Scientific, Technical and Organizational Summary for the new Atmospheric Research Station in Mérida, Venezuela

Mérida Atmospheric Research Station, MARS

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Executive Summary

Following the Montreal Protocol it is of paramount importance to monitor the ozone loss carefully in close connection with the chlorine loading of the stratosphere in order to prove or disprove our prediction of a recovery of the ozone layer. In this respect a global network of monitoring stations is particularly important in order to observe and understand the state and changes in stratospheric composition.

The most important elements with respect to changes in stratospheric composition needing careful and continuous monitoring, can be summarized as follows:

1. Long and short term trends in ozone amount and variations in ozone profile.

2. Variation in ozone depleting substances, in particular of anthropogenic origin.

Our present understanding of stratospheric chemistry is well advanced, however major issues are still not entirely solved, such as the measured ozone loss being larger than predicted by models, or the exact heterogeneous processes releasing active chlorine.

To continuously and globally monitor the state of the global stratosphere the Network for the Detection of Stratospheric Change (NDSC) was established in the early nineties. This network comprises presently only operational stations at polar and mid latitudes, a primary station operating below 10^{o} latitude is urgently needed. MARS will be a essential contribution to cover this scientific demand.

The tropical region is being increasingly recognized as playing a vital role in the evolution of the stratosphere and has been relatively little studied. A number of the relevant chemical, dynamical and radiative processes are poorly understood. For example, most air enters the stratosphere through the tropical tropopause but the details of this process still remain uncertain. The budget and trends of stratospheric water vapour (a topic of major current interest and uncertainty) and other source gases depend on this exchange. The details of the role in radiative transfer and chemistry of cirrus, ice and other particles would also need to be a major focus. It has been suggested that very short-lived ozone destroying chemicals (currently not regulated under the Montreal Protocol) can be lifted rapidly to the upper troposphere and lower stratosphere following tropical deep convection and so contribute to lower stratospheric ozone depletion. Atmospheric measurements of these chemicals are still necessary to test this suggestion.

The instruments aboard the ENVISAT satellite, launched on 1 March 2002, require validation by, among others, ground stations distributed over the earth's surface. In particular the need for validation of SCIAMACHY essentially stimulated the start of the MARS activities and will be a major assignment for the initial years of operation. The primary scientific objective of SCIAMACHY is the global measurement of various trace gases in the troposphere and stratosphere, which are retrieved from the solar irradiance and earth radiance spectra. The large wavelength is also ideally suited for the determination of aerosols and clouds.

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Introduction

By the end of the eighties it became clear that a global network to monitor the state of the stratosphere was urgently needed to allow to assess the state of the stratosphere with respect to its changing composition, and to understand the importance of anthropogenic effects on the stratosphere, and in particular to distinguish between natural and man made changes. The rapid increase of the "ozone hole" in Antarctica triggered a large scientific interest to investigate the complicated chemical and dynamical processes in the atmosphere. Therefore in 1991 the Network for the Detection of Stratospheric Change (NDSC) has been founded [1], the goal was to establish a world wide net of well equipped stations to monitor the stratosphere, using a complement of sensors to get the most accurate and reliable data sets. The latter required a very careful selection of observing methods and a strict protocol ensuring the comparability of data collected at different stations.

In the nineties the main interest was directed to both Polar Regions, where the largest ozone destruction has been observed. The very large effort, both in modeling and measurement activities has resulted in a much better understanding of the extremely complicated processes in the stratosphere. However it is important to note that there are still unexplained effects, e.g. our models today can not explain the total global ozone loss measured over the last 20 years, still the measured loss is some 20% larger than models would predict. However the NDSC has played a key role in getting the necessary data to develop models and also to test model predictions.

Nevertheless, even there are still shortcomings in our present understanding, the scientific effort to explain the strong ozone decrease was very successful leading to political decisions to stop to a large extent the production of ozone depleting substances such as CFC's. Measurements today show a reduction of CFC's in the troposphere as expected from this ban. However because of the long time delay between the release of these compounds at the Earth surface and their eventual effects in the stratosphere, we cannot expect to see a clear indication of a recovery of the ozone layer before 2010. A complete recovery will not take place until after 2050. However as mentioned above our models on which these predictions are based, have still deficiencies making these predictions questionable to say the least.

Major goals of NDSC can be summarized as follows:

- To make the observations, through which changes in the physical and chemical state of the stratosphere can be determined and understood.
- To make the earliest possible identification of changes in the ozone layer and to discern the cause of the changes.
- To provide an independent calibration of satellite sensors of the atmosphere.
- To obtain the data that can be used to test and improve multi-dimensional stratospheric chemical and dynamical models.

[1] For more information on NDSC see http://www.ndsc.ws

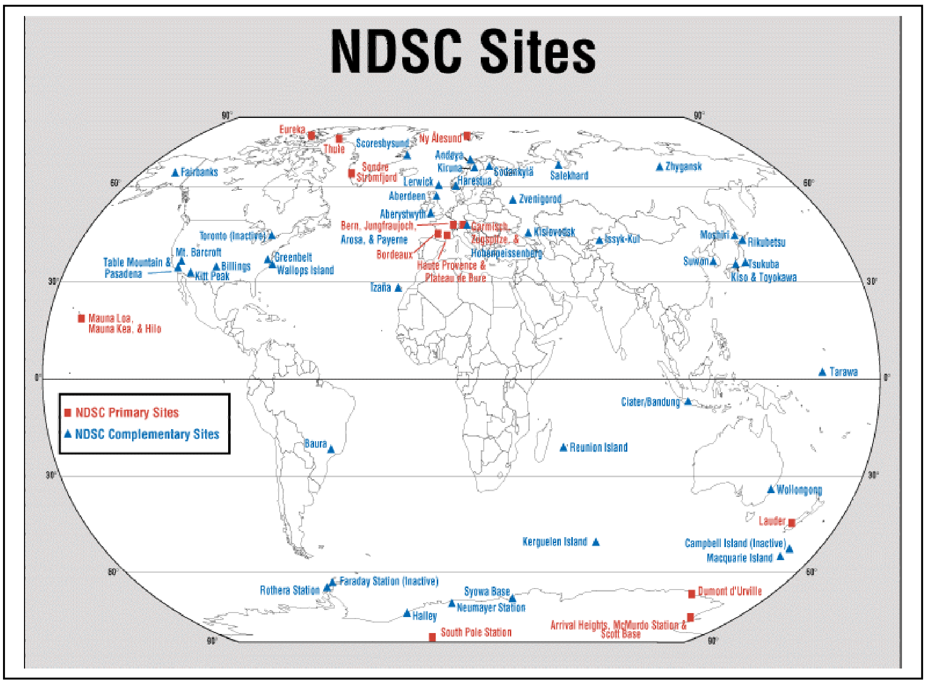
From what has been said so far it is clear that a continuation of NDSC is warranted. In fact NDSC should be expanded to comprise the whole globe, and not only concentrate on the polar and mid latitude regions. Therefore a tropical station at latitude below 10 degrees has been the subject of discussions since several years in the NDSC steering committee. In order to obtain all the required data at a NDSC station a whole range of instruments is required. A major technique is ground based remote sensing using electromagnetic radiation to probe the atmosphere. These sensors cover the electromagnetic spectrum from microwaves (wavelength <1.5 cm) to ultraviolet light. In consequence of such a large variety of instruments there are the very different requirements placed on the particular characteristics of a potential NDSC site.

However when selecting a site for a NDSC station also other considerations are important, such as accessibility, available infrastructure and cooperation with local scientists. These factors together with the requirements placed on the site by the sensors, have clearly shown that Mérida is one, and possible the best suited NDSC site in the tropics. More technical details are given in the following sections.

The present NDSC

The Network for the Detection for Stratospheric Change (NDSC) is a set of high-quality remote-sounding research stations for observing and understanding the physical and chemical state of the stratosphere. Ozone and key ozone-related chemical compounds and parameters are targeted for measurement. The NDSC is a major component of the international upper atmosphere research effort and has been endorsed by national and international scientific agencies, including the International Ozone Commission, the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WMO).

Below see a figure showing the present station net.



A map of the presently operational primary NDSC stations (red squares) and complementary stations, note the missing primary stations in the tropics. Only the primary stations are sites with a complete set of instruments required to collect all the required data. Secondary stations provide only limited data sets, and are not subjected to the rigorous protocol for data reliability.

ENVISAT-Validation

From the beginning of the project, Merida was proposed as a location for the validation of specific ENVISAT instruments. Substancial founds haven been made available by the Federal Ministry of Education and Research.

SCIAMACHY [2] (Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY) is a space based spectrometer onbord Envisat designed to measure sunlight transmitted, reflected and scattered by the Earth atmosphere or surface. SCIAMACHY measures simultaneously and contiguously radiation in the wavelength range from 240 to 1750 nm at moderate spectral resolution (0.2 nm - 1.5 nm). In addition it measures simultaneously in two short infrared bands around 2.0 µm and 2.3 µm. The absorption, reflection and scattering characteristics of the atmosphere are determined by measuring the up welling earthshine radiance observed in nadir, limb and occultation geometry and the extraterrestrial solar irradiance. Up welling radiance can be inverted to provide information about the amounts and distribution of important atmospheric constituents.

The SCIAMACHY project was conceived to improve our knowledge and understanding of a variety of issues of importance for the chemistry and physics of the Earth atmosphere (troposphere, stratosphere and mesosphere) and potential changes resulting from either anthropogenic behaviour or natural phenomena such as:

- tropospheric pollution arising from industrial activity and biomass burning;
- troposphere - stratosphere exchange processes;
- stratospheric ozone chemistry: the emphasis being on the understanding of the
- ozone depletion in polar regions and at mid-latitudes;
- special events such as volcanic eruptions, solar variability and related regional and
- global phenomena.

SCIAMACHY measurements provide amounts and/or distribution of O3, BrO, OClO, ClO, SO2, H2CO, NO2, CO, CO2, CH4, H2O, N2O, p, T, aerosol, radiation, cloud cover and cloud top height from atmospheric measurements in nadir, limb and occultation geometry. From the Limb and Solar/Lunar Occultation atmospheric observations vertical distributions of the atmospheric trace constituents are derived. This provides information about the stratospheric and upper tropospheric composition, yielding important information about stratospheric chemistry and physics as well as exchange between the stratosphere and troposphere. The combination of the near simultaneous limb and nadir observations yields unique information about tropospheric and lower stratospheric constituents (gases, aerosol and cloud).

SCIAMACHY is one of a limited number of instruments which is able to detect tropospheric column amounts of O3, NO2, CO, CH4, H2O, N2O, SO2 and H2CO down to the planetary boundary layer under cloud free conditions. Additionally, accurate profiles of atmospheric constituents having a relatively high vertical resolution result from the solar and lunar occultation measurements.

[2] for more information see http://envisat.esa.int/ or http://www.iup.physik.uni-bremen.de/sciamachy/

Scientific and technical summary of sensors to be deployed at Mérida

As mentioned earlier the very wide spectrum of sensors required for a NDSC station also places different constraints on the site. Presently four different types of sensors are planned for MARS. All sensors are of the remote sensing type, making use of different portions of the electromagnetic spectrum. We can list the sensor according to their wavelength range. They allow measuring key constituents and aerosols. The latter is a key element to understand the heterogeneous chemistry of particular importance with respect to chlorine activation.

- DOAS, Differential Optical Absorption Spectrometer. This instrument is measuring solar light scattered in the atmosphere in the ultraviolet and visible spectral range.

- Microwave Radiometer MWR. A MWR measures thermal emission from rotational transitions of atmospheric molecules at wavelength from the far infrared to microwaves.

A LIDAR and FTIR will be installed at the CIDA observatory site, where road access allows the deployment of heavy equipment, by the Alfred-Wegener-Institut, Bremerhaven, Germany. The science from both installations will be analyzed in a concerted effort.

- LIDAR, Light Detection and Ranging. A LIDAR operates similar to RADAR, using short light pulses from the near infrared to the ultraviolet, and measuring the signal backscattered by atmospheric molecules.

- FTIR, Fourier Transform Infrared Spectrometer. The FTIR measures solar or lunar light partly absorbed in a characteristic way in the atmosphere in the wavelength infrared spectral region.

In addition to the remote sensing activities focussing to the stratosphere mentioned above, the following troposphere related research projects will be carried out by the Universitad de Los Andes using the same high mountain facilities:

- SiBILA Project (Bioclimatological Information System for the Sur del Lago and Merida Region). An interinstitutional project of several research organisations: ULA -Institute for Environmental and Ecological Sciences (ICAE), National Center for Scientific Calculus (CeCalcULA), ULA .Geophysical Laboratory (LaGULA) and National Institute for Agricultural Research (INIA). One of the objectives of this project is to deploy a telemetric meteorological station (the highest in Venezuela) to monitor precipitation, air temperature and humidity, soil temperature, solar radiation, atmospheric pressure and wind. The meteorological data with data from other telemetric stations will be processed to generate daily weather maps over the Mérida and surrounding areas, and will be also use as inputs to models to evaluate adverse atmospheric conditions that may put at risk the Mérida region.

- Tropospheric Aerosol Characterisation for the Andean Region and its Implications for Air Quality and Energy Balance. An Integrating Nephelometer, a Particulate Concentration Measuring Device and an Aethalometer will be installed to determine the physical characteristics and chemical composition of the background aerosols and to know the implications for the air quality and energy balance, at this tropical situation. These data will be useful for research in climate change in the tropics.

The following sections will give details on the performance, techniques and site requirements for the sensors for the upper atmosphere to be deployed at Pico Espejo.

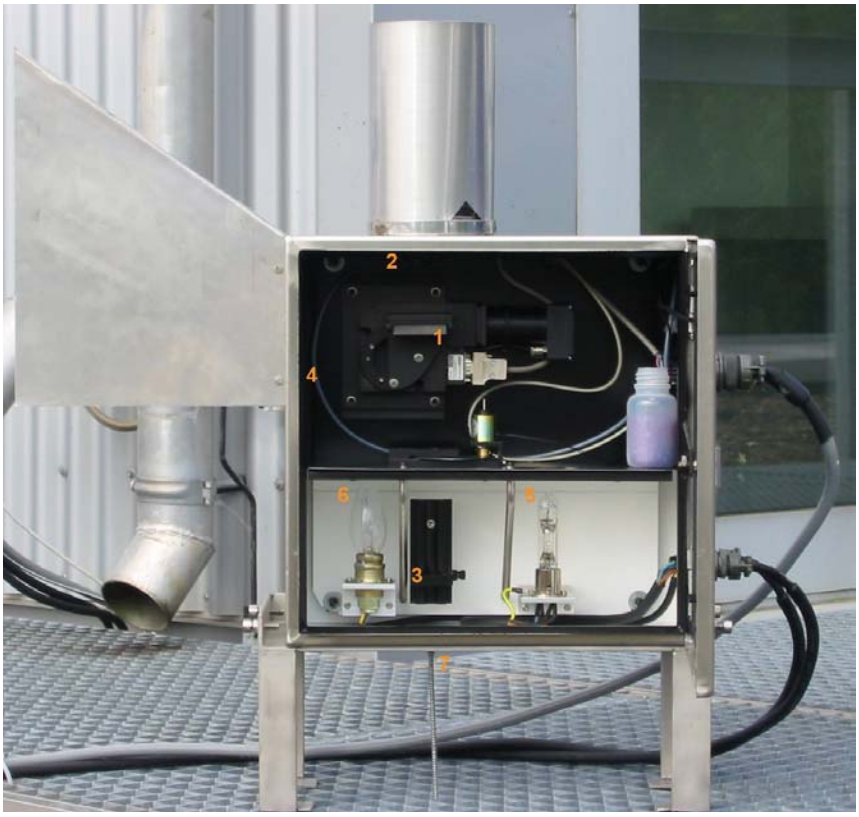
DOAS

Measuring the absorption of visible and near-ultraviolet sunlight scattered in the atmosphere can perform quasi-continuous observations of several atmospheric species. The determination of column abundance of molecules such as ozone, NO_2, OClO, IO, BrO, HCHO, H_2O and others is possible. These are key compounds in both the troposphere and the stratosphere, and several of them are not measurable by other means. The data retrieval will be performed by combined radiative transfer modeling and the well-known Differential Optical Absorption Spectroscopy (DOAS) method.

These data can be used for atmospheric research and for the validation of satellite data for example from the GOME instrument onboard the ERS-2 satellite and the SCIAMACHY instrument, which is onboard of the ENVISAT satellite launched on 1. March 2002. Both instruments are DOAS spectrometers of the same type as those operated by the IUP in Bremen, Nairobi, and Ny-Ålesund and the one described here and were developed by the same group. The comparison of the data sets will allow (i) the determination of long-term instrumental trends in the satellite data and (ii) to extend the data interpretation from a local to a hemispheric point of view. Furthermore the data set can be used in climate research and air pollution monitoring.

The DOAS instrument planned for Mérida has a strong connection to a similar one located in Surinam about 1700 km away on nearly the same latitude, which will be operated by the IUP Heidelberg. This site is located only 20 m above sea level and retrieved trace gas columns will be strongly influenced by anthropogenic and biogenic emissions into the troposphere. Consequently the main objective of the Merida instrument should be to monitor the stratosphere and the free troposphere. For this reason and because of the more favorable meteorological conditions the high altitude site on Pico Espejo is preferred for the DOAS instrument.

Brief description of the experiment: Sunlight scattered from the sky is collected by a telescope and transmitted to a Czerny-Turner spectrograph via a depolarizing quartz-fiber bundle. A charge coupled device (CCD) is used as a detector allowing simultaneous measurements over the complete wavelength range. The pointing of the telescope is alternating between zenith and horizon, which yield profile information of the above-mentioned absorbers under good weather conditions. The



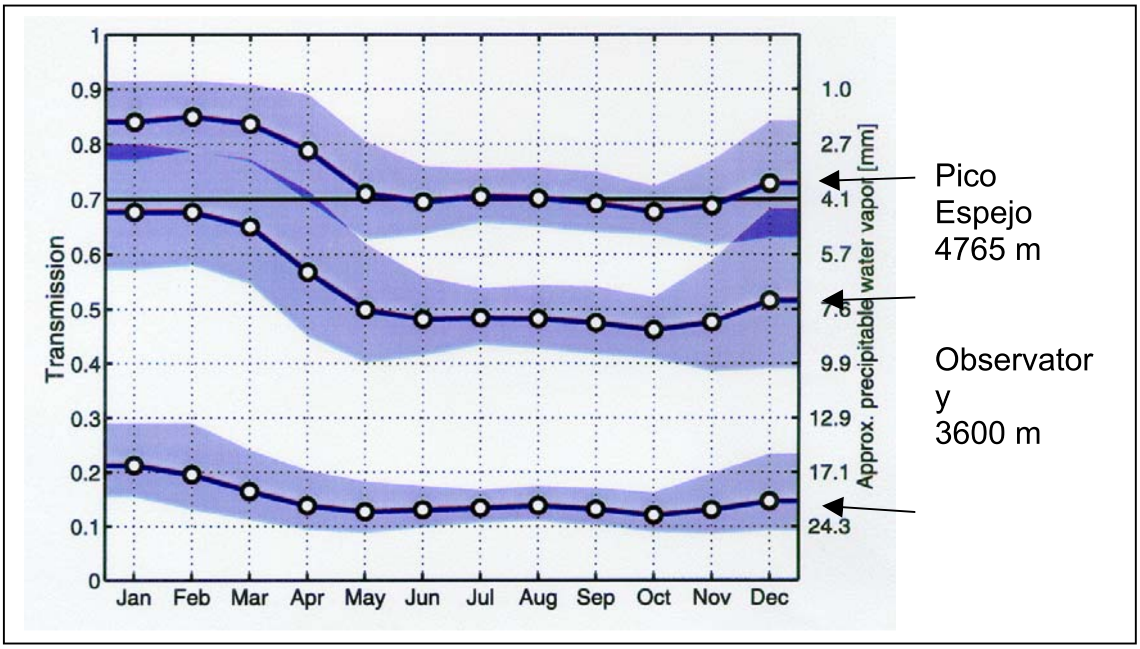
Setup of the DOAS telescope:
1 mirror
2 quartz glass window zenith
3 lens
4 quartz glass window off axis
5 HgCd lamp
6 tungsten lamp
7 quartz fibre

observation in different lines of sight is realized by a mirror (1) fixed on a rotation stage moved by a computer controlled servomotor. In zenith sky mode the lens (3) is directly illuminated. In the off axis mode the mirror is moved into the light path and reflects the collected light to the lens. The instrumental setup of the telescope is shown in the figure.

Microwave Radiometry

A Microwave Radiometer (MWR) measures thermal emission from the target species, and this sensor is therefore independent of solar illumination and can measure equally well at day- and nighttime. Furthermore the rather long wavelength used by these instruments makes MWR less sensitive to meteorological effects like cloud cover. However it is important to note that depending on the exact wavelength being used, meteorological conditions can be a limiting factor for this sensor, e.g. for a MWR operating at a wavelength < 3 mm, clouds and in particular precipitation can change the observing conditions significantly, restricting the possible integration times. Furthermore tropospheric water vapor is a very strong absorber at shorter mm wavelengths and in the sub-mm range. Therefore it is mandatory to operate the sensor at high altitudes.

When selecting the frequency range of observation it is important to consider the desired frequency range covering the emission lines of interest, and analyzing the seeing conditions at the envisaged site with respect to water vapor content. Since the lines of interest are best observed in a band between 250 and 300 GHz (approximately 1 mm wavelength) model calculations have been performed to decide where such measurements in the tropics are feasible. The calculations make use of the statistical data for tropospheric water vapor provided by NCEP (US National Center for Environmental Prediction) for the time span 1958-1997. The result is shown in the figure below.



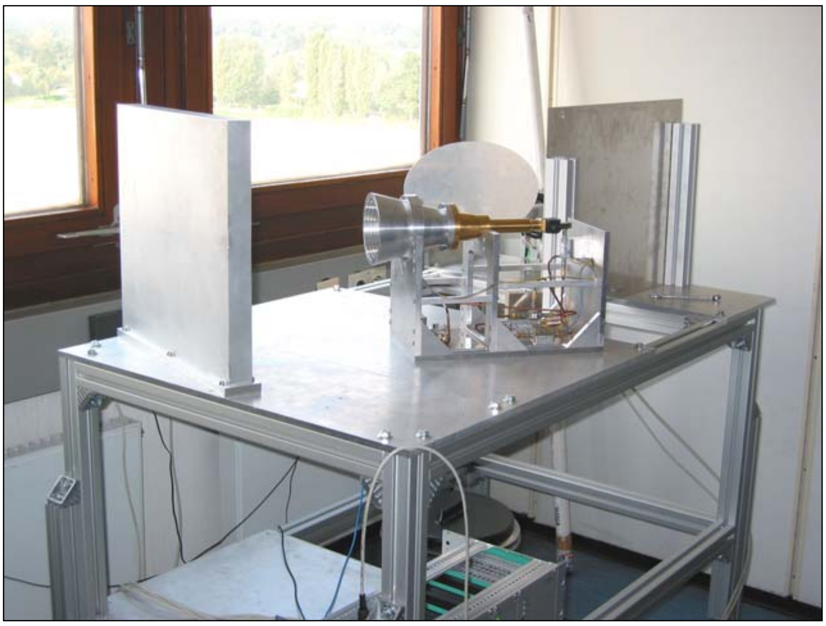
Successful measurements are feasible for a transmission > 0.7. Therefore it is obvious from the figure shown above that for year round operation only the high altitude site on Pico Espejo is suitable.

Further model calculations allow to estimate the accuracies achieved by sensors on Pico Espejo, see Table below.

Constituent	**Alt. range [km]**	**Precision**	**Accuracy**
H_2O (WARAM 2)	20 - 55	0.3 ppm	0.5 ppm
O_3 (MIRA 2)	15 – 55	0.3 ppm	0.5 ppm
ClO (MIRA 2)	17 – 45	0.2 ppb	0.4 ppb
HNO_3 (MIRA 2)	17 – 45	0.5 ppb	1 ppb
N_2O (MIRA 2)	17 – 45	30 ppb	50 ppb

Microwave radiometry on Pico Espejo is a joint venture of the Forschungszentrum Karlsruhe and the University of Bremen. The MIllimeter-wave RAdiometer MIRA 2 has been developed at the Forschungszentrum Karlsruhe and is well validated and tested during several arctic measurement campaigns since 1996. The WAter vapor Radiometer for Atmospheric Measure-ments WARAM 2 developed by the University of Bremen is based on a similar instrument in operation at the primary arctic NDSC station at Ny-Ålesund, Svalbard. Both radiometers will share the acousto-optical spectrometer and the PC control.

The MIllimeter-wave Radiometer MIRA 2 (in the right rack) covers the frequency range 268-280 GHz and can provide vmr-profiles of Ozone, ClO, N_2O and HNO_3 between 17-55 km. In addition from the measured spectra, the total column amount of water vapor can be derived. Both radiometers share the acousto-optical spectrometer and the PC for control and data accumulation in the left rack.



The WAter vapor Radiometer for Atmospheric Measurements WARAM 2 observes the H_2O line at 22 GHz and will provide vmr-profiles between 25-55 km.

Description of the Mérida site

Based on the various requirements of the sensors different sites in or near Mérida have been selected. It is the unique feature of Mérida that for each sensor a nearly ideal location near the city of Mérida can be found.

Map of the Mérida area with the 2 major locations for the instrument deployment, DOAS, MIRA-2 and WARAM at Pico Espejo (marked in blue), and LIDAR and FTIR at the Centro de Investigaciones de Astronomía, CIDA (marked in black). In read the campus of the ULA in Mérida.

On Pico Espejo the instruments will be located in a small building jointly owned by the Venezuelan Airforce and the Universidad de Los Andes. The Figures below give an impression of this site at an altitude of 4765 m. By end of 2001, the Airforce expressed their missing interest in future use of the building and ULA decided to rebuild the station.

The reconstruction of the building finally started in February 2002. Visits in April and August 2002 showed, that in spite of difficult weather conditions at this high altitude construction site continuous progress was achieved, and in August 2002 reconstruction work has been completed.

East side of the MARS building with the entrance door on the right. The microwave instruments use the completely unobscured view toward north through the right wall (in shadow).

MARS building with the cable car station and Pico Bolivar (5009 m) in the background. Pictures from Aug. 2002.

The local cooperation in Mérida includes the following organizations: The *Universidad de los Andes* and in particular the technical and scientific collaboration with the *Facultad de Ciencias*. For the logistics at Pico Espejo we will depend on the support by the *Teleférico de Mérida.*

Intensive talks with representatives from the *Universidad de los Andes* (ULA) have already taken place. In the meantime an Agreement of Cooperation has been reached between ULA and the two German [3] institutions involved in this project. Furthermore an exchange of personnel between the University of Bremen and ULA is also planned in order to allow ULA members to operate the DOAS, MIRA-2 and WARAM sensors, and to facilitate the scientific activities at the station. It is the expressed goal of all involved parties to establish an intensive cooperation to the benefit of all participating organizations. In close collaboration with local authorities the duty-free transfer of the necessary scientific equipment is envisaged.

Status

The reconstruction and modification work at the station building on Pico Espejo has been completed. A first part of the technical equipment already arrived at Mérida, the rest will be sent in September as soon as customs clearance can be achieved. The measurement instruments for MARS are ready to be sent to Mérida as soon as customs authorities agree to a duty-free transfer. The region of Merida is privileged by national law since 1995 for custom-free importation for cultural, technological and scientific purposes.

Appendix:

More Information on the participating institutes can be found in the appropriate Home Pages:

Universidad de los Andes:	www.ula.ve
Universität Bremen:	www.uni-bremen.de www.iup.physik.uni-bremen.de
Forschungszentrum Karlsruhe:	www.fzk.de www-imk.fzk.de/imk2/mira/home.html

[3] University of Bremen, Institute of Environmental Physics
Forschungszentrum Karlsruhe, Institute of Meteorology and Climate Research