AN AIRBORNE CRYOGENIC MID-INFRARED SPECTROMETER FOR THE INVESTIGATION OF MESOSCALE UTLS DYNAMICS

A. Kullmann[1], M. Riese[1], F. Stroh[1], F. Olschewski[2], and K. U. Grossmann[2]

[1]Research Center Jülich, 52425 Jülich, Germany, a.kullmann@fz-juelich.de
[2]University of Wuppertal, 42097 Wuppertal, Germany, kullmann@uni-wuppertal.de

ABSTRACT

A new airborne CRyogenic Infrared Spectrometer and Telescope for the Atmosphere (CRISTA-NF) experiment is currently developed and integrated for operation aboard the Russian high altitude research aircraft *M55-Geophysica*. Its first mission will take place during the European SCOUT-O3-tropics campaign from Darwin (Australia) in November 2005. Aiming at the investigation of fine-scale dynamic processes in the UTLS region, CRISTA-NF is designed as a limb-sounding instrument with highest spatial resolution, measuring thermal emissions of various atmospheric trace gases like water vapor, ozone and chlorofluorocarbons as well as clouds and aerosols in the mid-infrared spectral region. Here, we give a scientific motivation, some remarks on the measurement technique and an overview of instrument design and technology.

1. INTRODUCTION

A reliable prognosis of climate change in the earth's atmosphere due to natural and anthropogenic influences necessitates a detailed understanding of energetic, dynamic and chemical processes in the tropopause region. This transition layer, also known as UTLS (*upper troposphere - lower stratosphere*), seems to prove highly sensitive to changes in atmospheric parameters such as temperature and trace gas distributions. Especially the dynamic transport and exchange of chemical constituents between stratosphere and troposphere may cause significant changes in the atmosphere's chemical and radiative budget. But in spite of their great importance those processes and effects are far from being well understood [1]. Major uncertainties are still remaining, concerning the distribution, chemistry and radiative forcing of water vapor, clouds, aerosols, ozone, the hydroxyl radical and other chemical active species as well as the formation mechanisms of the various types of cirrus clouds. The processes to be investigated range from synoptical scale to microscale [2; 3]. While hitherto global satellite measurements (synoptical scale) are limited either by their horizontal or their vertical resolution, local in-situ measurements (micro scale) are limited by their little spatial coverage. Therefore we make the attempt to fill the lack of regional covering (meso scale) experimental data with high spatial resolution by a new airborne remote sensing instrument, called CRISTA-NF, aboard the Russian high altitude research aircraft *M55-Geophysica*.

CRISTA-NF is a limb sounding mid-infrared spectrometer, which succeeds the CRISTA satellite instrument operated twice during NASA space shuttle flights in November 1994 (STS 66) and August 1997 (STS 85) [4; 5]. The incoming radiation entering the optics through a Herschel telescope is analyzed by two independent Ebert-Fastie grating spectrometers with moderate spectral resolution of $\frac{\lambda}{\Delta\lambda} \approx 500$ and $\frac{\lambda}{\Delta\lambda} \approx 1000$, respectively. The radiation is finally registered by cryogenic semiconductor-detectors. The optical system is integrated into a compact cryostat which reaches temperatures down to 10K by cooling with supercritical helium. This allows fast measurements and provides good signal-to-noise ratio. The helium tank volume of 130 l is sufficient for two days of operation without refilling. The resolution of the CRISTA-NF spatial measurement grid is designed to be 200 m in vertical and about 15 km in horizontal direction along the flight track. Such a high spatial resolution results partially from a narrow vertical field of view of about 200 m. The well covered altitude regime reaches from the flight altitude downwards to the lower troposphere.

The combination with simultaneously measuring instruments on board the aircraft, especially MIPAS [6] and MARSCHALS [7], engenders synergy effects which should offer the opportunity to achieve a very detailed picture of the observed situation. This allows the observation of dynamic transport and exchange processes within the region of the tropical transition layer (TTL): for example, the entrainment of tropospheric air masses into the stratosphere, driven by deep convection in so called tropical "hot towers", and the following mixing processes in the lowermost stratosphere [e.g. 8]. Turbulent processes at mid-latitudes and isentropic mixing within small filaments may be part of the survey as well. At this the higher spatial resolution in combination with the versa-

Proceedings of the 17th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Sandefjord, Norway, 30 May – 2 June 2005 (ESA SP-590, August 2005)

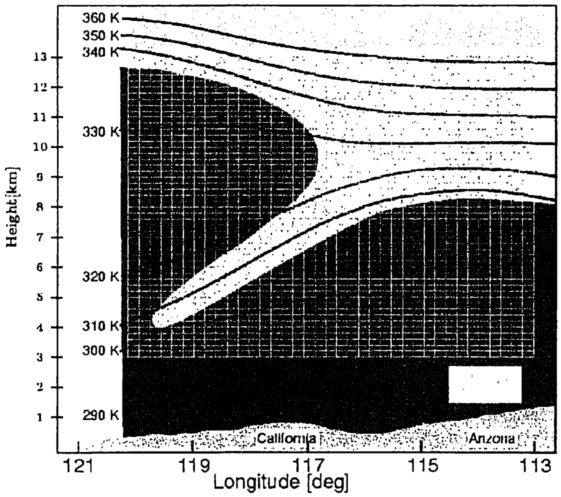

Figure 1. Illustration of the CRISTA-NF scanning grid superimposed on a schematical view of a tropopause fold [9], the attainable grid resolution is 200 *m vertically and* 15 *km horizontally.*

tility of the high altitude research aircraft will allow the analysis of local events like tropopause folds and cut-off-lows. This is illustrated by Fig. 1, showing a typical scanning grid for CRISTA-NF sampling a tropopause fold, as analysed by Shapiro [9]. CRISTA-NF measures at the same time the spectral signatures of water vapor, aerosol, ozone and other trace gases, among them also virtual conservative species like freons, which allows the analytical distinction between chemical and dynamical effects in the UTLS region. Water vapor, due to its steep gradient, is not only well suited for being used as a dynamical tracer, but first of all it is the most important and effective greenhouse gas, influencing the radiative budget directly by absorption, interfering in chemistry and furthermore being decisive for cloud formation. Beside the provision of water vapor- and aerosol-concentration the measured spectra contain information about thin and subvisible cirrus clouds. Different spectral signatures enable to distinguish ice water from nitric acid trihydrate (NAT) clouds. Improved algorithms, based on Spang [10], are currently under development to enhance our understanding of cirrus cloud formation as well as the mechanisms of stratospheric hydration and dehydration.

2. CRISTA-NF MEASURING TECHNIQUE: AIRBORNE LIMB SOUNDING

Using the method of limb sounding CRISTA-NF measures thermal emissions of the earth's atmosphere in the mid-infrared region ($\lambda \approx 4 - 15\,\mu$m) with two grating spectrometers. Fig. 2 illustrates how radiation originating from a distinct atmospheric volume enters the instrument along the line of sight (LOS). The volume is determined by the viewing direction and the instrument's field of view. The closest distance between the LOS and the earth's surface is called tangent height; the corresponding perpendicular intersection point is the tangent point. By vertical tilting of the LOS, different tangent heights can be adjusted to measure vertical profiles of the emitted IR-radiation. The vertical step size from one tangent height to the next is programmable. In the standard mode it equals the instrument's vertical field of view which extends approximately to 200 m within the atmospheric layer closest to the tangent point. While one single spectrum is measured within about one second, a complete vertical profile can be measured within 1.5 minutes. In consideration of the flight velocity the horizontal distance between two vertical profiles is about 15 km along the flight track. Due to the tilting of the LOS, tangent points of different tangent heights show horizontal displacement perpendicular to the flight direction.

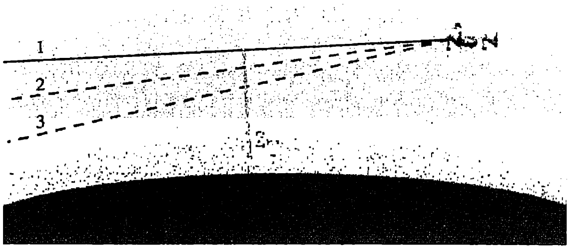

Figure 2. Illustration of limb sounding by airborne instruments: vertical panning of the LOS (here marked 1, 2, 3) leads to different tangent heights Z_T. The volume from which emitted radiation enters the instrument is determined by the instrument's field of view along the LOS.

The trace gas and aerosol concentrations, as well as cloud parameters can be derived from the measured radiance profiles by means of various retrieval-algorithms utilizing rapid radiation transfer models [11; 12]. The retrieval output is then available for dynamical and chemical analyses of the observed situation.

Figs. 3, 4 illustrate some results of radiation transport simulations carried out during a feasibility and sensitivity study for CRISTA-NF. The synthetic spectra were calculated assuming a reference atmosphere at mid-latitudes. The instrument function was considered by convolution with an adequate Gaussian curve, assuming a spectral resolution of $\lambda/\Delta\lambda \approx 500$. Fig. 3 shows the dependence of the radiance in the wavenumber range $780 - 860\,\mathrm{cm}^{-1}$ on the tangent height. The various spectral signatures correspond to different atmospheric constituents like water vapor, ozone, CFC-11, etc., which can be identified in fig. 4 showing not only the total radiance at 8 km tangent height but also contributions of single species which are relevant in this spectral region. To derive mixing ratios or concentrations of the trace gases from the measured spectra, suitable spectral regions have to be choosen for the retrieval process, where the signature of only one species

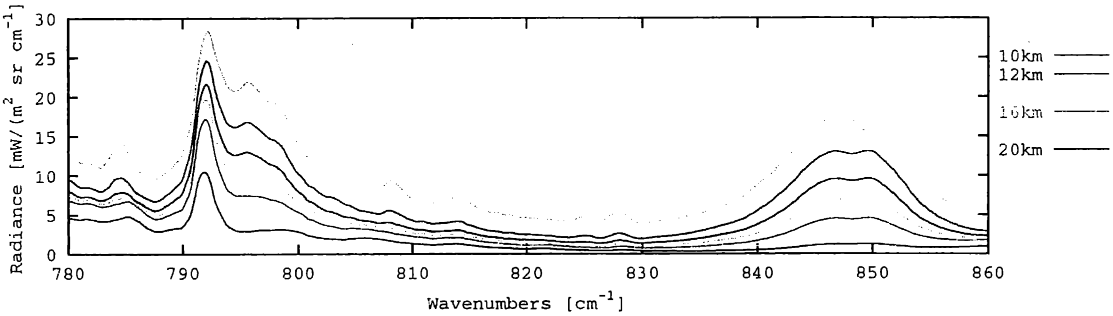

Figure 3. Synthetic radiance spectra in the wavenumber range 780 – 860 *cm*$^{-1}$ *for different tangent heights between* 8 *km and* 20 *km.*

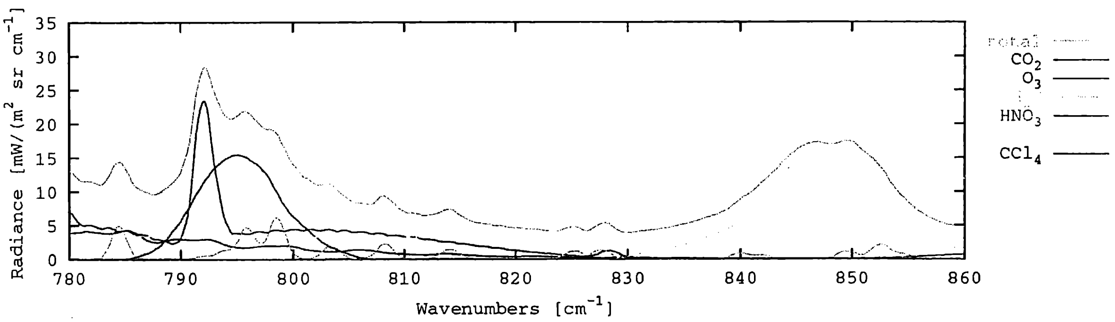

Figure 4. Spectra of total radiance and single contributions of the relevant trace gases in the wavenumber range 780 – 860 *cm*$^{-1}$ *for* 8 *km tangent height.*

of interest at a time is dominant while other emissions are suppressed.

In limb sounding experiments the collected signal for a single tangent height originates from along the whole LOS and therefore from various altitude levels of the atmosphere. Because of the exponential decrease of the total atmospheric density with increasing altitude and the geometry of the LOS, ensuring the LOS-segment immediately above the tangent point to be the largest of all, most of the measured signal can be assigned to a relatively thin vertical layer above the tangent point. This is true at least if optical thin conditions, a negligible field of view and vanishing gradients in the trace gas mixing ratios are assumed, and is even a strengthened effect for species with steep negative gradients like water vapor. Radiative transfer studies indicate that a percentage of approximately 50% of the measurable water vapor signal at 8 km tangent height originates from a vertical layer of 250 m extend only, which is within the scope of CRISTA-NF's vertical scan step.

3. INSTRUMENT DESIGN AND TECHNOLOGY

As mentioned above the CRISTA-NF experiment and its technology is based on the CRISTA-satellite experiment [4; 5]. Therefore the central optics and spectrometers of the former satellite instrument have been modified and integrated into a newly developed, compact and light-weighted cryostat to match the requirements for a set up in the Geophysica hull directly below the cockpit. An overview of the major components and their rough position is sketched in fig. 5, details are given below. The completely integrated instrument is of compact cylindric shape and is suspended to the top plate of the Geophysica front bays (optional bay one or two) using four shock absorbers. The instrument's dimensions are listed in fig. 5 as well. An optical ZnSe-window, flanged in a short nozzle on the right side of the CRISTA-NF vacuum shell, serves as entrance for the IR-radiation. It is placed behind a motorized shutter in the Geophysica fairing. The vacuum shell comprises the optical system, which consists of a Herschel telescope and an Ebert-Fastie twinspectrometer, embedded in a cryostat, which allows cooling of the semiconductor-detectors and the optics with supercritical helium. The electronic instrument control and data acquisition system is mounted under a separated shell on top of the optics top-plate and can be operated at differential pressures of up to 0.1 bar. To guarantee the essential thermal insulation between cryogenic instrument, helium tank and the warm outer vacuum shell a *glass-fibre-reinforced-plastic* (GFRP) cone of lowest heat conduction is used as the interior mounting and main structural support. It is attached to an adapter ring in the vacuum shell. The design of the composite material is optimized with respect to fibre orientation and thickness. To

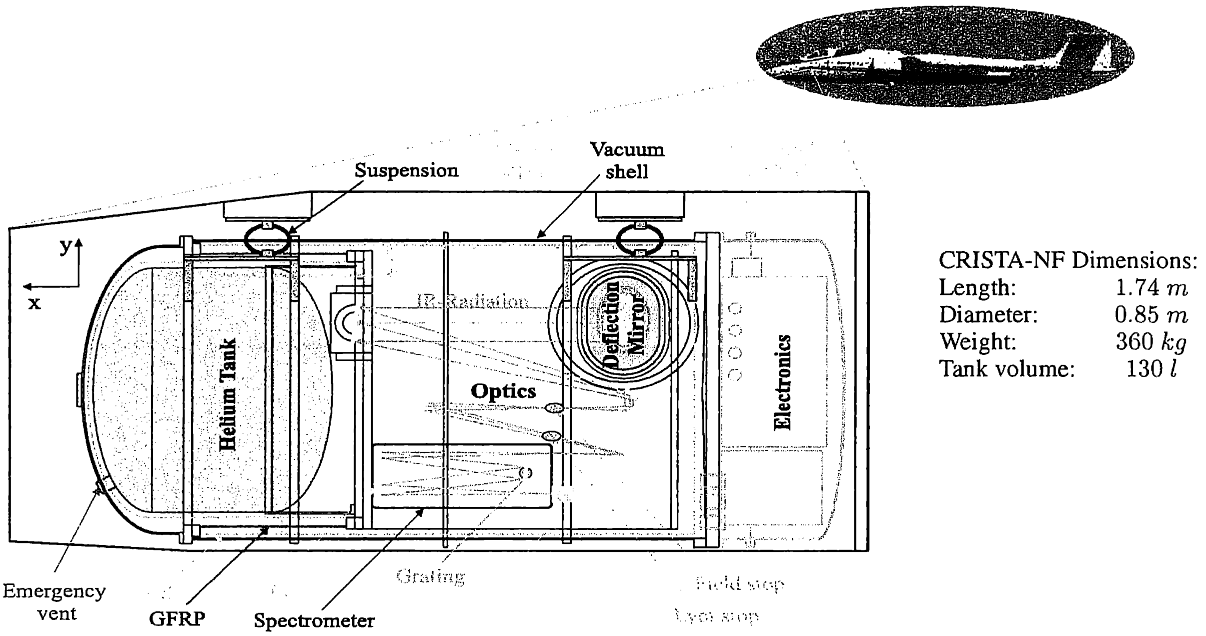

Figure 5. Configuration of CRISTA-NF's major components and its integration into M55-Geophysica. *Atmospheric radiation enters the instrument from z-direction. Instrument dimensions as listed per margin.*

avoid diffusive heat conduction the whole instrument is evacuated. The helium tank is operated at pressures of about 3 bar, which is maintained by CRISTA-NF's thermal and pressure control system. Possible failure conditions of the cryostat and pressure system are automatically handled by an independent safety system of mechanical valves and relief discs to prevent the instrument or aircraft operators from any kind of danger.

3.1. Optical system

A sketch of a ray trace from outside through the optics to the detectors is given in fig. 5: The incoming radiation, which passed the ZnSe-window, hits a fix adjusted deflection mirror, guiding the beam to the spherical primary mirror of a two stage off-axis telescope (Herschel, focal length 1000 mm). A purpose-built cryogenic motor drives the primary mirror of 120 mm diameter whose axis is beared by a flexural pivot. Thus the mirror is turnable by 4 degrees to an accuracy of 10 arcseconds, which allows tilting of the LOS to perform limb-sounding altitude scans in the atmosphere as described in section 2. Deflected by the primary mirror the radiation passes two folding mirrors and the field stop and enters a secondary optical system consisting of two spherical mirrors and a Lyot stop in between. A beam splitter (not shown in fig. 5) then provides a separate beam for each of the two independent Ebert-Fastie spectrometers of the twinspectrometer. Following one of these beams (analog for the other one) the focus of the telescope is reached, which is located in the entrance slit of the corresponding spectrometer. A tuning fork chopper in front of the entrance slit is used to modulate the incoming radiation at a frequency of 220 Hz for later phase sensitive (lock-in) amplification of the measured signal.

Inside the spectrometer the beam hits the Ebert mirror and is thus directed towards an echelette grating which is the diffractive element of the spectrometer. Each wavelength of the incident polychromatic radiation leaves the grating in a different direction and is deflected by the Ebert mirror once again so that only radiation of distinct direction, i.e. wavelength, can pass one of the several exit slits of the spectrometer. By turning the grating radiation of different wavelength, only depending on the turning angle, passes the exit slits and thus a complete spectrum can be scanned. Each spectrometer has seven, respectively eight, exit slits which are used in parallel to reduce the covered spectral interval for each slit and consequently the turning angle of the grating. This shortens the measurement time for one complete spectrum to approximately 1.2 seconds. Behind each exit slit band-pass filters ensure the selection of the desired spectral order and interval. A light conductor behind each band-pass filter leads the radiation to the semiconductor detector for the corresponding channel. Both spectrometers are not completely identic but utilize gratings of different grating constant and blaze angles. Also the turning angles of the gratings are unlike. Thus the spectrometers differ in their spectral resolution and cover different spectral intervals as listed in table 1.

The detectors are gallium doped silicon (Si:Ga) crystals of 1 mm^3 volume placed in an integrating gold-plated cavity and electrically connected to a trans-impedance

Low Resolution Spectrometer (LRS)					High Resolution Spectrometer (HRS)				
Ch.	N	Wavelength [μm]	Resol. $\lambda/\Delta\lambda$	Species	Ch.	N	Wavelength [μm]	Resol. $\lambda/\Delta\lambda$	Species
1	-1	7.29 - 8.62	362	CH_4, N_2O, N_2O_5	1	-1	10.74 - 11.42	1007	F-12
2	-2	4.15 - 4.81	407	CO_2	2	-1	11.23 - 11.90	1051	F-11, HNO_3
3	-1	8.92 - 10.25	436	O_3	3	-1	11.53 - 12.20	1078	CFC-11, Aerosol
4	-1	10.41 - 11.74	503	HNO_3, CFC-12	4	-2	5.98 - 6.32	1118	NO_2
5	-1	11.52 - 12.84	554	H_2O, CO_2, CFC-11	5	-1	12.24 - 12.91	1143	H_2O, CO_2, CCl_4
				HNO_3, $ClONO_2$, CCl_4	6	-2	6.39 - 6.72	1191	H_2O
6	-2	6.04 - 6.71	580	H_2O, (NO_2)	7	-3	4.35 - 4.57	1216	N_2O
7	-1	12.71 - 14.03	608	T, P	8	-3	4.45 - 4.67	1243	CO_2 , N_2O

Table 1. Spectral channels of both spectrometers: N is the spectral order; species refer to signatures in the spectral channel used in the retrieval process; temperature and pressure (T, P) are derived from CO_2– signatures.

amplifier circuit. Such a detector unit is surrounded by a gold-plated rectangular housing of 6 mm × 25 mm × 50 mm. Since each exit slit is followed by a band-pass filter, a light conductor and a detector unit, those units are located side by side next to each other forming a "detector block". The noise equivalent power (NEP) of the detectors is about $2.5 \times 10^{-16}\mathrm{W}/\sqrt{\mathrm{Hz}}$ and the signal integration time is 4.5 ms, which can only be reached by cooling with liquid helium. Therefore the temperature of the detector blocks is stabilized at 13 K.

Since the atmospheric IR-signal to measure is very weak compared to signals of stray light sources near the LOS (e.g. clouds and the earth's surface), a stray light suppression system consisting of beam limiting baffles and the former mentioned Lyot optics is used. The entire interior optics construction is coatet with black paint of highest IR-absorption. The outermost baffle between the ZnSe-Window and the deflection mirror is cooled to temperatures below 80 K by helium exhaust gas from the cryostat and is therefore called OVCB (outer vapor cooled baffle). It is mountet on GFRP supports to avoid thermal conduction into the inner optics which is cooled below 15 K. To avoid stray light from dust particles and other surface contaminants all optical components are cleaned meticulously and integrated in a cleanroom facility.

3.2. Cryostat

The CRISTA-NF vacuum shell is completely consumed by the cryostat in which the optics and the detector system are embedded. According to the requirements of aircraft campaigns the helium tank of the cryostat has a volume of 130 liters and is filled with 120 liters of liquid helium which provides a sufficient cooling reservoir for two consecutive flights within two days without refilling. The operational pressure of the tank is 3 bar, maintained by two electrical 100 W heaters and a mechanical valve. The tank is attached to the rear flange of the GFRP cone by a cylindrical aluminium extension and has therefore no thermal contact to the warm vacuum shell. The entire cryostat system is surrounded by a vapor cooled radiation shield (inner vapor cooled shield, IVCS) which is fed by helium exhaust gas from the tank. The IVCS exhaust gas then provides cooling for the OVCB. In addition to that, two multi-layer insulation (MLI) blankets surround the system to support the thermal insulation. To provide sufficient cooling for optics and detectors they are directly thermally linked to the helium tank. Thus the detectors can be operated at temperatures of $\sim$ 13 K, while the optics measure $T < 20$ K, IVCS 60 K, OVCB 80 K and the vacuum shell is stabilized at $-30°$ C. To ensure appropriate function of the electronics the separated electronics container, which is not embedded in the vacuum shell, is pressurized and thermally stabilized at $+30°$ C.

3.3. Calibrations

A complete calibration for CRISTA-NF consists of at least three single procedures: a LOS-calibration, a wavelength and a radiometric absolute calibration. The first leading to a definit relation between the angular position of the primary mirror and the viewing direction of the telescope and the spectrometers, the second between the grating position and the wavelength scale of each spectrometer and the last between the detector signals and the incoming radiation. In addition to that, a field of view (FOV) measurement and investigations of detector relaxation effects have to be accomplished.

The LOS-calibration to determine the viewing direction of the telescope is carried out including the spectrometers by measuring the position of an IR point source, which is also used to measure the instrument's FOV. The wavelength calibration results from measurements of spectral signatures which are produced by an optical absorption cell filled with a gas of known absorption spectrum. The cell is therfore placed between the instrument and a hot blackbody source. The wavelength calibration can be rechecked and improved during the retrieval using known spectral signatures of atmospheric emissions. The radiometric absolute calibration is accomplished using a conical blackbody source, which fills the instruments's FOV completely. The temperature of the blackbody source is varied between 10 K and room temperature and the corresponding detector signals are measured.

4. FIRST MISSION

After two integration test flights at Oberpfaffenhofen (Germany) in July 2005, the first mission of CRISTA-NF will take place during an extensive measurement campaign from Darwin (Australia) in November 2005 which is part of the European SCOUT-O3-tropics activity within the sixth European Framework programme [13]. SCOUT (Stratosphere Climate Ozone Links with emphasis On the UT/LS) is an integrated project consisting of aircraft, ground-based, balloon and satellite measurements as well as modelling activities. The main scientific questions are the transport mechanisms and residence times of air in the TTL, the influence of deep convection and cirrus formation on the UTLS and the consequences of TTL changes for stratospheric water vapor trends as well as the stratospheric aerosol layer. Strongest convection with the potential of tropopause penetration arises in the Western Pacific and Maritime Continent region which makes Darwin a preferable base for these investigations. Furthermore the Tiwi Islands north of Darwin feature an almost diurnal phenomenon nicknamed "Hector" during the transition to the summer monsoon period. Hector is a sea breeze driven, convective thunderstorm system appearing and dissipating on the time scale of one day, which is of sufficient intensity to reach and penetrate the tropopause [14; 15]. The local SCOUT-activities at Darwin are to be taken into the context of wider scales and therefore the observational focus of CRISTA-NF extends to measurements during the transfer flights between Europe (Oberpfaffenhofen, Germany, $48.1°N, 11.3°E$) and Darwin ($12.5°S, 130.9°E$). The combination of CRISTA-NF, MARSCHALS, MIPAS and selected in-situ instruments onboard the M-55 offers the opportunity to gain detailed along-track cross-sections of the UTLS region from the extratropical northern hemisphere to the tropical southern hemisphere. Local operations of CRISTA-NF and Marschals are also planned to investigate the updraft and outflow regions of the convective systems.

5. SUMMARY AND OUTLOOK

A new airborne cryogenic infrared grating spectrometer, called CRISTA-NF, was presented which is characterized by high spatial and temporal resolution as well as regional covering of the observation area, thus filling the gap between global satellite measurements on synoptic scale and local in-situ measurements. The first mission of CRISTA-NF will take place during the European SCOUT-O3 campaign in November 2005 on board the high flying research aircraft M55-Geophysica. The instrument is optimized for measurements of micro- and mesoscale dynamical structures in trace gas distributions around the tropopause using the limb sounding technique. Experiences from the operation of the former CRISTA satellite instrument encourage the assumption of gaining vertical trace gas profiles of high quality from the measured spectra by means of rapid retrieval algorithms. Furthermore CRISTA-NF allows to investigate the scientific potential of a new generation of limb sounding satellite instruments, distinguished from earlier instruments by unprecedented spatial resolution. Such are currently under development at the Research Centers Jülich and Karlsruhe (Germany).

ACKNOWLEDGMENTS

The contributions from the CRISTA-NF technical team at the University of Wuppertal and the Central Technology Devision at Research Center Jülich are gratefully acknowledged.

REFERENCES

[1] Watson, R. et al., editors. *Third Assessment Report*. Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2001. www.ipcc.ch.

[2] Holton, J., Haynes, P., McIntire, M., Douglass, A., Rood, R., and Pfister, L. Stratosphere-troposphere exchange. *Rev. of Geophys.*, 33:403–439, 1995.

[3] Stohl, A. et al. Stratosphere-troposphere exchange: A review, and what we have learned from staccato. *J. Geophys. Res.*, 108(D12):8516, 2003.

[4] Grossmann, K. U., Offermann, D., Gusev, O., Oberheide, J., Riese, M., and Spang, R. The crista-2 mission. *J. Geophys. Res.*, 107 D23:8173, Oktober 2002.

[5] Offermann, D., Grossmann, K., Barthol, P., Knieling, P., Riese, M., and Trant, R. Cryogenic infrared spectrometers and telescopes for the atmosphere (crista) experiment and middle atmosphere variability. *J. Geophys. Res.*, 104(D13):16311–16325, July 1999.

[6] Carli, B., Cortesi, U., Blom, C., Chipperfield, M., de Rossi, G., and Redaelli, G. Airborne polar experiment geophysica aircraft in antarctica (ape-gaia). *SPARC Newsletter*, (15):21–24, Jul 2000.

[7] ESA and EADS-Astrium. Marschals - millimetre-wave airborne receiver for spectroscopic characterisation in atmospheric limb sounding. www.astrium.eads.net/corp/prod/00000804.htm.

[8] Sherwood, S. and Dessler, A. E. A model for transport across the tropical tropopause. *J. Atmos. Sci.*, 58:765–779, 2001.

[9] Shapiro, M. A. Turbulent mixing within tropopause folds as a mechanism for the exchange of chemical constituents between the stratosphere and troposphere. *J. Atmos. Sci.*, 37:994–1004, 1980.

[10] Spang, R., Eidmann, G., Riese, M., Offermann, D., Preusse, P., Pfister, L., and Wang, P.-H. Crista observations of cirrus clouds arround the tropopause. *J. Geophys. Res.*, 107, No.D23(doi:10.1029/2001JD000698):CRI2,1–18, 2002.

[11] Riese, M., Spang, R., Preusse, P., Ern, M., Jarisch, M., Offermann, D., and Grossmann, K. Cryogenic infrared spectrometers and telescopes for the atmosphere (crista) data processing and atmospheric temperature and trace gas retrieval. *J. Geophys. Res.*, 104:16349–16367, 1999.

[12] Hoffmann, L., Spang, R., Kaufmann, M., and Riese, M. Retrieval of cfc-11 and cfc-12 from envisat mipas observations by means of rapid radiative transfer calculations. *Adv. Space Res.*, 2005. accepted.

[13] Brunner, D., Peter, T., Schiller, C., Harris, N. R. P., MacKenzie, R. A., Flüglistaler, S., and Pyle, J. A. The scout-o3 tropical aircraft measurement campaign in darwin, nov-dec 2005. *Geophysical Research Abstracts*, 7, 2005.

[14] Hamilton, K., Vincent, R. A., and May, P. Darwin area wave experiment (dawex) field campaign to study gravity wave generation and propagation. *JGR*, 109, 2004.

[15] Keenan, T. et al. The maritime continent experiment (mctex). *Bull. Am. Meteorol. Soc.*, (81), 2000.