# MANTRA 2002 and 2003

## A Balloon Mission to Study Stratospheric Composition

# Mission Description Document

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# Part One - Research Issues


## Abstract

Stratospheric ozone concentrations have declined significantly since about 1980 in response to enhanced levels of chlorine resulting from anthropogenic emissions of CFCs. This is particularly true in the polar regions, with catastrophic declines in ozone observed over Antarctica in early Spring. During the 1990s, Spring losses in lower stratospheric ozone have also been observed over the Arctic, with very low ozone columns recorded in 1996 and 1997. At mid-latitudes, ozone columns over Canada have decreased by about 6% in the last 20 years, and there have been statistically significant decreases in ozone at all altitudes from 12 to 45 km, with maxima of about -7.3% per decade at both 15 and 40 km.

Detailed chemical and dynamical modelling can now account for much of the reduction in the ozone column observed at northern mid-latitudes, however, "quantification of the processes contributing to this [mid-latitude] depletion is not complete" [1, p.7.53]. Careful analysis of seasonal, latitudinal, and vertical variations in mid-latitude ozone and related trace gases is required in order to clarify the impact of changes in atmospheric circulation, chlorine and bromine chemistry, aerosol loading, trends in other trace gases such as water vapour and nitrogen oxides, and temperature variations. Increasing attention is now being given to the links between climate change and the ozone budget, as models suggest that increasing greenhouse gas concentrations may cool the stratosphere and influence planetary circulation, leading to enhanced ozone depletion. Over the next decade, ozone research should thus focus on quantifying changes in the chemical balance of the stratosphere and their impact on the ozone budget.

This Mission Description Document is based on a proposal to the Second Small Payload Program of the CSA and describes a balloon mission that will measure the vertical concentration profiles of a suite of stratospheric trace gases that play a key role in ozone chemistry. These measurements, along with measurements of dynamical tracers and aerosols will be combined with similar data obtained at northern mid-latitudes over the past 20 years, in order to quantify changes in the chemical balance of the stratosphere, with a focus on changes in nitrogen oxides such as $NO_2$ and $HNO_3$. The interpretation of these data will involve the use of multidimensional model simulations of the stratosphere to compare retrieved and predicted abundances.

The MANTRA 2002/2003 project builds on the original MANTRA (Middle Atmosphere Nitrogen TRend Assessment) mission, which involved balloon flights in 1998 and 2000. It will extend the number of trace gases measured, and will fly most of the previous instruments (several of which date back 15-20 years and therefore provide a link to historical data) along with several new ones. This will enable a detailed comparison of measurements of the same gases made by different instruments, enabling the investigation of previously observed discrepancies and an assessment of the instruments' performance. Two balloon flights are proposed for Fall turnaround (August), the first in 2002 and the second in 2003. These dates will enable the concentration profiles to also be used for validation of three Canadian satellite instruments: OSIRIS (on Odin), and ACE-FTS and MAESTRO (on SCISAT-1).

The large experimental and modelling effort needed for this project will be provided in a collaboration between three Canadian universities, a federal government agency, an industrial partner, and two international partners. The University of Toronto, York University, the

University of Waterloo, and the Meteorological Service of Canada (MSC) will all provide personnel, equipment, and financial support to the project. The University of Denver in Colorado and the Service d'Aéronomie of CNRS, France will provide instrumentation for the flights, along with staff to operate it and analyze the data. Private sector support will be provided by Scientific Instrumentation Limited of Saskatoon, which will provide the gondola and payload systems, have responsibility for the balloon launch and recovery, and collect and distribute the data collected during the flights.

The MANTRA 2002/2003 project is consistent with the goals of the Second Small Payloads Program, and will address issues in the field of the Atmospheric Environment as defined by the CSA’s Space Science Program. It also falls clearly within the mandate of NSERC’s Collaborative Research Opportunities Program. The project will produce significant new data that can be used to address the issue of atmospheric change, utilizes low cost access to space, provides training to students, and supports Canada's industrial capability. In addition, it involves co-operation between a number of institutions, has links with current satellite projects, increases interaction with the international community, and provides opportunities to communicate with the public about a highly topical issue.

## 1.1 Mission Science

### 1.1.1 Scientific Objectives

This document describes a balloon mission to study stratospheric composition. The MANTRA 2002/2003 mission builds on the experience gained during the MANTRA 1998 and 2000 balloon campaigns. It consists of two high-altitude balloon flights, the first to take place in 2002 and the second in 2003, both to be launched from Vanscoy, Saskatchewan (52°N, 107°W).

The scientific objectives of MANTRA 2002/2003 are as follows:

(1) To fly a comprehensive suite of instruments in order to measure the vertical profiles of the key stratospheric species that control the mid-latitude ozone budget, particularly species in the $NO_y$, $Cl_y$, $Br_y$, and $HO_x$ chemical families, along with dynamical tracers and aerosols.
(2) To combine these measurements with those obtained from similar northern mid-latitude campaigns of the past 20 years, in order to quantify changes in the chemical balance of the stratosphere.
(3) To perform an intercomparison of multiple measurements of the same trace species made by different instruments, in order to resolve previously observed discrepancies and to assess the instruments’ performance.
(4) To use the 2002 balloon-borne measurements for validation and ground-truthing of the Odin satellite mission, and the 2003 measurements for validation and ground-truthing of the SCISAT-1 mission.

A related objective of the project is Canadian capacity building, comprising both the instrumental techniques and the training of highly qualified personnel. The relatively low cost of this balloon mission makes it an excellent route for assessing the potential of the scientific payload for more ambitious missions. In addition, it will assist in maintaining Canada's ability to mount balloon campaigns of this nature. As discussed in Section 1.7, the timescale and the nature of balloon campaigns make MANTRA 2002/2003 an excellent vehicle for training of students and post-doctoral fellows.

### 1.1.2 Relation to Previous MANTRA Flights

***The MANTRA 1998 Balloon Flight***

The overall objective of the first MANTRA balloon flight (August 24th 1998, from Vanscoy, SK) was to investigate changes in the odd-nitrogen budget of the stratosphere, building on the Stratoprobe balloon campaigns of the 1970s and early 1980s. The MANTRA 1998 payload included three of the original Stratoprobe instruments and three newer instruments. The three older instruments were a visible grating spectrophotometer for $NO_2$, an infrared emission radiometer for $HNO_3$, and a high-resolution scattering spectrometer for OH. In addition, $NO_2$ and $HNO_3$, along with a number of other key trace species, were measured using contemporary techniques, namely photodiode array spectrometry for $NO_2$, and solar absorption infrared interferometry for $HNO_3$. A new instrument based on acousto-optic tunable filter (AOTF) spectroscopy was also flown. Supporting ground-based observations were performed by three spectrometers, and regular radiosonde and ozonesonde flights were conducted.

The MANTRA 1998 flight was the first Canadian launch of a large high-altitude balloon in about 15 years. It carried a complex scientific payload, and although not all of the instruments worked as intended, a useful data set was collected [2]. Vertical mixing ratio profiles of ozone, $NO_2$, $HNO_3$, HCl, CFC-11, CFC-12, $N_2O$, and $CH_4$ were measured by the balloon-borne instruments [3,4]. Preliminary J values for $O^1D$ and $NO_2$ have also been retrieved. Total vertical columns of ozone, $NO_2$, $SO_2$, and aerosol optical depth were measured by the ground-based instruments [5,6].

The emission radiometers and the Fourier transform spectrometer (FTS) measured a number of the same species, and obtained generally consistent results. Of particular interest is $HNO_3$, as this was one of the primary species to be measured. Both instruments measured similar profile shapes and peak mixing ratio altitudes, but the emission radiometers obtained higher values above 20 km, with a peak mixing ratio of 9 ppbv at 24 km compared to 6.8 ppbv from the FTS. This discrepancy may be the result of the different slant paths and measurement times of the two instruments or due to different analysis approaches, but additional comparative measurements are needed to resolve this issue. Five different ozone mixing ratio profiles were also obtained by the various instruments. While these broadly agree, there are some differences, particularly for the FTS (up to 20%) that merit further investigation.

Output from a photochemical box model and the Canadian Middle Atmosphere Model (CMAM) [7,8] has been compared with the vertical profiles. Species correlations with the measured $N_2O$ profile were used to provide initial conditions for total nitrogen, chlorine, and bromine, and CMAM was used to initialize $H_2O$. Modelled and measured ozone and $HNO_3$ profiles generally agree within the error bars, but modelled HCl is consistently higher than the measured profile. The latter has also been compared to the closest available HALOE HCl profile and is within the expected variations for northern mid-latitudes [3]. A $NO_y$ mixing ratio of 17 ppbv at 30 km is derived from the box model. This is consistent with mid-latitude $NO_y$ measurements from 1974-1994, and suggests that the total nitrogen concentration has not changed significantly since the Stratoprobe balloon flights of the 1970s and 1980s. However, it should be noted that the errors associated with the early $NO_y$ measurements are quite large.

Of the three primary scientific objectives of MANTRA 1998, the first (to measure columns and profiles of the reactive species controlling ozone concentrations) has largely been accomplished. However, due to instrumental problems, it did not prove possible to measure all of the species required to quantify the nitrogen partitioning and to constrain the ozone budget. In addition, retrieval algorithms for some of the instruments continue to be improved. The second (to combine these measurements with those obtained during the 1970s and 1980s) and third (to assess long-term changes in the amount and partitioning of total odd-nitrogen) objectives are currently being pursued, with a focus on $HNO_3$. Raw emission radiometer data from flights conducted by MSC in 1989, 1990, 1991, and 1992 (two per year) are being reanalysed with new algorithms developed during MANTRA 1998.

***The MANTRA 2000 Balloon Flight***

A second balloon flight with a scaled down payload was undertaken on August 29$^{th}$ 2000, again from Vanscoy. The primary objective of this campaign was an engineering test flight of a new pointing control system in order to demonstrate its performance and capabilities for future balloon flights. In addition, this flight enabled further investigation of the stratospheric odd nitrogen budget at mid-latitudes, focusing on the measurements of vertical concentration profiles of ozone, $HNO_3$, and $NO_2$. The third objective was to continue the investigation and validation of techniques for the retrieval of $NO_2$ vertical profiles from ground-based zenith-sky spectra, and the fourth was to investigate the feasibility of retrieving vertical profiles of temperature and pressure from solar occultation measurements of the $O_2$ A and B bands, in support of the MAESTRO project.

The payload consisted of the new pointing control system, two emission radiometers, one SunPhotoSpectrometer, two ozonesondes, and an aerosol sonde. Additional supporting measurements were made with three ground-based spectrometers, a series of ozonesonde flights, and one additional aerosol sonde flight. All of the instruments performed well, and the minimum flight measurement requirements of one solar occultation and one limb scan observation were achieved. Flight data from the pointing control system have been analysed, showing that it provided an accuracy of 0.1° (1σ) in elevation and 3° (1σ) in azimuth [9]. Data analysis in support of the other three scientific objectives is underway, and we anticipate that all of the MANTRA 2000 objectives will be met.

### 1.1.3 Relation to Present State of Knowledge

It is now generally accepted that ozone concentrations have declined significantly since about 1980 [10,11,1] in response to the enhanced levels of chlorine in the stratosphere resulting from anthropogenic emissions of chlorofluorocarbons (CFCs). Catastrophic declines in ozone have been measured over Antarctica in late Winter and early Spring, and decreases in Arctic ozone during the same seasonal period have been reported [*e.g.*, 12]. Total ozone columns at northern mid-latitudes (*i.e.*, over Canada) have declined by 5-10% over the last 20 years, with these losses exhibiting seasonal and regional variations. Between 1979 and 1994-1997, total ozone columns at northern mid-latitudes (25-60°N) have decreased by about 5.4% in Winter/Spring and by about 2.8% in Summer/Fall [1]. On some recent Spring days at northern mid-latitudes, when ozone values are normally at their largest, ozone columns have been lower than any previously recorded at any time of the year over the entire 30-year ozone record. Also at northern mid-latitudes, there have been statistically significant decreases in ozone at all altitudes from 12 to 45 km, with maxima of about -7.3% per decade at both 40 km and 15 km [13]. Only tropical regions have not experienced a detectable decline in the ozone column.

Ozone destruction is controlled by $NO_x$ through both the $NO_x$ catalytic cycle and its influence on the level of free chlorine in the lower stratosphere. It follows that changes in the amount of total odd nitrogen ($NO_y$ = $NO_x$ + all oxidized nitrogen species = $NO + NO_2 + NO_3$

+ $2\times N_2O_5$ + $HNO_3$ + $HNO_4$ + $ClONO_2$ + $BrONO_2$) or changes in the partitioning of nitrogen compounds from $NO_x$ towards the longer-lived constituents will have an impact on the ozone budget. While $NO_x/NO_y$ partitioning is largely determined by ozone and aerosol concentrations [14], there are several mechanisms that can change the concentration of $NO_y$. Decreases in the total ozone column can modify the $NO_y$ source, $N_2O$. Global average concentrations of tropospheric $N_2O$ have increased from a pre-industrial value of 275 ppbv to 312 ppbv in 1996 [1]. Decreasing lower stratospheric temperatures in the polar regions may lead to $NO_y$ loss due to the formation of $HNO_3$ in and on polar stratospheric clouds and its subsequent sedimentation on the larger particles. Variable aerosol concentrations over the last 20 years, combined with cooler lower stratospheric temperatures, may also have increased the impact of denitrification. Finally, stratospheric $NO_y$ levels may be perturbed by the current fleet of subsonic aircraft [15].

Long-term studies of odd nitrogen in the stratosphere are few. The systematic monitoring of even the $NO_2$ column has only been done at a few locations and for only limited time intervals [*e.g.*, 16,17,18]. More recently, Liley *et al.* [19] have analysed 18 years of ground-based $NO_2$ columns over Lauder, NZ (45°S) and have derived a trend of +5% per decade. Satellite-based observations provide sporadic coverage, because of the limitations of the technique (such as poor coverage of a given region using solar occultation, *e.g.*, SAGE [20]), the limited temporal interval coverage due to short instrument lifetime (*e.g.*, LIMS and SME), and the problem of long-term calibration drift. In any event, the true state of the nitrogen budget cannot be assessed without making simultaneous estimates of several different nitrogen species, so that the relative amounts of both short-lived species (*e.g.*, $NO_2$) and long-lived species (*e.g.*, $HNO_3$) can be determined. To this end, Randel *et al.* [21] have analysed trends in several species from Upper Atmosphere Research Satellite data, and have identified a statistically significant increase in $NO_2$ (possibly due to a lengthy perturbation of the atmospheric circulation after the eruption of Mt. Pinatubo), as well as a trend of about -2% in $HNO_3$ between 1993 and 1997 which is not entirely accounted for by the change in $NO_2$.

In the 1970s and 1980s, the Atmospheric Environment Service led the Stratoprobe series of balloon flights that included measurements of $NO_2$ and $HNO_3$. These campaigns, conducted primarily at Churchill, Manitoba and at Yorkton, Saskatchewan, made a substantial contribution to our understanding of the stratosphere and included early estimates of the odd-nitrogen budget [22-27,16,17,28]. Changes to the mid-latitude ozone layer which started in the 1980s [29-32] followed shortly after the end of the Stratoprobe flight series. While measurements of stratospheric nitrogen compounds have also been made by others over a range of latitudes and locations (*e.g.*, MAP-GLOBUS in Europe; ATMOS; 33-39), the Stratoprobe results are notable because:

(1) they predate the onset of ozone decline (generally thought to be approximately 1980; see [10,40]),
(2) they connect to the Arctic through flights made using the same equipment in 1978 and 1979, and
(3) they have been compared to satellite results from lower latitudes (*e.g.*, LIMS – [41]).

The historical Stratoprobe measurements thus provide a useful benchmark against which current measurements can be compared to examine the possibility of detecting long-term changes in the stratospheric odd-nitrogen budget at northern mid-latitudes.

Detailed dynamical and chemical modelling can now account for much of the observed reduction in the ozone column observed at northern mid-latitudes [1]. However, at present, we cannot yet accurately separate transport effects from chemical effects, both at mid-latitudes and in the Arctic. In addition, over the next few decades, while the expected slow ozone-layer recovery is occurring, changing greenhouse gas concentrations (including $CO_2$ and $H_2O$) will alter the chemical balance of the stratosphere. In order to provide the scientific understanding of this changing chemical balance required to verify the efficacy of the Montreal Protocol and its amendments (which regulate the global production and release of ozone-depleting substances), MANTRA and similar studies are needed to reduce uncertainties regarding the central role of $NO_y$ in the stratospheric ozone budget.

### 1.1.4 MANTRA 2002/2003 Science and Anticipated Significance

***Scientific Objective (1)***

In order to quantify the chemical balance of the stratosphere, measurements of the concentrations and partitioning of species in the $NO_y$, $Cl_y$, $Br_y$, and $HO_x$ chemical families are required. The species comprising each of these families are as follows:

- $NO_y$ = $NO + NO_2 + NO_3 + 2\times N_2O_5 + HNO_3 + HNO_4 + ClONO_2 + BrONO_2$
- $Cl_y$ = $Cl + 2Cl_2 + OClO + ClO + 2ClOOCl + HOCl + COClF + HCl + ClONO_2 + ClONO + BrCl$
- $Br_y$ = $Br + BrO + 2Br_2 + BrONO + BrCl + BrONO_2 + HOBr + HBr$
- $HO_x$ = $OH + HO_2$

Ideally, one would measure the abundances of all of these species simultaneously. In practice this is difficult due to the range of instrumentation required. However, not all of these species are present in significant concentrations (*e.g.*, below about 35 km, $NO_y$ is mainly in the form of NO, $NO_2$, and $HNO_3$, although there are also non-trivial amounts of $ClONO_2$ and $BrONO_2$) and useful information can be obtained from a subset of measurements. For example, the rates of photochemical ozone loss due to the $NO_x$, $HO_x$, $ClO_x$ and $BrO_x$ catalytic cycles can be constrained from measurements of the key radical species. We propose to measure vertical profiles of the key species from each of these families, with the focus on the odd nitrogen family: NO, $NO_2$, $N_2O_5$, $HNO_3$, chlorine reservoirs HCl and $ClONO_2$, BrO, and OH. Temperature, aerosol loading, and J-values for $O^1D$ and $NO_2$ will also be measured, as these influence the relative importance of the various catalytic cycles. Other trace gases to be measured are ozone, CFC-11, CFC-12, $H_2O$, $N_2O$, $CH_4$, and $O_2$. This suite of measurements will provide a new data set for northern mid-latitudes that can be used to investigated stratospheric trends and processes.

***Scientific Objective (2)***

Due to the large role of transport in determining ozone values at mid-latitudes, the emphasis of this project is on quantifying changes in the chemical balance of the stratosphere, rather than trying to explain the observed ozone record. The goal is to quantify changes in $NO_y$ partitioning and associated chemical ozone loss rates between pre-1980 (*i.e.*, before the onset of ozone decline) and the present, and to determine whether this change can be clearly linked with the change in $Cl_y$. We propose to launch at Fall turnaround, which is a period of low variability in the stratosphere when the role of transport is minimized and photochemical control is maximized, thus making it easier to unravel the chemical processes. In addition, Fall turnaround is preferred in order to mitigate seasonal effects when comparing the new measurements with the historical Stratoprobe data (many of those flights were carried out at Fall turnaround) and with the MANTRA 1998/2000 data. Investigation of the stratospheric mid-latitude odd-nitrogen budget begun with MANTRA 1998/2000 will be continued. The emission radiometers will be reflown and vertical profiles of $HNO_3$, ozone, CFC-11, CFC-12, and $N_2O$ will be retrieved using new algorithms that were developed during MANTRA 1998. We have recently obtained raw emission radiometer data from flights conducted in 1989, 1990, 1991, and 1992 (two per year), and reanalysing these data with the new algorithms. Combining these with the MANTRA 1998/2000 profiles and the proposed MANTRA 2002/2003 flights would produce eight years of coverage in the past fourteen years, enabling a self-consistent analysis of the $HNO_3$ budget over an extended period.

***Scientific Objective (3)***

As mentioned in Section 1.1.2, during the MANTRA 1998 mission, simultaneous measurements of several trace gases were made using a variety of techniques in order to establish a common basis for data comparison. Of particular interest are the measurements of ozone and $HNO_3$. Vertical profiles of ozone were measured using spectroscopic techniques (two low-resolution infrared emission radiometers, a high-resolution Fourier transform infrared spectrometer, and a UV-visible grating spectrometer) and one in-situ sampling technique (two ozonesondes), while $HNO_3$ was measured by the radiometers and the FTS. The results show broad agreement between the different profiles. However, for $HNO_3$ the radiometer results appear consistently higher than the FTS results above 20 km, although all instruments use the same spectral line database. This discrepancy may be the result of the different slant paths and measurement times of the two instruments, or it may be due in part to the fact that the radiometer uses a fit to the whole band to derive the amount of $HNO_3$ present, whereas the higher resolution FTS spectral fits are based on fitting a group of the individual $HNO_3$ line manifolds [3]. In either case, additional comparative measurements are needed to resolve this issue. There are also differences between the ozone profiles that merit further investigation.

For the MANTRA 2002/2003 flights, we propose to again fly a suite of instruments that will make multiple measurements of certain trace gases. As described in Section 1.1.5 (see Table 1), the 2002 flight will carry the same set of instruments as were flown in 1998 to measure ozone (two emission radiometers, the University of Denver FTS, the UV-visible SPS, and ozonesondes). In addition, another UV-visible spectrometer (SAOZ) and a second FTS (from MSC) will be flown. This will enable a number of intercomparisons:

(1) Seven different measurements of the ozone vertical profile will be made so that we can investigate whether the discrepancies seen in 1998 are again observed, and if so, determine their cause.
(2) Four different measurements of the $HNO_3$ profile will be made (by two radiometers and two FTSs), so that discrepancies seen in the 1998 data can also be investigated (this is also true of CFC-11, CFC-12, $CH_4$, and $N_2O$, as all four species are measured by these instruments).
(3) The flight of the two FTSs will allow the performance of the newly refurbished MSC FTS to be compared and validated against the previously flown University of Denver instrument. The goal of this task is to develop a Canadian capacity for balloon-borne FTS measurements.
(4) The flight of two UV-visible grating spectrometers (the SPS and SAOZ) will allow a comparison of their measurements, particularly of $NO_2$, also providing redundancy for the validation of :the UV-visible OSIRIS satellite instrument (see below). It is also possible that a clone of the MAESTRO UV-visible spectrometer will be flown, enabling an assessment of its performance.

In addition to comparing the final retrieved vertical profiles obtained by the various instruments, it would also be instructive to undertake a comparison of the way in which the spectral data are analysed in order to eliminate software issues. For example, the University of Denver codes could be used to analyse the radiometer data, and the radiometer retrieval algorithm used to analyse the FTS data. The feasibility of this exercise will be investigated.

The payload for the proposed 2003 flight will be similar to that of 2002, with two exceptions. Firstly, only one of the two FTSs will be flown, with the other to be replaced by a clone of the ACE-FTS instrument. Measurements made by this instrument will be validated against the other FTS, and will also be compared with satellite observations by the SCISAT-1 ACE-FTS. Secondly, the AOTF spectrometer flown in 1998 will be added to the payload, and will provide a third set of UV spectra for comparison with the SPS and SAOZ.

***Scientific Objective (4)***

Canada is currently involved in two satellite missions that will be making global measurements of stratospheric trace gases for the purpose of investigating the stratospheric ozone budget. The Odin satellite, a Swedish-led mission with participation from Canada, Finland and France, was successfully launched in February 2001, while SCISAT-1 is a Canadian satellite due for launch in June 2002. As with most satellite missions, validation of the retrieved data products is essential if the scientific return is to be maximized. Validation activities involve comparisons with the best quality data available from ground-based, balloon, aircraft, and other satellite instruments. The proposed MANTRA 2002/2003 flights will provide the only Canadian-based balloon measurements available for Odin and SCISAT-1 validation. Balloon platforms have the advantage of providing vertical profile information which is not readily available from ground-based instrumentation, and as such, offer the only practical means of validating global trace gas profile retrievals. While one balloon flight cannot single-handedly validate a satellite instrument, it nevertheless represents one of the only independent checks that the satellite results are valid and meaningful.

***Odin and MANTRA 2002:*** Odin is a joint astronomy/aeronomy satellite that carries two instruments, a Sub-Millimeter Radiometer (SMR) and a combined Optical Spectrograph and InfraRed Imager (OSIRIS). The OSIRIS instrument was funded by the Canadian Space Agency and built by Routes Ltd. of Ottawa. Odin is in a sun-synchronous polar orbit at 97.8° inclination and 600-km altitude, with the ascending node crossing the equator at 18:00 LT. The OSIRIS Optical Spectrograph will record spectra of sunlight scattered from the limb, covering the UV-visible spectral range from 280-800 nm and an altitude range of 10-120 km. These spectra will be used to retrieve stratospheric vertical profiles of ozone, $NO_2$, OClO, BrO, $O_2$, and aerosols, for the investigation of both stratospheric and mesospheric processes, particularly those related to ozone chemistry. In contrast, the Infrared Imager will simultaneously image emission features at 1.27 μm from a range of tangent heights for the retrieval of atomic oxygen and ozone in both the stratosphere and the mesosphere. The SMR will measure vertical profiles of ozone, ClO, BrO, $HNO_3$, NO, $NO_2$, $N_2O$, CO, $H_2O$, HDO, $HO_2$, $H_2{}^{18}O$, and aerosols.

The Odin Validation Sub-Committee has defined two levels of priority for validation of the trace gases that will be measured by OSIRIS and SMR. The "first priority" species for validation are ozone, ClO, $H_2O$, $NO_2$, $N_2O$, and aerosols. The "second priority" species are BrO, OClO, $HNO_3$, NO, and CO. The MANTRA 2002 flight will carry instruments to measure all of the species in these two groups except ClO, OClO, and CO. As described in the next section, the

SPS and the SAOZ spectrometer cover similar spectral ranges and will make similar measurements to those of the Optical Spectrograph. Both of these instruments have been widely used and have considerable flight heritage, making them ideal for both OSIRIS and SMR validation. Other instruments on the balloon payload, particularly the University of Denver FTS with its extensive flight heritage, will provide measurements of additional species measured by the SMR. The MANTRA 2002 flight will take place in the second year of Odin's nominal two-year mission. Given Odin's orbit and the nature of the limb-viewing geometry, there should be a reasonable opportunity to co-ordinate the balloon launch with an overpass of the satellite. A number of balloon flights from France and from Kiruna, Sweden are planned between April and August 2001. These will provide the first set of targeted validation measurements for Odin. MANTRA 2002 will extend the temporal coverage of mid-latitude validation measurements and will provide an opportunity to resolve any questions or discrepancies that arise from the first phase of validation. Also, the SAOZ spectrometer will be flown on all of the European balloon flights, and so including it on the MANTRA payload will allow us to tie together the various sets of balloon data.

***SCISAT-1 and MANTRA 2003:*** SCISAT-1, funded by the Canadian Space Agency, will carry two instruments: the ACE-FTS (Atmospheric Chemistry Experiment-Fourier Transform Spectrometer) and MAESTRO (Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation). SCISAT-1 will fly in a high inclination (65°) circular orbit at 650 km. The principal goal this mission is to measure and to understand the chemical and dynamical processes that control the distribution of ozone in the upper troposphere and stratosphere using simultaneous measurements of trace gases, thin clouds, aerosols and temperature. ACE-FTS will record infrared solar occultation spectra from 700-4100 $cm^{-1}$ at 0.025 $cm^{-1}$ resolution, from which vertical profiles will be retrieved from cloud tops up to as high as 100 km at 3-4 km resolution. ACE-FTS will measure about 30 trace gases, including all of the species to be measured during MANTRA 2002/2003. The estimated accuracy of the ACE-FTS can be predicted on the basis of ATMOS measurements and ranges from about 5-6% in the most favourable cases (ozone, $H_2O$, $CH_4$, *etc.*) to about 20% for the minor species such as $ClONO_2$ and $CCl_4$ [42]. The MAESTRO instrument uses two diode array spectrometers to record UV-visible solar occultation spectra from 285-1000 nm at a spectral resolution between 1 and 2 nm, from which vertical profiles of ozone, $NO_2$, BrO, OClO, $SO_2$, and aerosols will be retrieved. Measurements of the spectral signature from $O_2$, $O_4$, and $H_2O$ will be used to determine information about the optical properties of the atmosphere, such as the height of the tropopause and the altitude of clouds below the instrument.

The MANTRA 2003 flight will carry instruments that will measure vertical profiles of all of the MAESTRO target species and many of the ACE-FTS species. The combination of a well-tested FTS and the ACE-FTS clone on the balloon payload will provide both accurate profiles for validation as well as the ability to compare balloon-borne and space-based measurements by two very similar instruments. As is the case for OSIRIS, the SPS and the SAOZ spectrometer will make similar measurements to those of MAESTRO, making them well-suited for its validation. The MANTRA 2003 flight will take place in the first year of the SCISAT-1 mission, assuming that the satellite launch proceeds on schedule. Co-ordination of the balloon flight with a SCISAT-1 overpass will be more difficult than is the case for Odin because there are only two occultations per orbit (about 30 per day) which occur at two latitudes which drift slowly across the globe over time.

***ENVISAT and MANTRA 2002/2003:*** We also note that ENVISAT, due for launch by the European Space Agency in Fall 2001, will be in orbit during both MANTRA flights. Three instruments on this platform will be measuring concentration profiles of stratospheric constituents: SCIAMACHY, MIPAS, and GOMOS. Several members of the MANTRA Science Team have links to the ENVISAT program, and we have contacted Dr. Patrick Wursteisen, co-ordinator of the ENVISAT Stratospheric Aircraft and Balloon Campaign. We anticipate that MANTRA 2002/2003 data will be useful for validation of SCIAMACHY, MIPAS, and GOMOS measurements.

### 1.1.5 Instruments and Experimental Methods

The MANTRA 2002/2003 mission consists of two balloon flights, each carrying instruments to measure the vertical profiles of the significant components of the odd nitrogen budget, as well as species which link the $NO_x$, $HO_x$, $ClO_x$ and $BrO_x$ catalytic cycles, specifically ozone, NO, $NO_2$, $N_2O_5$, $HNO_3$, $ClONO_2$, HCl, BrO, OH, $H_2O$, and aerosols. In addition, the tracers $CH_4$ and $N_2O$ will be measured, as will CFC-11, CFC-12, $O_2$, temperature, pressure, and J-values for $O^1D$ and $NO_2$.

Table 1 summarizes the proposed suites of balloon-borne and ground-based instruments to be deployed during the 2002 and 2003 campaigns. Two of the instruments date back to the Stratoprobe campaigns, providing a link to the earlier $HNO_3$ and OH measurements. Most of the instruments were previously flown on the MANTRA 1998 or 2000 balloon flights and will thus build on the experience gained during those campaigns. In addition, four new instruments will be flown: a clone of the MAESTRO instrument, the MSC FTS, the Service d'Aéronomie SAOZ spectrometer, and the University of Waterloo ACE-FTS clone. The proposed payloads for the two flights involve a large number of instruments which will require a significant integration effort. We have therefore characterized each of the proposed instruments as either “primary” or “secondary”, based on their importance to achieving the four scientific objectives discussed above. Loss of any of the primary instruments is considered likely to compromise the science, so the mission objectives should be reassessed if one is not operational.

Table 1: The proposed balloon-borne and ground-based instruments for MANTRA 2002/2003.

| FLIGHT | PRIMARY BALLOON-BORNE INSTRUMENTS | SECONDARY BALLOON-BORNE INSTRUMENTS | GROUND-BASED INSTRUMENTS |
|---|---|---|---|
| **2002** | • one MSC emission radiometer<br>• MSC SunPhotoSpectrometer<br>• one FTS (U of Denver)<br>• Service d'Aéronomie SAOZ<br>• MSC ozonesonde<br>• aerosol sonde | • second MSC emission radiometer<br>• MAESTRO clone<br>• second FTS (MSC)<br>• MSC OH spectrometer | • MSC Brewer spectrophotometer<br>• U of Toronto grating spectrometer<br>• CRESTech/York U AOTF spectrometer |
| **2003** | • one MSC emission radiometer<br>• MSC SunPhotoSpectrometer and/or MAESTRO clone<br>• FTS (MSC or U of Denver)<br>• U of Waterloo ACE-FTS clone<br>• MSC ozonesonde<br>• aerosol sonde | • second MSC emission radiometer<br>• MSC OH spectrometer<br>• CRESTech/York U AOTF spectrometer<br>• Service d'Aéronomie SAOZ spectrometer | • MSC Brewer spectrophotometer<br>• U of Toronto grating spectrometer |

The launch facilities will be provided by Environment Canada, which has a fully equipped balloon launching station at Vanscoy. The required float time (at least 10 to 12 hours) can only be achieved at turnaround (either May or late August) without additional down-range tracking. Fall turnaround is preferred because this corresponds to a period of low stratospheric variability, and also ties in with the historical Stratoprobe flights and the MANTRA 1998/2000 flights. Interpretation of the measurements in terms of the underlying processes will involve comparisons with atmospheric models, as discussed in Section 1.4. The primary components of the proposed experiment are described below.

***Experimental Methods: MSC Emission Radiometer***

The MSC emission radiometer is based on the balloon emission radiometer of Pick and Houghton [43], which was later modified by Evans *et al.* [44], and further improved in the early 1980s. The instrument measures thermal emission in the range 715-1250 $cm^{-1}$ at a resolution of 20 $cm^{-1}$, using a circular variable filter to provide spectral information. It is usually pointed at a 20 to 40° elevation angle to increase the atmospheric slant path and makes measurements during balloon ascent. The raw radiance data are analyzed using a forward estimation technique to recover vertical mixing ratio profiles of $HNO_3$, CFC-11, CFC-12, ozone, $CH_4$, and $N_2O$. The accuracy of these measurements varies with altitude: the accuracy bounds derived for the MANTRA 1998 retrievals show that a measurement of $HNO_3$ is possible with 20% accuracy up to 22 km. Typically, previous flights have included two instruments mounted at different viewing angles to provide independent atmospheric paths and to allow an assessment of instrument and retrieval performance. Double flights of this instrument have been flown successfully at least seven times over the past 12 years. We propose to continue this valuable measurement series. The reflight of these instruments should enable a consistent measurement and analysis of an $HNO_3$ trend from early flights of this instrument (c1989) to the present.

***Experimental Methods: MSC SunPhotoSpectrometer and MAESTRO Clone***

The MSC SunPhotoSpectrometer (SPS) has flown on STS-52 and aboard the ER-2 as part of the NASA Upper Atmospheric Research and High Speed Research Programs [45,46]. On the ER-2, the technique of differential absorption spectrophotometry. The instrument has flown at 21 km nearly 100 times with this program. In addition, the SPS was flown on both the MANTRA 1998 and 2000 balloon flights. It is based on a photodiode array detector, situated at the focus of an f/2 holographic diffraction grating. Spectra are recorded from 300-785 nm at 0.5 nm steps, with a spectral resolution varying from 1.2 to 4 nm (FWHM). Data can be collected in solar occultation mode and limb-scan mode, and are analyzed using spectral fitting to determine vertical profiles of ozone, $NO_2$, and aerosol. The SPS can also be used to make absolute radiometric measurements in order to obtain J-values for the photolysis of ozone and the photodissociation of $NO_2$ [47], which are needed to properly partition the odd-nitrogen family in photochemical model simulations. The SPS is the forerunner of the MAESTRO (Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation) instrument, which be launched on SCISAT-1. Flight of a MAESTRO clone would thus enable direct comparison of the balloon-based measurements with those of the satellite instrument. We propose to fly the SPS and, if available with resources to support a balloon flight, a clone of the MAESTRO instrument.

***Experimental Methods: MSC OH Spectrometer***

The MSC high-resolution scattering spectrometer was originally flown on Stratoprobe payloads in July 1975 from Yorkton, SK and in September 1976 from Palestine, TX [48]. It was also refurbished and flown during MANTRA 1998, however, due to a problem with its solar tracker tilt mechanism just prior to launch, the signal levels in the resulting spectra were too low for OH retrievals.. The OH resonance scattering technique has been used since 1975 by others [49], but without the MSC refinement of using polarization. This instrument measures polarized spectra of the sky at right angles to the sun and at about 10° above the horizon. It observes the direct solar beam (as reference), and strong and weak polarizations at 90° to sun to detect resonant scattering from OH. The spectral range and resolution of the instrument are 305 to 311 nm, and 0.04 nm, respectively. The OH signal-to-noise ratio in the altitude range 25 to 40 km is high, but the lack of sufficiently detailed, very-high-resolution data on the solar spectrum precluded an absolute calibration of the original historical measurements. This problem can be solved today, and the calibration factor will not have changed between the earlier flights and the present, allowing MANTRA OH measurements to be directly compared with those made in 1975 and 1976. The expected accuracy for an OH retrieval is 15%, based on the RMS combination of estimated errors in ozone coefficients, local ozone absorption effects, pointing accuracy at low incident elevation angles, OH spectroscopy, profile model shape, effective OH signal-to noise contribution, and correction for collisional de-excitation of OH. Improvements to gondola swing-detecting instrumentation, OH spectroscopy, and knowledge of ozone absorption effects could reduce this to <10%. We propose to fly the OH spectrometer on both the 2002 and 2003 campaigns.

***Experimental Methods: University of Denver Fourier Transform Spectrometer***

The University of Denver FTS is a Bomem DA2 that has flown many times as part of various balloon missions in the United States starting in 1977 [33,50,51]. This FTS has an unapodized FWHM resolution of about 0.01 $cm^{-1}$. The system has two infrared detectors, each covering approximately 600 $cm^{-1}$. The accuracy of the measurements obtained during MANTRA 1998 varies with altitude. In 5-km layers from 12-32 km, the following accuracy ranges were obtained: 20-25% for $O_3$, 10-30% for $HNO_3$, 20-25% for HCl, 20-43% for CFC-11, 19-24% for CFC-12, 10-25% for $N_2O$, and 20-40% for $CH_4$ [3]. The high uncertainties quoted here reflect problems with laser stability that arose during the 1998 flight and which also precluded the planned measurement of $ClONO_2$ and $N_2O_5$.

This instrument has since under gone an extensive refurbishment and performed well during a SAGE validation flight in June 2000 in which the $O_2$ A-band was measured. A morning occultation measurement would provide $N_2O_5$ to 15%. Depending on the exact choice of detectors and bandpasses, the FTS could also provide measurements of $NO_2$ and NO to 15% and $ClONO_2$ to better than 20% in a 5 km layer. In addition to flying one HgCdTe detector (for ozone, $HNO_3$, $CH_4$, $N_2O$, CFC-11, CFC-12, $ClONO_2$ and $N_2O_5$), there are two options for the second detector:

(1) InSb for HCl and for comparison with the MSC FTS InSb measurements, and

(2) a second HgCdTe for NO and $NO_2$ and for a comparison of two bands of $HNO_3$, $ClONO_2$ and $N_2O_5$.

The choice of detectors will be finalized during flight planing. We propose to fly this FTS in 2002, in conjunction with the re-furbished MSC FTS, thus enabling an intercomparison of the measurements by the two instruments. In 2003, one of the two will be flown depending on the results of the 2002 flight.

***Experimental Methods: MSC Fourier Transform Spectrometer***

The MSC Fourier transform spectrometer is a Bomem BBDA2 unit which operates in the spectral ranges 1840-1990 $cm^{-1}$ and 2870-2980 $cm^{-1}$ using HgCdTe and InSb detectors simultaneously. It has a spectral resolution of 0.02 $cm^{-1}$ (unapodized). This unit has been flown previously on four missions in 1985. The instrument will be extensively refurbished to modern standards before flight in 2002. The instrument will be optimised for the 700-1300 $cm^{-1}$ and 2500-3500 $cm^{-1}$ ranges to measure $O_3$, $HNO_3$, $ClONO_2$, $H_2O$, CFC-11, CFC-12, $CH_4$, $N_2O$, $NO_2$ and HCl. Its capabilities are similar to those of other FT spectrometers of equivalent resolution. The advantage of including it in the MANTRA payload is that it will provide a domestic instrument to make measurements if the other FTS instruments should be unavailable in the future.

***Experimental Methods: CRESTech/York University Acousto-Optic Tunable Filter Spectrometer***

The CRESTech/York University acousto-optic tunable filter (AOTF) spectrometer is a new instrument that was first flown on the MANTRA 1998 balloon. During the MANTRA 2000 campaign, it was operated on the ground at Vanscoy. It uses a $MgF_2$ acousto-optic filter to scan the spectrum in the visible and near-UV regions (250-400 nm). It has a wavelength-dependent resolution of 0.07 nm at 250 nm, 0.1 nm at 300 nm, 0.15 nm at 350 nm, and 0.21 nm at 400 nm. The detector is a photomultiplier tube with very low dark count. In 2002, the AOTF instrument will again be operated on the ground, making zenith-sky observations for the retrieval of total column densities of ozone and $NO_2$. In 2003, it will be flown on the balloon platform, where it will make solar occultation and limb-scanning observations, in order to measure vertical profiles of ozone and $NO_2$. For ozone, the estimated accuracy is 10-15% and the precision is 5% (for both ground and balloon), while for $NO_2$ the estimated accuracy is 15-20% and the precision 5% (for both ground and balloon).

***Experimental Methods: Service d'Aéronomie SAOZ Spectrometer***

The SAOZ (Systeme d'Analyse et d'Observations Zenithales) sonde is a lightweight UV-visible diode array spectrometer that looks at the absorption of the sunlight by the atmosphere during the ascent (or descent) of the balloon and during sunset (or sunrise) from the float altitude. There are currently three versions of SAOZ available for balloon flights. The first version of SAOZ (SAOZ-N) is very similar to the one in use for ground-based measurements of total ozone and $NO_2$ [52]. It is a commercial flat field, 360 grooves/mm, holographic grating spectrometer equipped with a 1024-diode linear array detector and an entrance slit of 50 μm. In this arrangement, measurements can be performed between 290 and 640 nm, with an average 0.8 nm resolution. SAOZ-N provides the vertical distribution of $O_3$, $NO_2$, OClO (when activated in cold polar vortex), tropospheric $H_2O$, $O_2$, $(O_2)_2$ and the wavelength dependence of the extinction coefficient of aerosol and PSCs [53,54]. SAOZ-N has been flown more than 100 times since the first attempt in September 1991.

A second version (SAOZ-BrO) has been developed dedicated to the UV region, with a 1200 groves/mm grating and a 250 μm entrance slit making measurements in the 330-370 nm range with a resolution of 0.3 nm, in order to provide vertical profiles of BrO and $CH_2O$. This instrument has been flown 20 times since October 1996, and BrO has been found activated at all latitudes (Arctic, mid-latitudes and tropics) and all seasons. A third version (SAOZ-$H_2O$) is now being developed, and is restricted to the visible part of the spectrum in the 400-750 nm region with a resolution of 0.8 nm. It is intended to retrieve the stratospheric profile of $H_2O$ in addition to $O_3$, $NO_2$, tropospheric $H_2O$, $O_2$, $O_4$ and the aerosol extinction coefficient. This instrument was first flown in February 2001 in Brazil. We propose to fly SAOZ-$H_2O$ on MANTRA 2002/2003 in order to obtain the water vapour measurement, however, the final choice of flight instrument will be made by the Science Team, based on the results of the February flight and the science requirements. The feasibility of flying a second instrument (SAOZ-BrO) will also be examined.

***Experimental Methods: University of Waterloo ACE-FTS Clone***

The ACE mission will place a high-resolution infrared FTS, along with the MAESTRO spectrometer and two solar imagers operating at 0.525 and 1.02 μm, into low Earth orbit in June 2002. The science goals of ACE overlap with those of MANTRA. Funding from the Canada Foundation for Innovation (matched by the Ontario government) has just been received to purchase two FTSs. One of these instruments will be very similar to the ACE-FTS that will be making solar absorption measurements from orbit. As part of the calibration and validation of the satellite mission, we propose to make ground-based measurements as well as fly the ACE-FTS clone on the MANTRA balloon. This FTS will have a maximum optical path difference of 25 cm (0.02 $cm^{-1}$ resolution) and a wide wavenumber coverage (750-4100 $cm^{-1}$) using both HgCdTe and InSb detectors. The measurement accuracy of the ACE-FTS clone is expected to be similar to the University of Denver and the MSC FTS instruments. On the 2003 MANTRA flight, the ACE-FTS clone will fly with one of the other FTSs so that an intercomparison can be made.

***Experimental Methods: Payload Configuration***

The payload will be built up on a light-weight aluminium frame. Payload pointing will be controlled by a new pointing control system that was developed and successfully tested during MANTRA 2000. The system can operate in both limb-scanning and solar occultation modes, to an accuracy of 0.1° (1σ) in elevation and 3° (1σ) in azimuth [9]. The system will be flown in a very similar configuration to the 2000 flight, but we propose to make some small modifications to the flight train to improve the azimuth pointing capability. Smaller instruments requiring sun and limb scanning (SPS, MAESTRO clone) will be mounted directly on the pointing system. Mirrors added to the elevation stage will be used to transmit direct or scattered sunlight into the larger instruments (MSC FTS, AOTF spectrometer, ACE-FTS clone). The University of Denver FTS will use its own pointing system to track the sun independently of the rest of the gondola. All of these optical instruments will be used to make solar occultation measurements during twilight, and the UV-visible spectrometers will also record limb spectra of scattered sunlight during the day. The MSC emission radiometers will be mounted on the gondola structure, but oriented at 180° to the solar direction so that the sun will not enter the instrument field-of-view. Observations will be made during the ascent and until the cryogen is exhausted. The OH spectrometer will be mounted at 90° to the solar direction, and will make daytime observations polarized spectra of the sky from float altitude. The MSC ozonesonde and University of Wyoming aerosol sonde will also be directly to the payload frame; these will record data during ascent.

### 1.1.6 Top Level Science Requirements

The top-level science requirements are the measurements, along with their precision and accuracy, that will be needed in order for the data to be scientifically useful. Table 2 presents the measurements that are anticipated from the MANTRA 2002/2003 campaigns. The overall accuracy will be improved by having a suite of complementary instruments. The vertical resolution of the profiles will be about 5 km, and possibly as good as 1 to 2 km with limb-scanning observations.

Table 2. The species to be measured during MANTRA 2002/2003, along with conservative estimates of their expected accuracies. * refers to ranges and accuracies achieved with the University of Denver FTS during the MANTRA 1998 flight. The high FTS uncertainties obtained in 1998 (given in brackets) reflect problems with laser stability that arose during that flight, and are larger than the more typical accuracy of 10% or better for this kind of measurement. # refers to ranges and accuracies obtained with the emission radiometers during the MANTRA 1998 flight. DOAS = University of Toronto zenith-sky grating spectrometer, GB = ground-based, OD = optical depth, DU = Dobson units.

| TRACE GAS | INSTRUMENT | TECHNIQUE | ESTIMATED ALTITUDE RANGE (km) AND RESOLUTION | ESTIMATED ACCURACY (%) |
|---|---|---|---|---|
| **ozone profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (20-25 *) |
| | ozonesondes | in situ chemical | 0-40 at 0.01 mPa | 10 |
| | radiometers | emission on ascent | 10-35 at 2 km # | 11-100 # |
| | SPS/MAESTRO | solar occultation & limb scanning | 10-35 at 2-4 km | 10 |
| | SAOZ | solar occultation | 10-35 at 1 km | 10 |
| | AOTF | solar occultation & limb scanning | 10-35 km at 2-4 km | 10-15 |
| **NO profile** | FTS | solar occultation | 10-35 at 5 km | 15 |
| **$NO_2$ profile** | FTS | solar occultation | 10-35 at 5 km | 15 |
| | SPS/MAESTRO | solar occultation & limb scanning | 10-35 at 2-4 km | 10 |
| | SAOZ | solar occultation | 10-35 at 1 km | 10 |
| | AOTF | solar occultation & limb scanning | 10-35 km at 2-4 km | 15-20 |
| **$HNO_3$ profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (10-30 *) |
| | radiometers | emission on ascent | 10-30 at 2 km # | 13-100 # |
| **HCl profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (20-25 *) |
| **$ClONO_2$ profile** | FTS | solar occultation | 10-35 at 5 km | 20 |
| **$N_2O_5$ profile** | FTS | sunrise occultation | 10-35 at 5 km | 15 |
| **CFC-11 profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (20-43 *) |
| | radiometers | emission on ascent | 10-30 at 2 km # | 15-100 # |
| **CFC-12 profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (19-24 *) |
| | radiometers | emission on ascent | 10-25 at 2 km # | 13-100 # |
| **OH profile** | OH spectrometer | scattered sunlight | 30-50 km at 5 km | 15 |
| **$H_2O$ profile** | FTS | solar occultation | 10-35 at 5 km | possibly |
| | SAOZ | solar occultation | 10-35 at 1 km | 50? |
| **$N_2O$ profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (10-25 *) |
| | radiometers | emission on ascent | 10-30 at 2 km # | 12-100 # |
| **$CH_4$ profile** | FTS | solar occultation | 12-32 at 5 km * | 10 (20-40 *) |
| | radiometers | emission on ascent | 10-30 at 2 km # | 12-100 # |

| | | | | |
|---|---|---|---|---|
| **J-values for $O^1D$ and $NO_2$** | SPS/MAESTRO | absolute radiometry | | |
| **aerosol** | SPS/MAESTRO | solar occultation & limb scanning | | |
| | aerosol sonde | backscatter | 0-40 at 1 km | 0.002 OD |
| | Brewer | GB direct sun | column OD | |
| **wind, P, T, humidity** | radiosondes | Vaisala RS 80 with GPS wind finding | 0-40: P at 0.1 mb, T at 0.1 °C, RH at 1% | P at 0.5 mb, T at 0.2 °C, RH at 2% |
| **ozone column** | GB Brewer | GB direct sun | column | ≤ 1 |
| | GB DOAS | GB zenith sky | column | 5 |
| | GB AOTF | GB zenith sky | column | 10-15 |
| **$NO_2$ column** | GB DOAS | GB zenith sky | column | 10-12 |
| | GB AOTF | GB zenith sky | column | 15-20 |
| **BrO column** | GB DOAS | GB zenith sky | column / upper limit | 15-35 |
| **OClO column** | GB DOAS | GB zenith sky | column / upper limit | 15-35 |
| **$SO_2$ column** | GB Brewer | GB direct sun | column | 0.2-0.6 DU |

## 1.2 The Science Team

**Principal Investigator Kimberly Strong** (University of Toronto) will have responsibility for managing the MANTRA 2002/2003 project. She will contribute her research experience in remote sounding of atmospheric composition from ground-based, balloon-borne, and satellite instruments. She was PI for the original MANTRA 1998/2000 project, and was responsible for the development of the University of Toronto zenith-sky spectrometer that was first used during MANTRA 1998. She is also the PI of the OH Measurements from Space (OHMS) concept study and the University of Toronto Atmospheric Observatory (TAO), and is a Co-I on the Canadian Odin Aeronomy Science Team and for both the ACE-FTS and MAESTRO satellite instruments. As PI, Prof. Strong will oversee MANTRA 2002/2003, liasing between the various participants, co-ordinating activities, and ensuring that the project achieves its scientific and technical objectives. In addition to her general responsibilities for the project, she will have primary responsibility for deployment of the University of Toronto zenith-sky spectrometer and subsequent data analysis. She will also collaborate with team members from MSC and the University of Toronto in the flight preparation of the MSC instruments.

**Co-Investigator Peter Bernath** (University of Waterloo) is an experimental molecular spectroscopist with experience working primarily in the infrared and visible regions. He works with both lasers and Fourier transform spectrometers to study species found in the laboratory, in the Earth's atmosphere and in astrophysical environments. Prof. Bernath is the Mission Scientist for the SCISAT-1 mission (Atmospheric Chemistry Experiment, ACE). His primary responsibility for MANTRA 2002/2003 will be the provision and operation of the ACE-FTS clone instrument.

**Co-Investigator James R. Drummond** (University of Toronto) is an experimentalist in the area of remote sounding instrumentation and specializes in measurements of atmospheric constituents using radiative techniques. He is the PI of the Measurements Of Pollution In The Troposphere (MOPITT) space instrument, a Co-I on both the MAESTRO and ACE-FTS instruments and holds the COMDEV/ BOMEM/AES/CSA/University of Toronto/NSERC

Industrial Research Chair in Atmospheric Remote Sounding from Space. He has participated in balloon campaigns for stratospheric measurements from the mid-1970s [55,56,57] to the mid-1980s [58] and in the previous MANTRA campaigns. He brings experience in all aspects of ballooning and field work to the team. Prof. Drummond's primary responsibility will be to support the integration and flight of several of the instruments, especially the SPS/MAESTRO and the Canadian FTS instruments. He will participate in the flight effort and in the data analysis. He will also supervise several students involved in the flights.

**Co-Investigator Hans Fast** (Environment Canada) has extensive experience in measurements of atmospheric constituents from balloon platforms at various latitudes and in particular using an FTS for solar occultation data recording and analysis. In 1982 and 1983 he participated in the international Balloon Intercomparison Campaigns conducted at the National Scientific Balloon Facility in Texas [59]. More recently he has carried out FTS ground-based measurements of atmospheric gases at the Arctic Stratospheric Ozone Observatory at Eureka [60] and at Environment Canada's Centre for Atmospheric Research Experiments north of Toronto [61]. Currently Dr. Fast manages the various measurement programs of the Eureka observatory. He is also PI of the solar absorption FTS at Eureka and a science team member for the validation of the MOPITT and ACE satellite measurements. Dr. Fast will supply a BOMEM BBDA2 interferometer to the MANTRA 2002/2003 measurement campaign, and will help with respect to operating and data characteristics of the balloon-borne instrument.

**Co-Investigator John C. McConnell** (York University) has extensive experience in stratospheric modelling and he is currently involved with the building and use of the Canadian Middle Atmosphere Model as well as the Canadian weather forecast model, GEM (Global Environmental Multiscale Model). His group will be involved with the chemical modelling aspects of the proposed study, both chemical and radiative transfer, that will be critical to understanding the data obtained from the balloon campaigns. Box models that have been built with current heterogeneous chemistry and photochemistry will be used to reanalyze the historical balloon data as well as the projected flight data. In a collaborative effort with RPN (Recherche en Prévison Numérique) at MSC, J. Kaminski (York U) and S. Eduoard (MSC) have (re-)added complex stratospheric chemistry to GEM and this may be used in the analysis and to provide background data.

**Co-Investigator C. Thomas McElroy** (Environment Canada) has extensive experience in remote sounding of the stratosphere from ground-based, balloon, aircraft, and Space Shuttle platforms. He was a co-inventor of the Brewer Ozone Spectrophotometer, and designed a novel double spectrometer version which is now in commercial production. He has played a key role in the measurement of $NO_2$, making the first measurements of $NO_2$ in the stratosphere using a balloon-based spectrophotometer. He was Deputy PI for the SunPhotometer Earth Atmosphere Measurement flown on the US Space Shuttle in October 1992, and PI for the CPFM experiment flown as part of the NASA SPADE, ASHOE/MAESA, and STRAT projects. He is also PI for MAESTRO. As Environment Canada Lead Scientist, Dr. McElroy will head MANTRA 2002/2003 activities at MSC. In particular, he will provide consultation and support for the MSC instrumentation that will be used in the campaigns.

**Co-Investigator Ben M. Quine** (University of Toronto) is a physicist specialising in the development of balloon and space-based instrumentation, atmospheric-profile retrievals and radiative-transfer modelling of planetary atmospheres. He was involved in both the previous MANTRA campaigns where his responsibilities included the flight preparation and data analysis of the MSC emission radiometers and the integration of the science payload. He was also responsible for the development of the new balloon pointing and control system for the MANTRA 2000 flight. Dr. Quine will continue to be responsible for all aspects of the emission radiometers. He will again be responsible for the integration of the science payload and the balloon pointing and control system.

**Co-Investigator Theodore G. Shepherd** (University of Toronto) brings expertise in stratospheric dynamics and transport. He was PI of the Canadian MAM project (1993-2000), which developed the Canadian Middle Atmosphere Model (CMAM), a chemical climate General Circulation Model. He is again PI of the follow-on GCC project (2000-2005) which will use the CMAM in support of Canadian middle atmosphere measurements. Prof. Shepherd has been a member of the WCRP SPARC Scientific Steering Group since 1994, and was a Lead Author (with A.R. Ravishankara) of the last WMO/UNEP Ozone Assessment [1]. Prof. Shepherd's role in MANTRA 2002/2003 will be primarily consultative, helping to refine the science goals and participate in the data interpretation. He will oversee the comparison of cross-correlations of long-lived species (which are indicators of transport) between MANTRA and CMAM simulated fields.

**Co-Investigator Brian Solheim** (York University) has extensive experience in optical aeronomy, with emphasis on deriving global wind, temperature, and emission rate distributions from the oxygen airglow. He helped to develop the data system, including algorithms and validation, for the WINDII instrument on UARS, and managed that live data system. He was involved in the development of the TOI photometer and the retrieval of high altitude ozone from $O_2(^1\Delta)$ rocket observations during the International Ozone Rocketsonde Intercomparison (1979). He is a member of the Odin Aeronomy Science Team, with responsibility for the ground segment, and is PI for the development of the AOTF spectrometer. Dr. Solheim's primary responsibility will be to operate and analyze the data from the AOTF spectrometer. He will be involved in the pre-flight calibration of the AOTF instrument and in the flight preparations. He will also assist in the inter-comparison of MANTRA and Odin/OSIRIS data.

**International Partner Pierre Fogal's** (University of Denver) current research interests center around the retrieval of atmospheric constituent and temperature profiles from ground-based high-resolution infrared spectra. He has written inversion software based on optimal estimation, and incorporating the University of Denver line-by-line model. He is also one of the foremost operators of the SEASCRAPE code developed initially at JPL. Dr. Fogal's research efforts include analysis of ground-based emission and transmission spectra recorded in the Arctic and at the ARM Southern Great Plains site, as well as analysis of aircraft and balloon-borne spectra from FTS and grating instruments. He has also gathered considerable experience with tunable diode lasers and their application to heterodyne spectroscopy, as well as experience with FTS systems, grating systems and UV photometers. Dr. Fogal will deploy the Denver FTS during the MANTRA 2002/2003 campaigns, and will be responsible for their operation and subsequent data analysis.

**International Partner Frank Murcray** (University of Denver) has designed and built UV, optical, and infrared instruments for operation on aircraft, balloons, and extreme environments on the ground. His primary research is in atmospheric remote sensing [33,50,51]. He is a science team member of the Improved Limb Atmospheric Sounder, an instrument on the Japanese Advanced Earth Observation Satellite, and the Tropospheric Emission Spectrometer, a NASA Earth Observing Satellite instrument. He is PI on research programs for NASA, NSF, DoE, and DoD, and serves as a consultant to several aerospace companies. Prof. Murcray will commit his Bomem FTS to the MANTRA 2002/2003 field campaigns. The University of Denver will supply the instrument and flight support personnel for the project. Analysis of data from the interferometer will be performed at the University of Denver.

**International Partner Florence Goutail** (Senior Scientist, Service d'Aéronomie) conducts experimental research in atmospheric chemistry based on optical UV-visible spectrometry for minor constituent measurements. She is responsible for the NDSC (Network for the Detection of Stratospheric Change) SAOZ network, as well as for the operations of the balloon-borne version of SAOZ. Her research interests are ozone depletion, stratospheric $NO_2$, the impact of aerosols, and satellite validation (GOME, TOMS, ILAS, SAGE II, POAM II, POAM III). Dr. Goutail will provide a SAOZ instrument for the MANTRA campaigns, and will have responsibility for their operation and data analysis.

## 1.3 Scientific Context within Canadian and International Programs

This is a critical point in time for the study of the stratosphere. Mid-latitude ozone has been declining since about 1980. Measures have been adopted which should stop the increase of ozone-depleting substances and lead to an eventual return to the pre-CFC period by the end of this century. However, the terms of the Montreal Protocol, which has brought the required changes to global CFC production rates, are based on the currently accepted science of the ozone layer. We now need to address the issues of ozone recovery and the long-term impact of rising greenhouse gas concentrations on stratospheric ozone. The interrelated issues of climate change, ozone depletion, and verification of the efficacy of the Montreal Protocol are three of the most important priorities outlined for the CSA Space Science Program and are also highly rated by the MSC and the World Meteorological Organization. CSA, NASA, ESA, and the Japanese Space Agency have all committed to satellite missions that are closely related to the science to be addressed by MANTRA 2002/2003. When the MANTRA flights take place, there will be a number of satellites in orbit making measurements which will complement the data to be collected under this initiative.

In addition to the direct benefit of addressing the issue of the changing chemical balance of the stratosphere, the MANTRA 2002/2003 balloon flights will provide a number of other valuable scientific returns. By providing an opportunity to fly clones of MAESTRO and ACE-FTS, they tie in closely with the SCISAT-1 program, enabling evaluation of the instrument performance and retrieval algorithms. They will also provide an good set of ground-truth data which will include multiple concentration profiles of ozone, $NO_2$, and $HNO_3$ that can be used to validate measurements by many of the international satellite instruments in orbit at the time of the launch, particularly SCIAMACHY, GOMOS, and MIPAS on ENVISAT (in addition to Odin and SCISAT-1 as described in Section 1.1.4). The project also provides an excellent opportunity to train the new scientists who will be essential to utilize the forthcoming data sets that will be provided at great cost by future satellite instruments.

## 1.4 Related Modelling Studies

Photochemical modelling will be required in order to use the results of the MANTRA 2002 and 2003 flights effectively. Because of the great variability of stratospheric species, chemical transport models will be required to ensure that the conclusions drawn from the data are actually related to the physics and chemistry of the stratosphere and not to any particularly anomalous events which happened to be sampled at the time of the balloon flight.

A collaboration will be established with the Global Chemistry for Climate (GCC) group, formerly the Middle Atmosphere Modelling (MAM) group, led by Prof. T.G. Shepherd. GCC is a five-year project (with a start date of January 1$^{st}$ 2001) involving a partnership between the university community, CSA, and MSC, with additional funding from NSERC through its Strategic Projects programme and by the Canadian Foundation for Climate and Atmospheric Sciences. The GCC project is building on the Canadian Middle Atmosphere Model, which is a state-of-the-art three-dimensional time-dependent climate simulation model. GCC will address a number of chemical climate questions, including future stratospheric ozone loss and the recovery of the ozone layer. This aspect of the GCC project overlaps with the scientific objectives of this project.

GCC is committed to making detailed comparisons between CMAM and measurements, from a process point-of-view, both to help interpret the measurements and to validate CMAM, and indeed one of the stated goals of the GCC project is "*use of the data assimilation and modelling capability to interpret Canadian measurements and aid in the design of new Canadian measurement systems*". This makes the collaboration between MANTRA and GCC a natural one. GCC can offer access to data sets from fully interactive chemical climate simulation experiments, providing output files of chemical fields and providing advice on their analysis and interpretation. This type of activity is part of GCC's mandate, with CSA supporting GCC in order to facilitate such collaborations with Canadian measurement groups. It is recognized that a single data point such as one obtained from a ground-based system or a balloon campaign is of limited use for the validation of a model climatology. However, the GCC approach is rather to validate the representation of processes in the model, looking at characteristic spatio-temporal structures and correlations between fields.

The goal of our collaboration with the GCC group is to obtain CMAM output of the measured chemical fields at the nearest grid point, and to compare these results with the retrieved MANTRA total column and vertical profile measurements. For CMAM run in climate mode, the data cannot be compared in a day-by-day manner, but only statistically. CMAM has a stable chemical climate over 20-year simulations, which can be used to assess how representative the MANTRA 2002 and 2003 measurements are of the mean mid-latitude stratosphere. CMAM can also be used to test assumptions about variability of different chemical species, and the extent to which one can constrain some species from knowledge of others. In addition, it may be possible to use trajectory calculations that are being developed for Odin and ACE as part of GCC (funded by CSA). The range of validity of this technique can be evaluated by extending the work of Shepherd *et al.* [62] to Summer.

In conjunction with the new MANTRA measurements and historical data, CMAM will also be used to investigate long-term trends in the concentration and partitioning of total nitrogen and the possible effects on ozone depletion. An interesting feature in the $NO_y$ time series has been identified in the mid-1980s in which decreased mixing ratios (~14 ppbv) appear to have been present in the middle stratosphere. This low value may be linked to solar cycle effects. The $NO_2$ time series of Liley *et al*. [19] also show a clear decrease in the years 1987-1988, but the authors find that the contribution to solar cycle effects are not statistically significant and are hesitant to state the solar cycle as the reason for the anomalously low values remaining after various short- and long-term variabilities are removed. Overall, the magnitude of their measured upward trend in $NO_2$ is about twice as large as that due to the $NO_y$ source gas $N_2O$. Using the GISS CTM, McLinden *et al*. [63] have shown that a large part of the remaining trend may be due to changes in ozone but only a very small part due to changes in $Cl_y$. Further investigation of both the solar-cycle effects on total nitrogen and the $NO_2$ trend could be undertaken using CMAM and the MANTRA 2002/2003 data.

## 1.5 Supporting Ground-Based and Sonde Measurements

Background atmospheric measurements will be conducted to characterize the local atmospheric conditions in the viscinity of the main balloon flights. These will be performed using ozonesondes, radiosondes, and several ground-based instruments (MSC Brewer spectrophotometer, University of Toronto zenith-sky grating spectrometer, CRESTech/York University AOTF spectrometer).

The University of Toronto zenith-sky grating spectrometer was assembled in 1998, and was deployed during both MANTRA 1998 and MANTRA 2000 [5,64]. It has also been deployed in three Arctic Spring campaigns (1999, 2000, 2001) at Environment Canada's ASTRO facility in Eureka, NT. It consists of a triple-grating spectrometer with diffraction gratings of 400, 600 and 1800 grooves/mm, providing spectral resolutions of 2.0, 0.9, and 0.5 nm (FWHM). The detector is a thermoelectrically cooled CCD array. Total column abundances are retrieved from zenith-sky spectra using differential optical absorption spectroscopy (DOAS) [65]. During the MANTRA 2002/2003 campaigns, spectra will be recorded throughout the integration period, and will be used to measure ozone columns (to 5% accuracy) and $NO_2$ columns (to 10-12%), and possibly to establish detection limits for OClO and BrO. In addition, algorithms that use the dependence of slant column on solar zenith angle to retrieve vertical profiles of $NO_2$ will be implemented [18,66], and the results compared with the balloon profiles.

MSC will contribute a Brewer spectrophotometer to the balloon campaigns. The Brewer is fully automated, and can make quasi-simultaneous observations of total column ozone, $SO_2$, aerosol optical depth, and UV-B radiation. Measurements are usually made using direct solar and lunar viewing. In addition, vertical profiles of ozone can be derived using the Umkehr inversion technique. During MANTRA 1998 and 2000, the Brewer spectrophotometer was used to measure ozone columns to $\leq$1% accuracy, $SO_2$ columns to 0.2-0.6 DU accuracy, and aerosol optical depth [6]. Similar measurements will be undertaken during MANTRA 2002/2003.

A series of MSC ozonesondes will be launched from Vanscoy to obtain accurate vertical profiles of ozone, as was done during MANTRA 1998 and 2000 [4]. Ozonesondes make *in situ* measurements of ozone partial pressure on ascent, typically at 0.01 mPa vertical resolution with an accuracy of ±10%. MSC will also supply radiosondes to provide a record of winds for flight planning and for interpretation of the column and profile measurements. These provide information on wind speed and direction, as well as pressure (0.1 mb resolution, ±0.5 mb accuracy), temperature (0.1 °C resolution, ±0.2 °C accuracy), and humidity (1% RH resolution, ± 2% RH accuracy). Aerosol backscatter sondes, obtained from the University of Wyoming, will also be flown during the campaigns. These instruments use a photodiode to measure backscattered light from a xenon flashlamp at 490 and 940 nm. Observations are made on ascent during darkness and are used to derive vertical profiles of aerosol backscatter [67,68].

## 1.6 Data Analysis

The following subsections describe the methods and techniques that will be used to analyze the data from each of the science instruments. In general terms, it is anticipated that there will five levels of data, as follows: level 0 - raw telemetry data, level 1 - geolocated engineering units, level 2 - geophysical units (profiles, columns, *etc.*), level 3 - gridded products, level 4 - integration with models.

Data will be archived and made available on the World Wide Web, as appropriate (this was done on a limited access internal web site for all of the MANTRA 1998 and 2000 level 0 and level 1 data). We propose to set up a public archive for data from all of the MANTRA campaigns as part of this project. Presentation of the results, both technical and scientific, arising from the MANTRA project will be done through the usual channels, at workshops, conferences, and in the refereed literature. This will follow the pattern set by the MANTRA 1998/2000 mission, for which four data workshops have been held, 15 conference presentations and at least 14 other talks given, and nine papers written (one published, seven submitted, one in preparation). Data analysis will be performed within a set time frame (12 months) after each flight, to ensure prompt dissemination of the results.

In addition, given the strong public interest in environmental issues such as ozone depletion, MANTRA 2002/2003 will provide an excellent opportunity for educational public outreach. There are several fairly simple approaches to informing the public about MANTRA and its scientific context, such as preparing lively and informative pages on the World Wide Web that would appeal to both elementary and high-school students. Given the photogenic nature of a balloon launch, we propose to keep a comprehensive visual record of the MANTRA 2002/2003 project (as was done for MANTRA 1998/2000), both photographic and video, from instrument assembly and calibration, through payload integration, to launch and recovery. This could then serve as a vehicle for educating students about the mission and about the wider topic of atmospheric research being pursued in Canada and worldwide.

### 1.6.1 Data Analysis for Balloon-Borne Instruments

***Data Analysis: MSC Emission Radiometers***

The original analysis approach for the emission radiometers involved differentiating radiance profiles with respect to height to assign a radiance change to each layer, from which the concentration of $HNO_3$ is calculated [22,23,44]. A new more computationally intensive analysis technique was developed for analysis of the MANTRA 1998 flight data. It combines a line-by-line forward model of the instrument response for a given atmosphere with a bounded least-mean-squares optimization criterion and gradient-driven solution search to find the best global fit for the underlying volume mixing ratio profiles. Measurement residuals that indicate how well the mixing ratio matches the instrument measurements are also generated, indicating how well the assumptions fit the experimental regime. This technique enabled the simultaneous retrieval of mixing ratio profiles of $HNO_3$, ozone, CFC-11, CFC-12, $N_2O$, and $CH_4$, all species having emission features in the 8-14 μm window. The same approach will be used for the MANTRA 2002/2003 emission radiometer data, and the analysis will be performed by Dr. Quine at the University of Toronto.

***Data Analysis: MSC SunPhotoSpectrometer and MAESTRO Clone***

The MSC SPS will record UV-visible spectra in both solar occultation and limb-scan modes. These raw spectra will be corrected for bias, stray light, dark current, both wavelength and absolute lamp calibration, and telemetry dropouts. A chi-squared minimization technique will then be used to retrieve the apparent column density of both ozone and $NO_2$ as a function of tangent height. Ozone slant column retrieval in the UV will be done over the spectral range from

315 to 380 nm, while in the visible, the region from 450 to 635 nm will be used. Similarly, $NO_2$ will be fitted from 400 to 550 nm.

Vertical profiles of ozone and $NO_2$ are derived by applying the Chahine relaxation method to the to the SPS slant column densities [69,71]. A series of iterations starting from the arbitrary initial guess for the mixing ratio of each stratospheric constituent is made until the residuals of all layers converge. The weighted version of the Chahine iterative equation is used in order to stabilize the convergence of the solution in the presence of correlation between the amount of constituent in each layer of the model.

In addition, absolute radiometric measurements of the direct solar beam, the brightness of a point on the horizon, and the brightness of the upwelling radiation from below the balloon will be combined to obtain total estimated J-values for reactions such as the photolysis of ozone and the photodissociation of $NO_2$ [47]. The SPS may also be used to retrieve temperature and pressure profiles from solar occultation measurements of the $O_2$ A and B bands (at 760 and 680 nm, respectively). The feasibility of this approach is currently being investigated using MANTRA 2000 data and line-by-line models that are being developed at MSC for MAESTRO temperature and pressure retrievals. Data analysis for the SPS (and a MAESTRO clone, if flown) will be done in a collaboration between MSC and the University of Toronto, led by Dr. McElroy and Prof. Drummond.

***Data Analysis: University of Denver Fourier Transform Spectrometer***

The University of Denver FTS will record infrared solar occultation interferometric data. The DU group is very experienced in the process of transforming interferograms into spectra and applying fitting and inversion techniques to those spectra. The spectra are fit using a line-by-line, layer-by-layer computer code developed at DU over many years. Vertical profiles are retrieved using the "onion peeling" approach, whereby the mixing ratio for each tangent height is determined in sequence, starting with the highest tangent height and working downwards through the atmosphere. We also intend to use the SEASCRAPE computer code to perform spectral inversions for comparison to the more traditional methods and possibly profiles determined from ground-based spectra. Dr. Fogal will be responsible for analysis of the DU FTS data. Funding for this analysis will be sought from other sources and from internal funds as appropriate.

***Data Analysis: MSC Fourier Transform Spectrometer***

Data analysis methods for FTS instruments recording solar occultation spectra are well-established. Several computer packages are available for the conversion of the raw data into spectral form and the fitting of the spectra to slant path concentrations. However, all flights are different and some interaction with the data is expected. Conversion of slant amounts into vertical profiles is accomplished by "maximum likelihood" or similar techniques. Older techniques, such as "onion peeling" and more modern techniques, such as "global fitting" are also possible and we are eager to try these in research mode. Data reduction will be a joint responsibility between MSC and the University of Toronto with participation from senior personnel (Fast, Drummond) and junior personnel (Wunch).

***Data Analysis: CRESTech/York University Acousto-Optic Tunable Filter Spectrometer***

The AOTF data analysis will use essentially the same DOAS technique as the ground-based zenith-sky spectrometer. The data will first be corrected for dark current and then corrected for responsivity. The wavelength scale will be determined from the pre-flight calibration and the in-flight calibration, correcting for any temperature variations. At this point the spectra are analyzed with the standard DOAS retrieval, including a shift and stretch of the wavelength based on the known spectral features. An iterative least squares algorithm is then used to derive vertical profiles of number density from the slant columns obtained as a function of solar zenith angle. Dr. Solheim will have primary responsibility for the AOTF data analysis.

***Data Analysis: Service d'Aéronomie SAOZ Spectrometer***

The spectral analysis and the inversion scheme for the SAOZ are similar to the ones used for processing the data of sun-oriented instruments. The inversion assumes the diffuse light component to be negligible, an important point because of the use of a 360° conical mirror plus diffuser instead of a tracker which was discussed by Pommereau and Piquard [53].

Spectral analysis. Actual spectra are first aligned in wavelength by correlation of the Fraunhofer solar lines (precision ± 0.05 pixel or 0.02 nm) and ratioed to a reference spectrum recorded at high altitude and low sun zenith angle (SZA). Absorbing constituents are derived by a differential method, that is by looking at their narrow absorption features after subtraction of the broad spectral variations. The atmospheric attenuation spectrum – the logarithm of the above ratio - is correlated to literature cross-sections by a sequential and iterative least squares fit, which provides together a slant column amount and an evaluation of the uncertainty for each measurement. Ozone is measured in the visible at 450-620 nm, where its absorption cross-sections are not sensitive to temperature; $NO_2$ at 405-470 nm; $(O_2)_2$ at 360, 380, 477 and 576 nm; tropospheric water vapour at 505 and 590 nm, OClO in the polar Winter, between 345 and 390 nm. Stratospheric $H_2O$ will be measured around 760 nm.

Profile retrievals: The vertical distributions of the concentrations, and their uncertainties, are retrieved by a linear tangent ray inversion technique known as onion peeling.

***Data Analysis: University of Waterloo ACE-FTS Clone***

Like the Denver FTS, the ACE-FTS clone will work in solar occultation mode. The data reduction procedures are well established at Waterloo, based on the NASA ATMOS mission. We have up-dated much of the legacy computer code and, for example, are now using a "global fit" approach to calculate vertical profiles of species rather than the "onion peeling" method used by ATMOS. The ACE satellite mission also works in solar occultation so we will be able to use essentially the same computer programs and molecular line lists.

### 1.6.2 Data Analysis for Ground-Based Instruments

***Data Analysis: University of Toronto Zenith-Sky Grating Spectrometer***

The detection of stratospheric constituents from the ground by measuring the absorption of sunlight scattered from the zenith sky is a well established technique. Analysis of spectra recorded with the zenith-sky spectrometer will start with the necessary pre-processing procedures, including subtraction of dark current, flat fielding, and wavelength calibration. DOAS algorithms will then be used to ratio the spectra to a reference, calculate the differential optical depth, and perform simultaneous least squares fitting of the differential absorption cross sections to obtain slant column densities as a function of solar zenith angle. A radiative transfer model [64] is used to calculate the path of scattered light through the atmosphere to convert the retrieved slant columns into vertical columns. This work will be performed at the University of Toronto under the direction of Prof. Strong.

***Data Analysis: MSC Brewer Spectrophotometer and Sondes***

Analysis of data from the Brewer spectrophotometer, ozonesondes, radiosondes, and aerosol sondes will use standard proven techniques. This analysis will be performed at MSC, with Dr. McElroy co-ordinating the work.

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# MANTRA 2002 and 2003
# A Balloon Mission to Study Stratospheric Composition
# Part Two - Technical Issues

## 2.1 Mission Concept Definition

MANTRA 2002/2003 is a mission to investigate the composition of the stratosphere. It builds on experience gained during the MANTRA (Middle Atmosphere Nitrogen TRend Assessment) 1998 and 2000 balloon campaigns. Two high-altitude balloons will be launched from Vanscoy, Saskatchewan (52°N, 107°W), the first in August 2002 and the second in August 2003. Each will carry a suite of instruments to measure the vertical concentration profiles of the significant components of the odd nitrogen budget, as well as species which link the $NO_x$, $HO_x$, $ClO_x$ and $BrO_x$ catalytic cycles, specifically ozone, NO, $NO_2$, $N_2O_5$, $HNO_3$, $ClONO_2$, HCl, BrO, OH, $H_2O$, and aerosols. In addition, the tracers $CH_4$ and $N_2O$ will be measured, as will CFC-11, CFC-12, $O_2$, temperature, pressure, and J-values for $O^1D$ and $NO_2$. These measurements will be combined with those obtained from similar campaigns mounted at northern mid-latitudes over the past 20 years, in order to quantify changes in the chemical balance of the stratosphere. In addition, measurements of the same trace species made by different instruments will be compared in order to resolve discrepancies observed during MANTRA 1998/2000 and to assess the instruments' performance. The 2002 measurements will also be used for validation and ground-truthing of the Odin satellite mission, and the 2003 measurements for validation and ground-truthing of the SCISAT-1 mission.

The first balloon payload will consist of six primary instruments and four secondary instruments. The primary instruments, defined as those that are key to achieving the scientific objectives, are one emission radiometer, a SunPhotoSpectrometer (SPS), a Fourier transform spectrometer (FTS, from the University of Denver), a SAOZ (Systeme d'Analyse et d'Observations Zenithales) spectrometer, an ozonesonde, and an aerosol sonde. The secondary instruments for this flight are a second emission radiometer, a clone of the MAESTRO satellite instrument, a second FTS (from MSC), and an OH spectrometer. In addition, three ground-based instruments will be deployed during this field campaign: a Brewer spectrophotometer, a zenith-sky grating spectrometer, and an AOTF (acousto-optic tunable filter) spectrometer. With this suite of instruments, a comprehensive set of trace gases will be measured, as listed in the paragraph above. There will be multiple measurements of most species, allowing comparisons between the different measurement techniques, as well as comparisons between the two FTSs and the various UV-visible spectrometers.

The payload for the 2003 flight will be similar to that of 2002, with two exceptions. Firstly, only one of the two FTSs will be flown, with the other to be replaced by a clone of the ACE-FTS satellite instrument. Measurements made by this instrument will be validated against the other FTS, and will also be compared with satellite observations by the SCISAT-1 ACE-FTS. Secondly, the AOTF spectrometer will be added to the payload, and will provide a third set of UV spectra for comparison with the SPS and SAOZ. Many of the measurements will be obtained using solar occultation as the sun rises or sets, when the atmospheric path increases rapidly with solar zenith angle by as much as 70 times the vertical air mass above the lowest point on the path. This path increase, combined with the strong weighting of absorber amount to the tangent point, enables the retrieval of concentration profiles at altitudes below the balloon, as well as some ability to determine column amounts above the balloon.

The balloons will be launched from Vanscoy, SK, using facilities provided by Environment Canada, which has a fully equipped balloon launching station there. This facility is operated by Scientific Instrumentation Limited (SIL), which will provide payload and launch support to the project. The equipment on hand includes a telemetry and command package, power and pointing systems, and all ground, launch, and recovery support gear. In addition, a new pointing control system, developed for the MANTRA 2000 flight, will be used on both the 2002 and 2003 flights. A new gondola will be built for this mission, and will be based on existing structures which have flown successfully

In addition to the scientific goals of the MANTRA 2002/2003 project, it is intended to contribute to Canadian capacity building, including both instrumental techniques and training of highly qualified personnel. The relatively low cost of this balloon mission makes it an excellent route for developing expertise in the various measurement techniques and for assessing the potential of the scientific payload for more ambitious missions. In addition, it will assist in maintaining Canada's ability to mount balloon campaigns of this nature.

## 2.2 Flight Instrument Description

### 2.2.1 MSC Emission Radiometers

Emission radiometers were first developed by Pick and Houghton [1]. The instruments consist of an insulated liquid-nitrogen dewar containing a cooled detector and optics and originally made measurements of the atmospheric thermal emission in the 10.3-12.5 μm (800-970 $cm^{-1}$) region. The instruments employ reflective optics to maximize signal intensity and to simplify radiometric calibrations. A 200 Hz mechanical chopper modulates the detector signal at the entrance slit. Incoming radiation is passed though a filter and is focused onto a mercury-cadmium-telluride detector. A low-noise linear pre-amp amplifies the detector signal. The instrument produces low and high-gain output channels via independent linear amplifiers and associated phase-sensitive detectors.

A Canadian version of the instrument was developed by Evans *et al.* [2] in the early 1970's. The early instrument design employed five discrete band-pass filters. Later instrument designs replaced the discrete filters with continuously variable filter segments (see [3]) to scan a wavelength region from 8-14 μm (715-1250 $cm^{-1}$). The instrument is operated in a continuous scan mode, completing each scan cycle in 40 seconds. Part of the filter wheel is blanked off, providing a background radiometric calibration for each scan.

The instruments have a wide toroidal field-of-view with a sensitivity extending over a ±20° range with peak sensitivities at ±10°. A correction factor for the slant path elevation angle is used in the analysis. A blackbody calibration flap is automatically lowered to cover the field of view every six scans. The flap, mounted externally to maintain a temperature above that of liquid nitrogen, has an embedded platinum resistance thermometer to provide an in-flight radiometric calibration. The instrument is mounted in an anti-sun pointing configuration at an elevation angle of approximately 20° above the horizon to increase the atmospheric slant path. Measurements of the atmospheric radiance profile are made during the balloon ascent.

### 2.2.2 MSC SunPhotoSpectrometer

The MSC photodiode array spectrometer is based on the MSC SunPhotoSpectrometer which has flown on STS-52 and aboard the NASA ER-2 as part of the NASA Upper

Atmospheric Research and High Speed Research Programs [4,5]. On the ER-2, the instrument is called the Composition and Photodissociative Flux Measurement (CPFM) Experiment, and is used as an absolute spectroradiometer and to provide ozone data using the technique of differential absorption spectrophotometry. The instrument has flown at 21 km nearly 100 times with this program.

The SPS is based on an EG&G randomly addressable 1024-element photodiode array detector, situated at the focus of an f/2 holographic diffraction grating. Spectra are recorded from 300 to 785 nm at 0.5 nm steps, with a spectral resolution varying from 1.2 to 4 nm (FWHM) across this wavelength range. The field-of view is 2° with a sun diffuser, and 1.2°×6° without it. The dynamic range is greater than $10^6$, and the signal-to-noise ratio is of order 1000:1.

Data can be collected in both solar occultation mode and limb-scan mode, and are analyzed using a spectral fitting code to determine concentration-height profiles of ozone, $NO_2$, $O_2$, $O_4$, and aerosol, and upper limits for OClO and BrO columns. A second version of this instrument may be flown to make absolute radiometric measurements of the direct solar beam, the brightness of a point on the horizon, and the brightness of the upwelling radiation from below the balloon. These three fields, appropriately combined and integrated with the cross-sections of the relevant absorbers produce J-values for photolysis reactions of ozone and $NO_2$ [6], which are needed in photochemical model simulations.

### 2.2.3 MSC OH Spectrometer

The MSC high-resolution scattering spectrometer for measurements of OH was first flown on Stratoprobe payloads in July 1975 from Yorkton, SK and in September 1976 from Palestine, TX [7]. The OH resonance scattering technique has been used since 1975 by others [8], but without the MSC refinement of using polarization. This instrument measures polarized spectra of the sky at right angles to the sun and at about 10° above the horizon. It observes the direct solar beam (as reference), and strong and weak polarizations at 90° to sun to detect resonant scattering from OH. The spectral range and resolution of the instrument are 305 to 311 nm, and 0.04 nm, respectively. The OH signal-to-noise ratio in the altitude range 25 to 40 km is high, but the lack of sufficiently detailed, very-high-resolution data on the solar spectrum precluded an absolute calibration of the original historical measurements. This problem can be solved today, and the calibration factor will not have changed between the earlier flights and the present. Thus measurements made with this instrument of OH during MANTRA would be directly comparable with those made in 1975 and 1976.

Refurbishment of the OH spectrometer will be conducted at York University, under Dr. Solheim, in collaboration with MSC. Data analysis, involving implementation and improvement of existing algorithms will be undertaken at the University of Toronto, under Prof. Strong, again in collaboration with Dr. McElroy of MSC.

### 2.2.4 University of Denver Fourier Transform Spectrometer

The University of Denver FTS is a Bomem DA2 (originally manufactured by Bomem, Quebec City, Quebec) that has been used in a large number of flights in the United States since 1977 [9,10,11]. The instrument is owned and operated by a group led by Dr. F.J. Murcray's research group at the University of Denver, Denver, Colorado. This group has extensive experience in spectroscopic measurements and in balloon instrumentation stretching back over several decades.

The interferometer has a 50-cm path difference, which results in an unapodized FWHM resolution of about 0.01 $cm^{-1}$. Each interferogram takes about 90 seconds to acquire. The system has a dichroic beamsplitter that directs the output beam from the interferometer onto two infrared detectors, each covering approximately 600 $cm^{-1}$. The interferograms from the two detectors are digitally filtered, and transmitted by telemetry as well as being recorded on board. In addition to flying one HgCdTe detector covering 700-1300 $cm^{-1}$ (for ozone, $HNO_3$, $CH_4$, $N_2O$, CFC-11, CFC-12, $ClONO_2$ and $N_2O_5$), there are two options for the second detector:

(1) an InSb, covering 2650-3250 $cm^{-1}$, for HCl and for comparison with the MSC FTS InSb measurements, and

(2) a second HgCdTe for NO and $NO_2$, and for a comparison of two bands of $HNO_3$, $ClONO_2$ and $N_2O_5$.

The choice of detectors will be finalized during flight planing, in conjunction with plans for the MSC FTS and the ACE-FTS clone.

The interferometer with the solar tracker and data systems weighs 84 kg. Power consumption is 4 A at 30 V (1.5 A standby). The instrument and tracker are about 48 inches long, 20 inches wide, and 48 inches tall (at the solar tracker, about 16 inches tall on the back 30 inches). The TM encoder is about 14 by 14 by 26 inches. There are two power commands, one for the laser and heaters (1.5 A) and the other for the solar tracker, TM, and the rest of the interferometer (2.5 A). The downlink is 480 kbits NRZ synchronous, using a dedicated transmitter.

The instrument uses light from the central 70% of the solar disk. A servo-controlled solar tracking system keeps the sun on the entrance aperture. Spectra are recorded as the sun rises or sets, when the atmospheric path increases rapidly with time, or equivalently with solar zenith angle. Concentration profiles are obtained at altitudes below the balloon, and there is some ability to determine column amounts above the balloon. The total quantity of each gas is retrieved by a spectral least squares matching algorithm that adjusts the amount of absorbing gas to match the spectral lines observed [12].

### 2.2.5 MSC Fourier Transform Spectrometer

The MSC Fourier Transform Spectrometer is a Bomem BBDA2 unit which operates in the spectral ranges 1840-1990 $cm^{-1}$ and 2870-2980 $cm^{-1}$ using HgCdTe and InSb detectors simultaneously. It has a spectral resolution of 0.02 $cm^{-1}$ (unapodized). This unit has been flown previously on four missions in 1985. The instrument will be extensively refurbished to modern standards before flight in 2002. The instrument will be optimised for the 700-1300 $cm^{-1}$ and 2500-3500 $cm^{-1}$ ranges to measure $O_3$, $HNO_3$, $ClONO_2$, $H_2O$, CFC-11, CFC-12, $CH_4$, $N_2O$, $NO_2$ and HCl. Its capabilities are similar to those of other FT spectrometers of equivalent resolution. The advantage of including it in the MANTRA 2002 payload is that it will provide a domestic instrument to make measurements if the other FTS instruments should be unavailable in the future.

The refurbishment of the instrument will be made with other funding and with participation from the manufacturer (ABB Bomem) under contract. The instrument will be extensively tested in the vacuum facility at the University of Toronto before launch on the payload. Particular attention will be paid to weight reduction and data recording. It is hoped that we will be able to produce an instrument that can be used extensively in the future.

### 2.2.6 CRESTech/York University Acousto-Optic Tunable Filter Spectrometer

York University and CRESTech will provide an acousto-optic tunable filter (AOTF) spectrometer. The AOTF instrument has been built for balloon-borne operation, under the direction of Dr. Solheim, with funds provided by CRESTech. It is capable of observing ozone, $NO_2$, OClO and BrO in the 250 to 400 nm spectral region. It uses a $MgF_2$ acousto-optic filter to scan the spectrum in the visible and near-UV regions (250-400 nm). It has a wavelength-dependent resolution of 0.07 nm at 250 nm, 0.1 nm at 300 nm, 0.15 nm at 350 nm, and 0.21 nm at 400 nm. The detector is a photomultiplier tube, with very low dark count. The system throughput is $5.7\times10^{-4}$ $cm^2$ sr with an external field-of-view of 0.05° half angle. During flight, an on-board mercury lamp is used to calibrate the wavelength.

The AOTF instrument consists of two cylinders mounted one on top of the other. The main cylinder is 1.5 metres long and contains the baffle, telescope optics, a filter wheel, a mercury calibration lamp, the AOTF itself and the detector (with its high voltage supply). All components except the baffle and telescope are in a sealed housing to maintain ground-level pressure. The second cylinder, 1 metre long, is also air-tight and contains the control and AOTF RF electronics which are connected to the instrument housing by three low-voltage cables. The total mass, excluding batteries, is 41 kg.

The AOTF spectrometer is designed for balloon-borne solar occultation and limb-scanning observations, in order to measure profiles of ozone and $NO_2$, and to set detection limits for OClO and BrO. Both modes require balloon pointing (azimuth control) and altitude scanning (tilting platform). The limb-scanning observation requires the gondola to be pointed so that the AOTF instrument looks at 90° (scattering angle) to the sun during the daytime. The instrument is then scanned in altitude by tilting the platform to pre-defined angles.

### 2.2.7 Service d'Aéronomie SAOZ Spectrometer

The SAOZ sonde is a lightweight UV-visible diode array spectrometer that looks at the absorption of the sunlight by the atmosphere during the ascent (or descent) of the balloon and during sunset (or sunrise) from the float altitude. The gondola-orientation or sun-tracker system that is generally used with large balloons is replaced by a simple conical mirror. An on-board CPU controls and runs the instrument automatically, which then does not require any remote control and needs a single channel telemetry for the transmission of the spectral data and the house keeping information or even none the spectra being recorded an on-board memory.

As discussed in Section 1.1.5, there are three versions of the SAOZ instrument. The original SAOZ-N is a commercial flat field, 360 grooves/mm, holographic grating spectrometer equipped with a 1024-diode linear array detector and an entrance slit of 50 µm, that is of the size of two diodes. Spectra are recorded from 290-640 nm, with an average 0.8 nm resolution for the retrieval of $O_3$, $NO_2$, OClO (when activated in cold polar vortex), tropospheric $H_2O$, $O_2$, $(O_2)_2$ and the extinction coefficient of aerosol and PSCs [13,14]. SAOZ-BrO operates in the UV region, with a 1200 groves/mm grating and a 250 µm entrance slit making measurements in the 330-370 nm range with a resolution of 0.3 nm, in order to provide vertical profiles of BrO and $CH_2O$. SAOZ-$H_2O$, now being developed, operates in the visible part of the spectrum at 400-750 nm with a resolution of 0.8 nm. It is intended to retrieve stratospheric $H_2O$ as well as $O_3$, $NO_2$, tropospheric $H_2O$, $O_2$, $O_4$ and the aerosol extinction coefficient.

For all three versions, the optical entrance is a 360° conical mirror with diffuser plates to homogenize the signal. The field-of-view is limited at +10°, -5° in elevation by two baffles. The sonde is powered by rechargeable NiCd batteries. The SAOZ is equipped with a Global Positioning System (GPS) receiver, which gives its location with an uncertainty of ±150 m in the three directions, and with an ARGOS transmitter for the localisation of the gondola after landing. All of the above equipment is installed in a polystyrene gondola coated fiber glass whose thickness and external paint were designed from the results of a thermal simulation in order to keep the sub systems at an acceptable temperature. The excess power dissipated by the computer is evacuated by conduction toward a radiator at the outside of the gondola. The total weight of the SAOZ is 20 kg. The SAOZ instrument is usually installed on the flight train, just below the parachute. It may be completely independent with own power supply and data recorded on-board. The instrument installed on the flight train gives the 360° field-of-view. The instrument does not need TM and TC. It can be dragged on the ground during the launch.

### 2.2.8 University of Waterloo ACE-FTS Clone

The ACE-FTS clone has not been built yet by ABB Bomem so the exact design and performance are not known. Bomem, however, has extensive experience with balloon-borne FTSs and our basic design will be based on the ACE-FTS satellite instrument. The interferometer has a symmetric compact design with a maximum optical path difference of ±25 cm (0.02 $cm^{-1}$ resolution). A double-sided interferogram can be acquired in 2 seconds. An InSb and a HgCdTe detector will cover the full 750 – 4100 $cm^{-1}$ range using either a dichroic splitter or a sandwich arrangement of the detectors.

There will be an integral solar tracker and a telemetry system based on the existing Bomem balloon-borne FTSs. The data will be stored on board as well transmitted to the ground. On board co-addition of scans will be implemented to reduce the effective data rate to match the downlink data capacity. The FTS will record a sequence of interferograms as the sun rises or sets. The series of interferograms will be converted into spectra on the ground and inverted to give vertical profiles.

## 2.3 Other Systems Required

### 2.3.1 Pointing Control System

For the MANTRA 2000 balloon flight, a new pointing control system was developed. The system is capable of pointing a platform of optical instruments at an inertial target from a pendulating gondola suspended below a high-altitude balloon. It operates in both a traditional occultation-scan mode, to observe solar absorption, and a limb-scan mode, to make measurements of the Earth's limb. The system employs integrated sensors and high-level icon-based software (Labview). A microprocessor controller derives real-time estimates of gondola attitude, employing an extended Kalman filter to combine gyro, magnetometer, tilt-sensor and shaft-encoder information. These estimates are used to develop control demands that point a platform of instruments in elevation and azimuth rotation. The system was successfully flown during the MANTRA 2000 mission and demonstrated a pointing accuracy of $0.1^{o}$ ($1\sigma$) in elevation and $3^{o}$ ($1\sigma$) in azimuth.

The azimuth performance was affected by the undamped torsional flexure mode of the flight train, which the PID controller failed adequately to control. This caused the azimuth angle to oscillate about the required pointing direction. There is evidence that the previous occultation-only pointing system also suffered from a similar oscillation of smaller amplitude; an instrument video shows a 1 degree oscillation while sun pointing. This problem might be overcome using the existing suspension hardware by implementing a more sophisticated digital controller tuned to avoid exciting the flexure mode, but the presence of a low-frequency harmonic in the dynamics will always complicate control. We propose instead to adopt a more practical approach of including an additional azimuth pivot in the flight train, above the mass boom. This will have the affect of decoupling the flight train dynamics from those of the mass boom. The mass boom, top mount and pivot would then behave like a crude momentum wheel. The mass boom would oppose torques applied to rotate the gondola by storing angular momentum as free rotation. The technique would be similar to that used by Kopp and Huguenin [15] and would virtually eliminate the torsional flexure mode from the gondola dynamics.

We also propose to make some modifications to the pointing system's software. We will extend the use of the pointing system's automated event handler to schedule data-collection activities autonomously. We will include a modification to switch the pointing-system operation into an autonomous mode if a watchdog timer is not reset by ground command. Implementing this along with on-board data collection will enable the pointing system to command instrument data acquisition and to gather data during periods of complete communication blackout. We will also investigate the integration of a GPS unit, use of a different sampling board, and inclusion of on-board data storage.

### 2.3.2 Payload Systems

The MANTRA payload will consist of the instruments, the pointing control system, and flight support systems, all mounted on an aluminum gondola frame. All instruments except the University of Denver FTS (which has its own sun tracker) will use the new pointing system for altitude scans and solar occultation observations. The gondola will be based on existing structures which have flown successfully, and will be made of a light-weight frame, consisting of cross braced aluminum square tubing. Solar shields will be mounted on the gondola support frame in order to reduce the thermal load on the instruments at float altitude. The command and telemetry package, batteries, ballast, crush pads and floatation, flight train, parachute and recovery package are all standard components which have been flown before on previous balloon flights.

The entire gondola will be swung around by an azimuth pointing joint so that the elevation pointing platform can be pointed at the sun for the solar occultation observations. During the day, the instruments will be pointed at roughly 90° to the sun and the tilting platform scanned in altitude for the limb scan observations. A GPS unit will be used to provide position and altitude information.

The Bristol Aerospace STandard Architecture Support (STARS) system will be used for power distribution and switching. STARS was originally designed as a set of components to encapsulate all electronic functions provided to a rocket payload, but was modified and successfully used for MANTRA 2000. It has been qualification tested to +60°C, vacuum tested down to $10^{-5}$ Torr, and vibration tested to 25g. STARS allows a single common lithium battery pack to be used by all instruments with 28 V supplied to each device (has 1 and 5 Amp for 28 V output). The supplies will be unregulated, with each instrument or device to have its own regulator for current control.

SIL will also provide the digital telemetry system and data recording facilities. The data collected will be returned in real time and also in permanent media form after the flight has taken place. A 16-channel 115.2-kbaud serial statistical multiplexer and an S-Band transmitter will be used to provide telemetry between the instruments and the ground station. The standard S-Band transmitter can provide PCM data at rates up to 460.8 Kbps (bits per second). The data rates for the instruments are all less than 460.8 Kbps and we expect to be able to use the standard telemetry system. There is both an up and down 1200 baud serial command link. This enables commands to be sent in real time to the payload or a specific instrument and responses from the instrument to be received at the ground station. Thus one can command and confirm that the command was received in real time. This facility will be used to change instrument operation modes and to initiate in-flight calibrations. There are also various analog, VCO and pulse counting interfaces available in addition to the PCM and serial command interfaces. Data are recorded at the ground station, requiring a line-of-sight view of the balloon.

The payload mass budget is given in Table 3 below. The total mass of all instruments and their supporting electronics and cryogens is 275 kg for the 2002 flight and 324 kg for the 2003 flight. A balloon of 11.8-mcf volume is needed to lift a 324-kg scientific payload to 37 km.

Table 3. Estimated mass budget for the scientific instruments on the balloon payload.

| CAMPAIGN | BALLOON-BORNE INSTRUMENTS | MASS (kg) |
|---|---|---|
| **2002** | Two MSC emission radiometers + liquid nitrogen | 15 |
| | MSC SunPhotoSpectrometer and/or MAESTRO clone | 8 |
| | MSC OH spectrometer | 36 |
| | University of Denver Fourier transform spectrometer | 84 |
| | MSC Fourier transform spectrometer | 60 |
| | Service d'Aéronomie SAOZ spectrometer | 20 |
| | MSC ozonesonde | 2 |
| | University of Wyoming aerosol sonde | 5 |
| | Pointing control system | 45 |
| | **TOTAL MASS** | **275** |
| **2003** | Two MSC emission radiometers | 15 |
| | MSC SunPhotoSpectrometer and/or MAESTRO clone | 8 |
| | MSC OH spectrometer + cradle | 44 |
| | Fourier transform spectrometer (MSC or U of Denver) | ≤ 84 |
| | CRESTech/York University AOTF spectrometer | 41 |
| | Service d'Aéronomie SAOZ spectrometer | 20 |
| | University of Waterloo ACE-FTS clone | 60 |
| | MSC ozonesonde | 2 |
| | University of Wyoming aerosol sonde | 5 |
| | Pointing control system | 45 |
| | **TOTAL MASS** | **324** |

## 2.4 Facilities Description

The launch facilities will be provided by Environment Canada, which has a fully equipped balloon launching station at Vanscoy, Saskatchewan, 25 km from Saskatoon, at 52° 01' N, 107° 02' W, and 511.0 m elevation. Scientific Instrumentation Limited (SIL) operates this permanent balloon launch facility and was the launch contractor for the MANTRA 1998 and 2000 flights. SIL and staff have been launching balloons since 1986 and building payload systems since 1974. To date, over 120 balloons have been flown by SIL. The launch area consists of paved runways (30m × 760m) and two buildings for payload preparation, ground support and storage. Launch equipment includes a launch truck, two helium trailers, a spool trailer, a flood light trailer, recovery trailer and flight train equipment. Ground support includes S-Band receivers, data recorders and uplink commanding.

The maximum balloon size that can be launched from Vanscoy with the existing equipment is 22 million cubic foot (mcf) with a 500-kg science payload. We propose to launch a 11.8-mcf balloon with a science payload of up to 324 kg. This is well within SIL's launch capability. We have a spare 7.6 mcf balloon in stock that (purchased for MANTRA 1998) that can be used as backup, although it will require a reduction of the instrument complement or a lower float altitude. The launches will be planned for either Spring turnaround (May) or Fall turnaround (August) in 2002 and 2003, with the season to be chosen to optimize Odin and SCISAT validation opportunities.

## 2.5 Instrument Calibration

### *General Comments*

The calibration of any solar occultation interferometer or spectrometer is similar and relatively straightforward. The solar signal is relatively strong and the time of the measurement short, so the instrument is, to first order, invariant during the measurement. The spectrum is determined essentially by the wavelength calibration, the zero line and the 100% line. The zero line is obtained by blanking the input signal, which in practice involves either using a beam obscurer or moving the instrument off of the solar disk. The 100% line is obtained by using the fact that the instrument sees relatively small amounts of atmosphere for high sun angles shortly before the measurement. By using known regions of low absorption between the lines, the 100% point can then be obtained. The wavelength calibration is fixed by the instrument itself and is self-calibrating by identifying lines of well-known species or solar Fraunhofer lines. The resulting spectra are fitted using an appropriate algorithm to obtain slant path amounts and vertical profiles. There are also specific calibration issues for each instrument which are noted below.

### *Calibration: MSC Emission Radiometer*

The MSC emission radiometers will undergo a series of pre-flight checks, both prior to and during the field campaign, using a custom designed blackbody reference. This reference consists of a massive anodized metal source equipped with liquid nitrogen cooling, a servo-controlled precision heating system and a collection of thermistors which are used to monitor the blackbody surface temperature.

The radiometers will be calibrated during the flight using integrated calibration source. The instruments will operate in a continuous scanning mode in sequence of six atmospheric observations followed by one blackbody calibration scan. Instrument sensitivity as a function of spectral point and altitude will be derived from these calibration scans and from platinum resistance thermometer measurements of the blackbody temperature. Radiometer elevation mount angles will be measured with respect to the gondola frame using a calibrated digital tilt sensor, prior to the flight.

***Calibration: MSC SunPhotoSpectrometer and MAESTRO Clone***

The SPS and MAESTRO clone follow the general comments above for solar occultation. The solar occultation measurements are radiometrically self-calibrating. The limb-view measurements can be calibrated by using a pre-flight calibration against a known source and inflight reference to an internal lamp. Wavelength calibration will use a dispersion equation to assign the correct wavelength to each pixel of the detector. The passbands of the individual elements of the diode array will be determined using the grating tilting mechanism which is part of the spectrometer. It may also be possible to use a tunable laser source to confirm the results of the internal measurements. The passbands of the detector elements will be used as weightings to calculate the effective absorption coefficient spectrum to be used for the various constituents to be fitted in the observations. Pre-flight measurements of gas samples will also be performed, not to determine precise absorption coefficients but to confirm that the proper values of all critical parameters have been determined (as in [16]). The wavelength calibration will be validated in the flight spectra by examining the positions of solar Fraunhofer absorption features.

***Calibration: University of Denver Fourier Transform Spectrometer***

The FTS instrument follows the general comments for solar occultation above. There are a number of second order effects which are important in the exact retrieval of the scientific information. These are handled at a number of levels depending upon their nature, but the long experience of instrument teams with the Fourier transform technique make these relatively routine corrections.

***Calibration: MSC Fourier Transform Spectrometer***

The MSC FTS instrument also follows the general comments for solar occultation above. It will also be calibrated in the University of Toronto facilities where its performance can be more readily assessed. We hope that we will have access to the test systems use for the SCISAT project which include appropriate sources, etc. for the operation.

***Calibration: CRESTech/York University AOTF Spectrometer***

The AOTF spectrometer employs a simple photomultiplier tube (PMT) as its detector. Pre-flight calibration of the instrument will include responsivity as a function of wavelength, linearity over the full dynamic range and dark current measurements. Various filters may be used to reduce bright background light or to isolate a wavelength region while observing a particular species. The minimum filter bandpass is 5 nm. Each filter will be fully characterized before flight. The optical system uses a simple reflecting telescope, filters, the AOTF device and the PMT detector. All these elements are not expected to change or change very slowly so that pre-flight calibration will provide accurate characterization of the system.

The acousto-optic tunable filter exhibits a variable bandpass during a wavelength scan, however, this effect can be well characterized and is observed to be repeatable with each frequency scan. An acoustic transducer bonded to the $MgF_2$ crystal is driven by a radio frequency source, in the range 90 to 160 MHz. This sends acoustic waves through the crystal which interfere with light passing through the crystal, thus defining the wavelength that is transmitted. The wavelength selected depends directly on the RF drive frequency. The frequency to wavelength relation has been fully characterized in the laboratory and will be checked using the on-board mercury calibration lamp during flight.

The wavelength transmitted by an AOTF device also depends on the temperature of the crystal. The housing containing the AOTF is temperature controlled to 0.1°C which provides a measured wavelength stability of 0.0005 nm. The RF drive frequency-to-wavelength relationship and the temperature dependence will be fully calibrated on the ground before flight. During flight, the on-board mercury lamp will be used to calibrate the wavelength at predefined intervals or on uplink command. DOAS retrievals require very good wavelength knowledge, however, the observed spectra contain many well known lines which can be used to improve the wavelength registration between spectra. The AOTF spectrometer calibrations will be carried out at York University.

***Calibration: Service d'Aéronomie SAOZ Spectrometer***

The spectrometer is first aligned in the laboratory by looking at the location of Fraunhofer solar lines compared to a reference spectrum. During the flight, the alignment of the spectrometer changes due to temperature and pressure variations. The variations are taken into account by the software by stretching and shifting the spectrum (precision ±0.05 pixel or 0.02 nm). After alignment, the actual spectrum is ratioed to a reference spectrum recorded at high altitude and low sun zenith angle (SZA). Absorbing constituents are derived by a differential method, that is by looking at their narrow absorption features after subtraction of the broad spectral variations. The atmospheric attenuation spectrum - logarithm of the above ratio - is correlated to literature cross-sections by a sequential and iterative least squares fit, which provides together a slant column amount and an evaluation of the uncertainty for each measurement.

***Calibration: University of Waterloo ACE-FTS Clone***

The ACE-FTS clone also follows the general comments on solar occultation above. The wavenumber scale is set by using atmospheric molecules with known line positions. Various other corrections (*e.g.*, for HgCdTe detector non-linearity) need to be carried out but these procedures will all be available from the ACE-FTS part of the satellite mission.

***Calibration: Instrument Line-of-Sight Pointing***

Instruments mounted on the pointing-system elevation stage will be initially co-aligned using a laser-level survey with respect to reference mirrors mounted on each instrument and corrected using three-point adjustable instrument mounts. This line-of-sight calibration will then be verified during an occultation ground-test using the sun as a reference and employing the pointing system to track sun motion. Further field tests will be employed to measure pointing system sensor offsets and calibrate the system with respect to magnetic north (in azimuth) and the level horizon plane (in elevation and roll). Lastly, the gondola will be suspended from a 50 m crane in order to perform a hanging test and to set pointing-system control parameters.

## 2.6 Launch Requirements

The launch requirements are simple and are driven by the science goals. Three primary operational modes are defined: ascent, solar occultation, and limb scanning. Solar occultation requires observation of at least one sunrise or sunset at float altitude, while limb scan measurements require several hours during the day at float altitude. The preferred (baseline) flight profile is the same as that for the MANTRA 1998/2000 flights: a night launch at 3 AM, stabilizing at float altitude by 6 AM to allow sunrise occultation measurements, float and limb viewing through the day (for ~13 hours from 7 AM to 8 PM), sunset occultation, and start descent at 10 PM. This provides two solar occultations, when the payload will be positioned to point at and track the sun through sunrise and sunset, as well as a long period at float. Alternative flight profiles, which may be necessitated by ground level wind conditions, are a mid-morning launch with descent the following morning and a mid-afternoon launch also with descent the following morning.

In all cases, the required float time (at least 10 to 12 hours) can only be achieved at turnaround in May or late August without additional down-range tracking. At turnaround, stratospheric winds change direction, from westward to eastward in Spring, and from eastward to westward in Fall. This provides a brief period of sufficiently low winds that the balloon will remain within telemetry range (about 400 km) for a full day of measurements from float altitude. .Fall turnaround is preferred in order to mitigate seasonal effects when comparing the new measurements with the historical Stratoprobe data (many of those flights were carried out at Fall turnaround) and with the MANTRA 1998/2000 data. This is also a period of low variability in the stratosphere when the role of transport is minimized and photochemical control is maximized, thus making it easier to unravel the chemical processes.

## 2.7 Operations

The launch and ground support facilities operated by SIL at Vanscoy meet all the operational requirements for the proposed launch. The University of Denver FTS will provide its own telemetry package. All the other instruments will be fully supported by the existing telemetry and ground support. Payload integration and calibration facilities exist at SIL, the University of Toronto, MSC, and CRESTech. These facilities will be used to calibrate individual instruments and to assemble the final payload. There are no special operational tasks which require new facilities.

As was done quite successfully during MANTRA 2000, as much as possible of the gondola assembly and integration will be done at the University of Toronto, in collaboration with MSC and SIL, in order to minimize launch preparation time required at Vanscoy. After shipment of the instruments to Vanscoy, final instrument preparation and calibration will be completed, in parallel with gondola preparations and payload integration. Prior to the main launch, the following tests will be performed: electrical and RF interference tests; full-up electrical tests with all instruments and telemetry integrated on the gondola, including external and battery power tests; and dynamic and balance tests with the gondola hanging and all instruments installed. A launch dry run will also be undertaken..

Daily forecasts and plots of current winds will be produced using the Canadian Meteorological Centre's global weather forecast model, GEM – global environmental multiscale model [17,18]. This can be used in both global and high-resolution modes to characterize both the surface and stratospheric winds for flight planning. The high-resolution version provides 48-

hour forecasts of the surface and low-altitude winds at 15-km and 35-km horizontal resolution to aid in identifying suitable launch conditions at the surface. The global version of the GEM model with a model top at 10 mb provides 5-day forecasts up to 10 mb. These global GEM forecasts will also be used to calculate balloon trajectories, providing information on the most opportune time to launch by helping to identify the period of stratospheric wind reversal at launch height.

## 2.8 Schedule and Milestones

The project schedule and milestones are outlined in Table 4 below. A more detailed summary of the status of each instrument and the major tasks to be undertaken for the MANTRA 2002 and 2003 flights is given in Table 5, based on discussion elsewhere in this document.

The schedule assumes that both the 2002 and 2003 launches will take place near Fall turnaround; it is possible that one or both of these may be changed to Spring turnaround in order to better co-ordinate with Odin and SCISAT validation activities. The actual date of the launch will depend on the weather conditions, and will be chosen to be as close as possible to turnaround. As Fall turnaround may occur in late August or early September, planning for a launch by mid-August will ensure that the flight systems and payload will be ready in advance. August 15 is the nominal launch date for both 2002 and 2003.

Preparations for the first flight will begin as soon as a contract is awarded by the CSA. A Requirements Review will be held at the start of the contract, nominally on September 1, 2001, just less than one year before the nominal 2002 launch date. This meeting will bring together the project team (the Principal Investigator, Co-Investigators, the industrial partner, the international partners, students, relevant management and technical personnel, and the CSA Project Manager). At this time, the mission definition, design concept, and performance requirements will be established. Trade-offs between the scientific objectives, availability of standard subsystems, costs, and scheduling will be made.

Nine months before the nominal launch date (November 15, 2001), the Preliminary Design Review will be convened to finalize all requirements and review the preliminary design of the payload. A payload weight estimate will be specified to within 30%, the flight profile estimate will be determined, and preliminary science support requirements will be addressed. The primary goal of this meeting will be to update the current status and clearly identify the technical work required for: each instrument, payload integration, and the balloon and launch.

Six months before launch (February 15, 2002), the Critical Design Review will be held, at which point all flight hardware will be given final approval. The payload weight estimate will be specified to within 10%, the flight profile will be updated as needed, and the final science support requirements will be established. The flight support system design, including thermal, mechanical, and electrical components, will be finalized. A Class II Notam will be filed, and any necessary long lead items will be ordered.

A Flight Readiness Review will be held six weeks prior to launch (June 15, 2002). At this time, the flight profile will be finalized, the flight systems hardware will have been built and tested, and the ground-station will be fully operational. Two weeks before the nominal launch date (August 1, 2002), the instruments will be shipped to the launch site at Vanscoy and payload integration will begin. Launch will take place as close as possible to August 15, 2002, as determined by the prevailing wind conditions at the launch site.

Once the launch and recovery have been completed, the instruments will be returned to their respective institutions. A post-flight data and reports will be submitted by October 1, 2002.

The First Data Workshop will be organized for three months after launch (November 15, 2002), at which time preliminary data and results will be presented by the members of the Science Team. More detailed results of the data analysis and scientific interpretation will be presented at a Second Data Workshop, to be held ten months after launch (June 15, 2003). Further dissemination of the results to the wider atmospheric science community will take place at national and international scientific meetings.

If a second balloon flight is approved, to be launched one year after the first flight, a reduced version of the above schedule will be followed. The Requirements Review will not be required, as the instrument payload will remain largely the same. The Preliminary Design Review will be held nine months before launch, and will coincide with the First Data Workshop (November 15, 2002). The Critical Design Review will again be held six months before launch (February 15, 2003), at which point, any changes arising from lessons learned during the first flight will be finalized. The Flight Readiness Review will occur at the same time as the Second Data Workshop, two months before the second launch (June 15, 2003), and shipping and integration will begin two weeks before launch (August 1, 2003). Launch will again be scheduled take place as close as possible to August 15. The schedule for post-flight data, reports, and workshops will follow the same pattern as for the first balloon flight. CSA/NSERC support will end on August 31, 2004, three years after the start of the project.

Table 4. Program schedule and milestones for the MANTRA 2002/2003 balloon flights.

| MILESTONE | TIMING | NOMINAL DATE |
|---|---|---|
| **First Balloon Flight:** | | |
| Start of CSA/NSERC support | launch – 11.5 months | September 1, 2001 |
| Requirements Review | launch – 11.5 months | September 1, 2001 |
| Preliminary Design Review | launch – 9 months | November 15, 2001 |
| Critical Design Review | launch – 6 months | February 15, 2002 |
| Flight Readiness Review | launch – 2 months | June 15, 2002 |
| All instruments to U of Toronto for integration. | launch – 1 month | July 15, 2002 |
| Ship to Vanscoy | launch – 3 weeks | July 24, 2002 |
| Science team arrival at Vanscoy | launch – 2 weeks | August 1, 2002 |
| On site integration | launch – 1 week | August 8, 2002 |
| Instrument line-of-sight calibrations | launch – 6 days | August 9, 2002 |
| Hanging test | launch – 5 days | August 10, 2002 |
| Launch dry run | launch – 3 days | August 12, 2002 |
| Balloon launch | | August 15, 2002 |
| Post-flight report | launch + 1.5 months | October 1, 2002 |
| First Data Workshop | launch + 3 months | November 15, 2002 |
| Second Data Workshop | launch + 10 months | June 15, 2003 |
| **Second Balloon Flight:** | | |
| Preliminary Design Review | launch – 9 months | November 15, 2002 |
| Critical Design Review | launch - 6 months | February 15, 2003 |
| Flight Readiness Review | launch - 2 months | June 15, 2003 |

| | | |
|---|---|---|
| Arrival at launch site | launch - 2 weeks | August 1, 2003 |
| Balloon launch | | August 15, 2003 |
| Post-flight report | launch + 1.5 months | October 1, 2003 |
| Third Data Workshop | launch + 3 months | November 15, 2003 |
| Fourth Data Workshop | launch + 10 months | June 15, 2004 |
| End of CSA/NSERC support | | August 31, 2004 |

Table 5. Instrument and payload status and tasks to be undertaken for the MANTRA 2002/2003 flights.

| COMPONENT | STATUS | TASKS | RESPONSIBILITY |
|---|---|---|---|
| **Flight Instruments for 2002:** | | | |
| MSC emission radiometers | Flew on MANTRA 1998/2000 – essentially flight ready | Minor refurbishment | U of Toronto |
| MSC SPS | Flew on MANTRA 1998/2000 – essentially flight ready | Minor refurbishment | U of Toronto and MSC |
| U of Denver FTS | Flew on MANTRA 1998 – essentially flight ready | Minor refurbishment | U of Denver |
| Service d'Aéronomie SAOZ | Essentially flight ready | Payload integration | Service d'Aéronomie |
| MSC ozonesonde | Flight ready | On site preparation | MSC |
| Aerosol sonde | Flew on MANTRA 1998/2000 – essentially flight ready | Minor refurbishment | U of Wyoming for SIL |
| MAESTRO clone | Under construction by EMS Technologies | Build, flight preparation, payload integration | MSC and EMS Technologies |
| MSC FTS | Has previously flown, needs repair | Repair/upgrade, flight preparation, payload integration | U of Toronto and MSC |
| MSC OH spectrometer | Flew on MANTRA 1998 – needs repair | Repair/upgrade, flight preparation | York U, MSC, and U of Toronto |
| **Ground-Based Instruments for 2002:** | | | |
| MSC Brewer spectrophotometer | Deployed during MANTRA 1998/2000 – operational | No work needed | MSC |

| | | | |
|---|---|---|---|
| U of Toronto zenith-sky grating spectrometer | Deployed during MANTRA 1998/2000 – operational | No work needed (minor improvements to hardware and software ongoing) | U of Toronto |
| CRESTech/York U AOTF spectrometer | Deployed on ground during MANTRA 2000 – operational | No work needed (minor improvements ongoing) | York U |
| **Additional Systems for 2002:** | | | |
| Pointing control system | Flew on MANTRA 2000 – will be upgraded | Add an additional azimuth pivot in the flight train, modify software, add mirrors | U of Toronto |
| Payload support systems (gondola, command and telemetry package, power distribution system, batteries, ballast, crush pads and floatation, flight train, parachute and recovery package) | Most flew on MANTRA 1998/2000 – essentially flight ready | Assembly of gondola, minor refurbishment and possible upgrade of some components | Scientific Instrumentation Limited |
| Ground support systems (S-Band receivers, data recorders, uplink commanding) | Used during MANTRA 1998/2000 – essentially flight ready | Minor refurbishment and possible upgrade of some components | Scientific Instrumentation Limited |
| **Additional Flight Instruments for 2003:** | | | |
| U of Waterloo ACE-FTS clone | To be built by ABB Bomem | Build, flight preparation, payload integration | U of Waterloo and ABB Bomem |
| CRESTech/York U AOTF spectrometer | Deployed on ground during MANTRA 2000 – operational | Integration with new pointing control system | York U |

## 2.9 Risk Analysis

### 2.9.1 Technical Risks

There are four major technical risks associated with this project: the instruments, the launch and descent, the balloon and termination mechanism, and the support systems (including tracking and data recovery).

The instruments are a low-risk item. At the time of writing, all of the primary flight instruments and nearly all of the secondary instruments have been designed and built, and most have been flown on previous balloon missions. The exceptions are the MAESTRO and ACE-FTS clones which are under construction. Some refurbishment and adaptation of the instrumentation is necessary to integrate all the systems together, but this poses a very minor risk to the mission success as the electronic modifications are relatively simple and can be thoroughly tested before launch. The necessary processes and procedures to be followed to permit reliable operation in the expected environment are well-known to both the industrial partner and the Science Team. All instruments will be individually tested, including vacuum testing, before integration and then again as part of a full-up integration test. Where possible, duplicates of all key instrument component will be taken to Vanscoy; this policy proved to be very useful during MANTRA 1998/2000, particularly for the SPS and emission radiometers.

The payload launch and descent are the most serious risk items. Launch failure is usually traceable to balloon problems or launch conditions. The first prerequisite is an experienced launch contractor such as Scientific Instrumentation Limited. By launching in the most favourable meteorological conditions available, the launch condition risk can be minimized. The choice of launch site and launch season are major factors in this mitigation process; the choices made for MANTRA 2002/2003 represent the lowest risks possible. In addition, availability of a backup balloon will enable a second launch attempt if the first fails. Payload descent poses a risk to the instruments, as total loss of the payload can result from parachute failure and from an inappropriate landing site (*e.g.*, a lake). Risk to the mission will be minimized by transmitting all data to ground during the flight, so that data recovery is not dependent on instrument recovery. The potential for a problem during descent will be reduced by the careful choice of when to trigger the separation of the payload and parachute from the balloon, so that the payload lands in a remote location away from water.

Balloon problems normally cause a lower than required altitude or shorter than desired duration rather than a catastrophic failure. If it is determined that these problems prejudice the scientific success of the mission, then it is proposed to refly on a short turnaround with the backup balloon. This will necessarily increase costs, but represents the only way in which this risk can be lowered. It should be stated that stratospheric balloons of this broad type have been flown by various groups for more than twenty-five years with great success, so that even this is a small risk.

A recurrence of the failure of the termination device that occurred on the MANTRA 1998 flight is considered unlikely, as the cause of that failure has been identified and appropriate actions have been taken and successfully tested during the MANTRA 2000 flight. Another potential risk is the failure of the balloon's helium valve, preventing the release of helium and therefore preventing the balloon descent. During MANTRA 1998, it appeared that the rip cord plastic (attached to the inside of the balloon) came loose and covered the valve opening. This may have been due to the use of inappropriate tape to hold the plastic in place, or to static build-up during the launch. In future, modification of the balloon destruct device may be needed to ensure that the plastic cannot cover the valve opening. No balloon valve problems were encountered during MANTRA 2000.

The ground support systems at Vanscoy are aging, and therefore have some risk associated with them. During MANTRA 2000, despite verifying all instrument telemetry immediately before launch, problems were encountered with the telemetry, leading to higher than expected data dropouts. This was apparently caused by damage to the onboard antenna (of circa 1975 vintage), and could be avoided in future by adding onboard storage capability and automation to reduce communication reliance, upgrading to a steerable onboard antenna, and adding redundancy in the telemetry system. The uplink command was also lost seven hours into the MANTRA 2000 flight due to failure of the onboard receiver. Such transceiver failures are not uncommon, but their consequences may be avoided by upgrading the onboard receiver and adding a backup. In addition, it should be possible to extend the use of the pointing system's automated event handler to schedule data-collection activities autonomously. Future flights of the system will include a modification to switch the pointing-system operation into an autonomous mode if a watchdog timer is not reset by ground command. Implementing this along with on-board data collection will enable the pointing system to command instrument data acquisition and to gather data during periods of complete communication blackout.

### 2.9.2 Schedule Risks

Risks to the schedule due to instrument and support system delays are low, given the current near-flight-ready status of most of these components. The schedules for both the MANTRA 1998 and 2000 campaigns were met and the balloons launched on time, so a similar situation is anticipated for the two proposed flights. The greatest risk to the schedule is the status of the satellite missions that MANTRA 2002/2003 will be validating. Odin is now on orbit, and so the 2002 balloon launch should proceed on schedule. SCISAT is due for launch in June 2002; this could slip by almost a year before having an impact on the proposed 2003 balloon launch. If SCISAT launch slips beyond mid 2003, then the balloon launch will have to be delayed if the objective of participating in ACE-FTS and MAESTRO validation is to proceed.

### 2.9.3 Cost Risks

The risk of the mission going significantly over budget is considered small. Again, the experience gained during MANTRA 1998/2000 enables an accurate estimate of the mission costs. The biggest cost risk is probably that associated with payload support; this is the only item that was over budget during the previous two flights.

## 2.10 Management Plan

Each of the scientific instruments, their deployment, calibration, data analysis, *etc.*, will be the responsibility of one or more members of the Science Team. As Principal Investigator, Prof. Strong will oversee the MANTRA 2002/2003 project, liasing between the various participants, and ensuring that the project achieves its scientific and technical objectives as described in this document. A project manager will be employed to assist with co-ordination of activities. In addition to her general responsibilities for the project, Prof. Strong will have primary responsibility for deployment of the University of Toronto zenith-sky spectrometer and subsequent data analysis. She will also be involved in collaborating with team members from MSC and the University of Toronto in the flight preparation of the MSC emission radiometers, SunPhotoSpectrometer, OH spectrometer, and FTS.

Dr. McElroy, who is the Environment Canada Lead Scientist for the project, will have primary responsibility for most of the MSC instruments: the emission radiometers, the SPS, the MAESTRO clone, the OH spectrometer, the Brewer spectrophotometer, and the sondes, although other co-investigators will also participate in the calibration of these instruments and the subsequent data analysis and interpretation. Dr. Quine will oversee work with the emission radiometers and with the pointing control system, Prof. Drummond will be involved in work with the SPS and the MAESTRO clone, and Prof. Strong and Dr. Solheim will collaborate on the OH spectrometer.

Dr. Fast will have primary responsibility for the MSC FTS, but refurbishment, operation, and data analysis for this instrument will be carried out in collaboration with Profs. Drummond and Strong. Dr. Solheim will have sole responsibility for the CRESTech/York University AOTF spectrometer, and Prof. Bernath for the University of Waterloo ACE-FTS clone. Prof. Bernath and Dr. McElroy will provide input to the validation activities undertaken for ACE-FTS and MAESTRO, respectively. Dr. Fogal and Prof. Murcray will be in charge of the University of Denver FTS, and Dr. Goutail will be responsible for the Service d'Aéronomie SAOZ spectrometer. Prof. McConnell and Prof. Shepherd will advise on scientific issues that arise and that may have implications for the later modelling and interpretation of the data, and will lead the modelling effort.

As all of the instruments are either assembled or under construction, no instrument development will be required. The major pre-launch tasks to be completed are improvements to the pointing control system, refurbishment of the MSC FTS, construction of the MAESTRO clone and ACE-FTS clones (the latter two activities are being undertaken as part of other projects). The principal pre-launch activity relating to the instruments will be the calibration, and responsibility for this task will lie with the team members as discussed in the previous paragraph.

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