a B.Sc. in Computer Science from the University of Saskatchewan. He is currently in his final year in the MBA Program in the College of Commerce.

J.E. Giesbrecht holds a B.Sc. in Computer Science, a B.E. in Electrical Engineering, and an M.Sc. in Electrical Engineering from the University of Saskatchewan. In 1995 he was admitted to the Association of Professional Engineers of Saskatchewan as a Professional Engineer (P.Eng). He has extensive research and development experience in non-contact instrumentation, analog and digital electronics, digital signal processing, and database construction. He is currently a Ph.D. candidate in Electrical Engineering with research interests in non-contact measurement of moisture in potash.

D.P. Harris holds an B.Sc. (Hons.) in Physics and an M.Sc. in Upper Atmospheric Physics, both from tbe University of Saskatchewan. He is currently in his final year in the MBA Program in the College of Commerce.

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M. Huber holds a Vordiplom from the University of Oldenburg, Germany, and is currently a M.Sc. candidate in Space Physics at the University of Saskatchewan, with a research project on magnetospheric vortices using SuperDARN data. He has industrial experience with several German firms in the areas of electronic and mechanical fabrication, acoustical and optical testing, and management.

E.B. McDougall holds a B.Sc. (Dist.) in Engineering Physics from the University of Saskatchewan, and is currently completing an M.Sc. thesis, on the feasibility of measuring vertical profiles of minor constituents in the Earth's atmosphere using ground-based incoherent spectroscopy at 150-1200 GHz, in the Department of Physics and Engineering Physics.

J.J. Offiong holds a B.Sc. in theoretical physics from McMaster University. He is currently a research assistant with the Infrared Group in the Institute of Space and Atmospheric Studies, working on the ALIVE (A Limb Imaging Vertical spectrograph Experiment) concept study.

J.A. Steele holds a B.E. in Mechanical Engineering from the University of Saskatchewan, and is currently a Ph.D candidate, with a project on the application of accelerated convergence algorithms to tomographic analysis in the context of nondestructive testing.

M.M. White holds a B.E. in Engineering Physics from the University of Saskatchewan, and is currently an M.Sc. candidate, with a research project on the determination of ozone profiles, temperature recovery methods and the ring effect using the O_2 Atmospheric band.

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