Introduction to Spatial Heterodyne Observations of Water (SHOW) Project and its Instrument Development

Yunlong Lin, Gordon Shepherd, Brain Solheim, Marianna Shepherd, Stephen Brown, [*]John Harlander, James Whiteway
Center for Research in Earth and Space Science (CRESS), York University, Toronto, Ontario, CANADA
[*] Department of Physics, St. Cloud State University, St. Cloud, Minnesota, USA

Abstract
Water is a critically important constituent throughout the stratosphere and mesosphere. The SHOW project will develop a new instrument to measure water vapour from 15km to 85km height, on a global scale, using the unique capabilities provided by Spatial Heterodyne Spectroscopy (SHS). This work builds on Canadian expertise in fabricating solid Michelson interferometers to fill a significant niche in our current capability.

The SHS setup the FTS with the mirrors replaced by diffraction gratings at Littrow configuration, wavelength depended Fizeau fringes are recorded by a 320*256 CCD camera without any scanning elements, the high resolution spectral information along one detector dimension can be obtain from Fourier analysis, and the other dimension will provide the spatial information. At a limb view point, a field-widened SHS with half-angle of 6 degrees for water observations at 1364nm is desired, the resolution is 0.02nm within full bandwidth of 2nm, and the resolving power is about 68,000.

Introduction
Water vapour plays a fundamental role in the dynamics and radiation budget of the atmosphere. It is the single most important greenhouse gas, contributing more than 80% to the total greenhouse effect. Water vapour not only plays a central role in weather and climate phenomena but in atmospheric chemical processes as well. Recent observational studies indicate that there is an increasing trend of lower stratospheric water vapour in the midlatitudes in the last 50 years. It is very crucial to determine the details of the various processes that move air across the tropical tropopause into the stratosphere and the relative importance of these processes in determining stratospheric humidity. By observing the sun scattering light in near Infrared region (the atmospheric winder is around 1364.5nm) in limb view configuration, the proposed spatial heterodyne instrument is intended to provide simultaneous observations from 15 to 85 km and thus will provide better understanding of these critical issues and help to resolve outstanding questions.

The primary objective of the SHOW project is to develop a new instrument designed to measure water vapour from the upper troposphere, through the stratosphere and into the lower mesosphere, on a global scale, using the unique capabilities provided by Spatial Heterodyne Spectroscopy (SHS).

The development of the new SHOW instrument will enable us to address these important scientific objectives:

- To demonstrate the capability of long-term measurement of water vapour in the stratosphere.
- To study the process of water vapour entry to the stratosphere.
- To study the transport of water vapour in the stratosphere and mesosphere.
- To study mesospheric water vapour and mesospheric clouds.

The SHOW mission science objectives include the study of PMCs at high latitudes. Initial study indicates that a polar, sun-synchronous orbit is suitable for SHOW project and provides adequate coverage of both equatorial and polar region. SHOW will look at the water vapour absorption in the 101–000 band at 1364nm since it has several lines which are well isolated from other atmospheric absorbers. The simulations are shown in fig 1. The instrument will record spectral information along the horizon and resolves 1 km in the vertical at the limb tangent point but averages the horizontal field of view to take advantage of field widening and improve throughput.

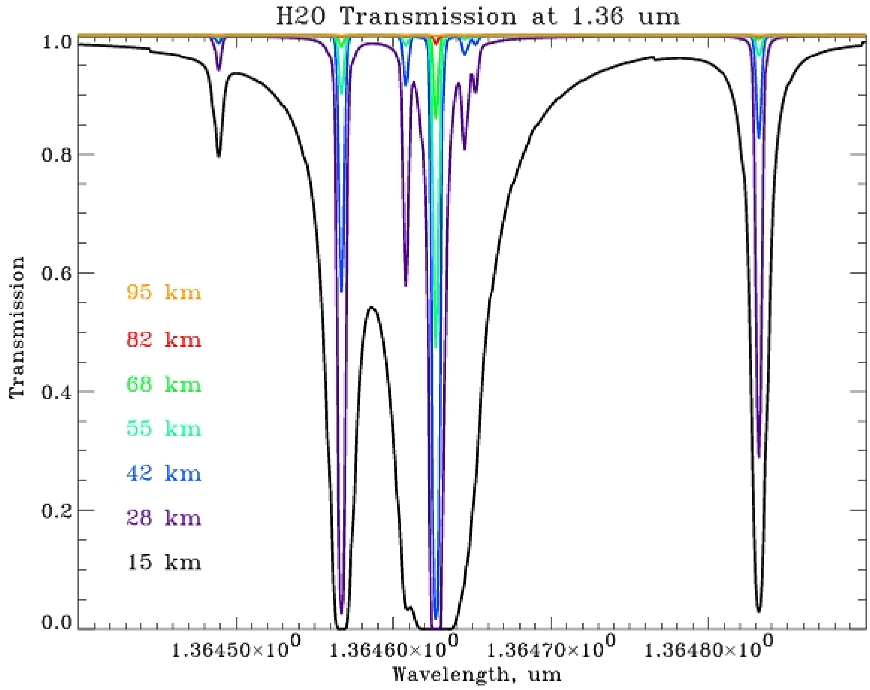

Fig 1: SHOW Instrument Atmospheric window illustrating the water absorption in NIR region along the line of sight in limb view configuration

The proposed SHOW instrument will provide good vertical resolution with high horizontal spatial resolution and good latitudinal coverage in a relative small size. This provides an advantage over occultation observations (i.e. ACE, HALOE and SAGE) since SHOW will provide better latitudinal coverage and better horizontal resolution, without sampling restricted to sunrise and sunset. The global coverage provided by SHOW is limited to daytime measurements, so is not as good as that provided by MIPAS or ODIN, however, SHOW is much less complex than either of these and has the potential to provide the long term, repeatable observations needed for climate change studies. Comparing with AQUA's instruments dedicated to the observations of humidity, AMSR-E is a large instrument with a 1.6 m diameter antenna and a mass of 323 kg, and AIRS is an infrared nadir-viewing grating spectrometer with a resolving power of 1200, compared with 63,000 for SHOW.

At present, various laboratory tests have been carried out to assure the design is correct before the monolithic SHS is conducted. The SHS and SHOW instrument design, the lab tests on the breadboard and its results and future work are discussed in more detail in following sections.

SHS and SHOW Instrument Design

SHS (Spatial Heterodyne Spectroscopy) was developed to suit any application on any spectral regions for any species with high spectral resolution and large throughout over a relatively narrow band.

A spatial heterodyne interferometer is similar to a Michelson interferometer with its mirrors replaced by fixed diffraction gratings. The interferometer does not require any moving parts.

Diffracted, monochromatic beams that recombine at the beamsplitter each have the angle γ towards the optical axis, this can be expressed by grating equation as follows:

$$\sigma[\sin(\theta_L) + \sin(\theta_L - \gamma)] = m / d$$

where σ is the wavenumber, θ_L is the Littrow angle, m is the order of diffraction, and 1/d is the grating groove density.

The path difference along the crossed wavefronts results in a Fizeau fringe pattern, which is detected using a detector array. The spatial frequency f_x of the fringes is a function of the wavenumber of the incident radiation, which is

$$f_x = 2\sigma s \sin(\gamma) = 4(\sigma - \sigma_L)\tan(\theta_L)$$

by assuming a small value for γ, where σ_L is the Littrow wavenumber.

In the general case of a polychromatic source, the intensity I(x) in the fringe localization plane can be written as a function of the spatial dimension x in the dispersion plane:

$$I(x) = \int_o^\infty B(\sigma)\{1 + \cos[\, 2\pi(4(\sigma - \sigma_L)tg(\theta_L)x_0]\}\, d\sigma$$

Note that I(x) is the cosine Fourier transformation of the incident radiance spectrum B(σ) added to a constant term. An interference filter is used to reject out of band wavelengths that would result in the alias fringes and/or a non-unique recovery of the incident spectrum.

Field-widened spatial heterodyne spectrometers can be achieved using fixed field-widening prisms shown below in fig 2. The Prisms also provide contribution towards the Field Widening. This gives the SHS concept an enormous throughput advantage over conventional grating spectrometers with similar spectral resolution. Field-widened SHS instruments have no moving parts and low power and volume requirements.

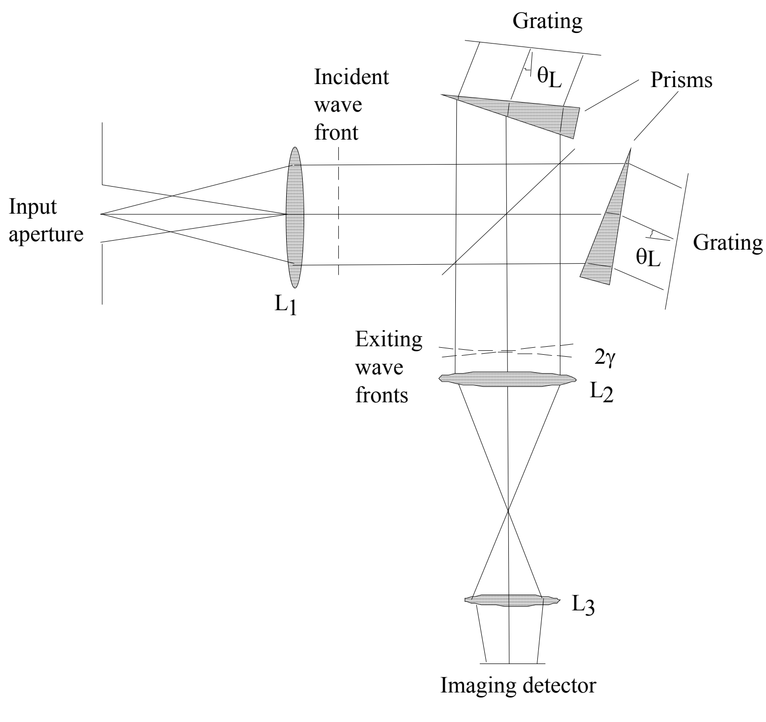

Fig 2: Field-widened SHS for SHOW Instrument (refer to EMS document)

SHS Design Engine was further developed to get the design of SHS setup at 1364.5nm for observation of water. This ray-tracing software provides the capability to design field-widened SHOW optics and for now it has been used to produce preliminary designs for the laboratory breadboard work. The SHOW SHS can achieve larger than 9^0 in field widening angle when a very high refraction index wedge is used. A ZnSe prism with the APEX angle of 11.96^0 is selected at a Littrow wavelength of 1364nm for the breadboard tests. The design parameters are listed in table 1.

Table 1: Parameters of Breadboard Design in Water Window

Design wavelength	1364.5 nm
Lines per mm of Gratings	600
Grating width and height	50 x 25 mm
Littrow angle	24.1415^0@ Order: 1
ZnSe Prism field-widening angles	11.96^0
Field of View (Inside)	9^0 (inside SHS, Angle to be tested: 6^0)
Beamsplitter size	50 x 50 mm
Beamsplitter angle	-45^0
Arm length	115 mm
Bandwidth (minimum)	1362.5 nm to 1366.5 nm
Resolution	0.02nm
Resolving Power	68000

Lab Test and Results

In general, a spatial heterodyne spectrometer can be tuned to operate in any spectral region and it is possible to control the trade off between spectral resolution and bandwidth. The SHOW laboratory breadboard work has demonstrated this with the development of both a visible and near IR test setup. After the successful design, setup and test of breadboards at 632.8 nm and 1264 nm, two emission lines from a Krypton and a Xenon lamp were used to demonstrate the SHS at water window (1364.5nm). All of these were implemented at minimal cost using off the-shelf components and existing equipment in the CRESS Space Instrumentation Laboratory (CSIL).

Visible Region Setup and its Results

The basic parameters for the visible breadboard were derived using the SHOW SHS Design Engine. Table 2 gives the design parameters using off the shelf components available in the laboratory.

Table 2: Parameters of Breadboard Design in Visible region

Design wavelength	632.8 nm
Lines per mm of Gratings	600
Grating width and height	50 x 25 mm
Littrow angle	10.94^0@ Order: 1
BK7 Prism field-widening angles	11.46^0
Field of View (Outside)	2^0
Beamsplitter size	50 x 50 mm
Beamsplitter angle	-45^0
Arm length	120 mm
Bandwidth (minimum)	632.8 nm to 642 nm
Resolution	0.03nm
Resolving Power	21093

A HeNe laser (continuous, polarized output at 632.8 nm) is used as a source to set up the SHS breadboard in the visible region. The maximum resolution limit is about 642 nm, with the reference or Littrow wavelength set at 632.8 nm. The passband, resolution and resolving power can be examined using lines from a Neon lamp (633.4 nm, 638.3 nm, 640.2 nm). The basic setup begins with the on-axis, not field-widened (no prism) configuration. A 45^0 cube beamsplitter (50*50*50 mm, non-polarized, designed for the visible) was available in the laboratory and so was used for the visible setup. Standard gratings, 600 grooves/mm were used to disperse the light and reflected the desired ones to construct the fringes. At 632.8 nm the grating efficiency is only about 12 – 14%. An IMG1300 large array CCD camera was used to obtain images. It incorporates a full-frame 1280(H) X 1024(V) mega pixel CCD array, with 16 µm square pixels which have a full well depth of 150,000 electrons per pixel. The photosensitive area is 20.5 mm (H) x 16.4 mm (V) and the chip size is 22.0 mm (H) x 17.1 mm (V). The basic configuration of SHOW in Visible region (no prisms for field-widening) is shown in Fig 3, with the laser's fringes shown in Fig 4. A narrow band filter (FWHM from 631.082 to 635.195 nm) is placed in the input in order to isolate one of the neon emission lines. With the visible SHS set at the Littrow condition for 632.8 nm, various images have been obtained to show that the SHS works as expected at other wavelengths. Fig 5 shows the SHS fringes of 640.2nm of Neon lamp.

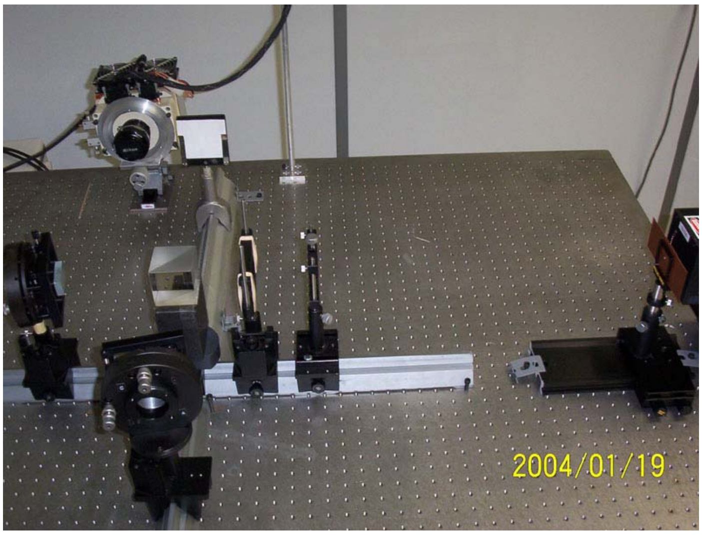

Fig 3: Visible Breadboard Configuration

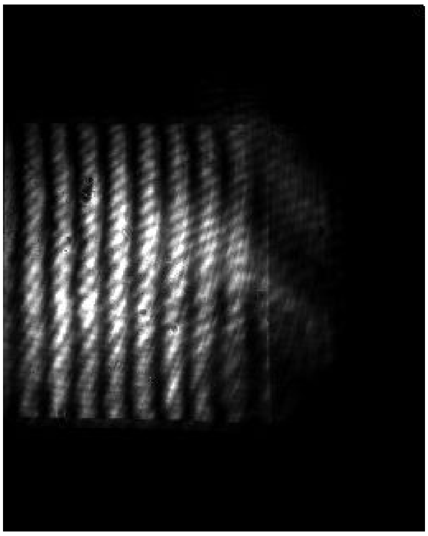

Fig 4: HeNe laser fringes

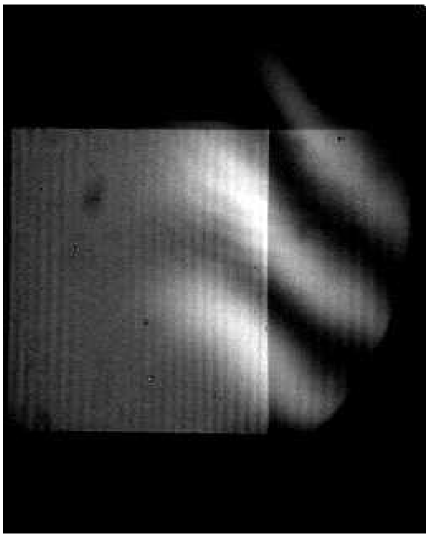

Fig5: Neon lamp fringes (640.2 nm)

Near IR Region (1264 nm) Setup and its Results

The near IR breadboard is shown below in Fig 6. An image of the spatial fringes recorded at 1265 nm (for the SHS set to a Littrow wavelength of 1264 nm) is shown in the right hand Fig 7 below. The successful implementation of both SHS Design Engine and the laboratory breadboard demonstrate that the current SHOW instrument design is feasible and achievable. In the region of 1264 nm, the best grating groove density is also 600 lpmm. New gratings, blazed at 1250 nm, and a beamsplitter suitable for the near IR were purchased from the catalogue. In order to record the image and monitor the system while adjusting the setup, a POWER Technology IRVC (300 - 1700nm) camera was purchased (Figure 5). The blaze angle is larger than the one in the visible region, so the IR gratings require a larger range of adjustment than the visible gratings, the grating efficiency is 75%. The basic design parameters for 1264 nm are given in table 3.

Table 3: Parameters of Breadboard Design in NIR region (1265nm)

Design wavelength	1264 nm
Lines per mm of Gratings	600
Grating width and height	50 x 25 mm
Littrow angle	22.28^0@ Order: 1
BK7 Prism field-widening angles	21.23^0
Field of View (Outside)	2^0
Beamsplitter size	50 x 50 mm
Beamsplitter angle	-45^0
Arm length	120 mm
Bandwidth (minimum)	1263 nm to 1267 nm
Resolution	0.02nm
Resolving Power	63200

Fig 6: Near IR Breadboard

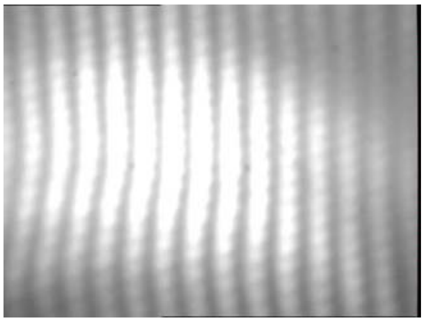

Fig 7: SHS Image at 1265nm

Figure 8 is a plot of one slice through the image to obtain the variation in the spatial domain. The signal level is in arbitrary units from the frame digitization. The Fourier transform of the above spatial sample provides the wavelength difference with respect to the Littrow wavelength. Figure 9 shows the plot of the FFT of the slice image (there is a ghost in negative direction which is not shown here).

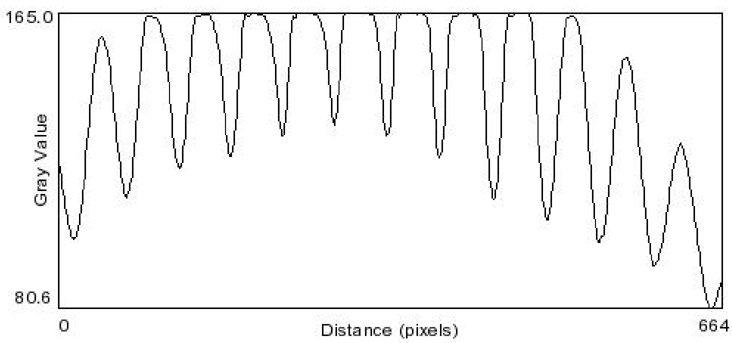

Fig 8: Horizontal slice showing spatial fringes at 1265 nm

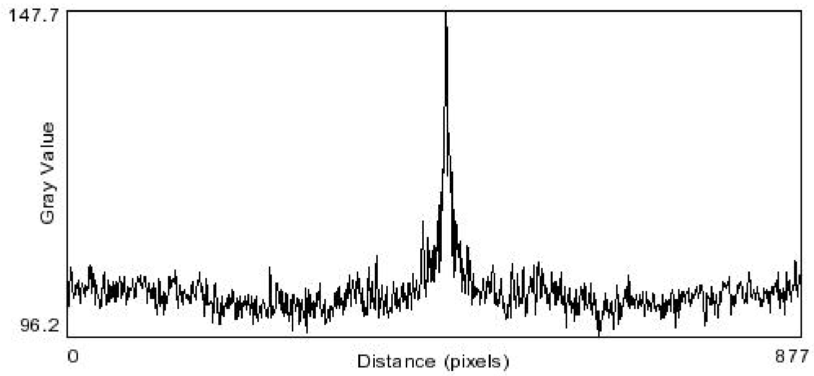

Fig 9 Emission line of 1265nm is obtained after FFT

Current Water window Experiment Setup and its Development

At present, we are working on breadboard tests to demonstrate field widened configuration at a wavelength of 1364nm, which is the identified window of water. One of the sources is a Xenon lamp with an emission line at a wavelength of 1365.7 nm, the other is a Krypton lamp with a 1363.4 nm line. The basic design parameters for 1364.5 nm are given in table 1 above. The same Beamsplitter and gratings working in NIR region are used. ZnSe Prisms are inserted for field widening in present breadboard test. Since the requirement of the Prism APEX angle is very critical, a dual prism set replaced the single prism to perform the field widening. The two prisms, with 8^0 apex respectively, can rotate with respect to one another to get an adjustable joint apex angle. This setup also demonstrates the dual-twist prisms' set, the prism may also be tilted. A magnetic stick holder is designed for the easy control on rotation. According to the design engine, the angular relationship is critical for the setup. Although one can set the prism angle by fixing the rotation angle, in practice, a HeNe Laser beam is used to determine whether the setup is correct. One can also arrange and measure the angles between components by apply the reflection law. The setup is shown in Figure 10. A new filter within bandpass of 10 nm is placed in front of SHS in order to isolate various lines of Xe and/or Kr lamps. A new low noise InGaAs Camera will record the field-widened image while the same POWER Technology IRVC (300 - 1700nm) camera is used for alignment.

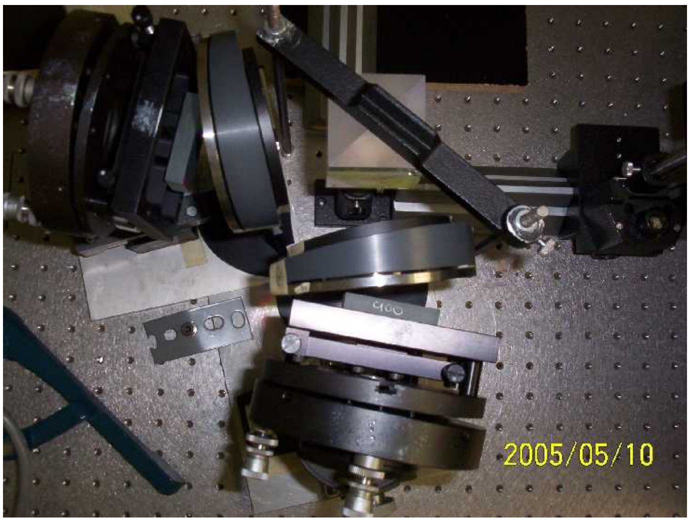

Fig 10: the Field Widened SHS System

Conclusions and Future Work

The current work has clearly demonstrated that the SHS works well in the near infrared at 1264 nm. The SHS Design Engine was used to provide initial parameters for this work and the breadboard setup verified that the values were correct for the on-axis case. The SHS Design Engine has been used to develop parameters for an SHS design at 1364 nm, using off the shelf components.

Analysis software, used to process image data (FFT and so on), pass-band, resolving power and resolution, will be developed. InGaAs Camera will record the field widened image, and the Characteristic of the 1364 nm breadboard can be carried out soon.

Field work will also be carried out by mounting the SHOW instrument onto an aircraft to do real observation of water vapour at the altitude of the aircraft. The observation configuration can be either an air cell with a white source, or limb view of the local atmosphere. A prototype instrument will be built for this purpose, and design tools will help the setup, build and test.

References

Brasseur, G.P., and S. Solomon, 1986, Aeronomy of the Middle Atmosphere, 2nd edition, D. Reidel, Dordrecht

Harlander, J.M., 1991, Spatial Heterodyne Spectroscopy: Interferometeric Performance at any Wavelength without Scanning, Ph.D. dissertation, University of Wisconsin-Madison

Harlander, J.M., 2002, SHIMMER: a spatial heterodyne spectrometer for remote sensing of Earth's middle atmosphere, Applied Optics, Vol. 41, No. 7, pp. 1343-1352

Harlander, J.M., C.R. Englert, J.G. Cardon, R.R. Conway, C.M. Brown, J. Wimperis, A robust monolithic UV interferometer for the SHIMMER instrument on STPSat-1. App. Optics, 2003

Nedoluha, G.E., R.M. Bevilacqua, R.M. Gomez, W.B. Waltman, D.L. Thacker, W.A. Matthews, 1996, Measurements of water vapour in the middle atmosphere and implications for mesospheric transport, J. Geophys. Res., 101, 21,183-21,193

Seele, C. and P. Hartogh, 1999, Water vapour of the polar middle atmosphere: Annual variation and summer mesosphere conditions as observed by ground-based microwave spectroscopy, Geophys. Res. Lett., 26, 1517-1520

Shindell, D.T., 2001, Climate and ozone response to increased stratospheric water vapour, Geophys. Res. Lett., 28, 1551-1554

SPARC, 2000: Assessment of water vapour in the upper troposphere and lower stratosphere, WMO/TD-1043, Stratospheric processes and their role in Climate, World Meteorological Organization, Paris