Spatial Heterodyne Spectrometer for Temperature Measurements in the Middle Atmosphere

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In this work, we aim at performing temperature measurements of the middle atmosphere, obtained by remote spectroscopy. The sensor, a Spatial Heterodyne Spectrometer (SHS), is mounted on a satellite. The data provide insights into atmospheric processes and help to improve weather and climate models.

1 Introduction

Understanding the atmosphere of the earth is a challenging endeavour owing to the complexity of the physical processes involved. Improving and testing weather and climate models requires the recording of atmospheric data on a global scale, preferably with a high spatial and temporal resolution, to be able to resolve the small scale dynamics of the atmosphere with sufficient accuracy. Furthermore, phenomena like gravity waves (or: buoyancy waves), which couple different sections of the atmosphere, need to be understood much better to improve climate projections.

With the "Development Initiative for Small Satellites Exploring Climate Processes by Tomography" (DISSECT), we aim at performing temperature measurements of the middle atmosphere to provide temperature data obtained by remote spectroscopy, see Fig. 1.

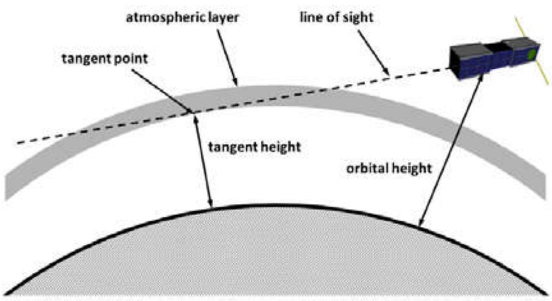

Fig. 1 Temperature measurements in the middle atmosphere via remote sensing.

Temperature is a key quantity for understanding atmospheric processes, since it is a proxy for atmospheric dynamics. Gravity waves move air parcels adiabatically, thus imprinting a three-dimensional wave structure on the temperature, as shown in Fig. 2. Amplitude, phase, and wavelength of the wave can then be determined. As an improvement over existing techniques, a target mode observation in contrast to mere limb sounding is used here, leading to increased resolution and accuracy.

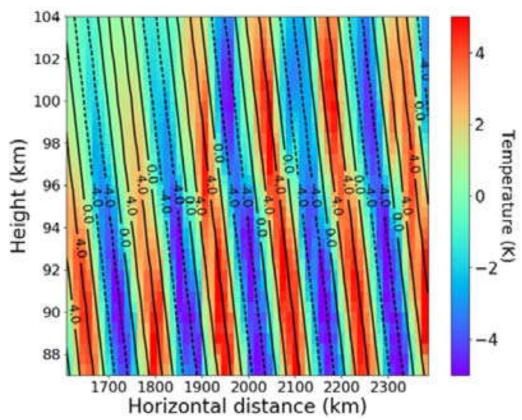

***Fig. 2** Simulation of the temperature distribution characteristic of a gravity wave.*

The sensor, a Spatial Heterodyne Spectrometer (SHS), is mounted on a satellite. An SHS is used because of its high spectral resolution and inherent robustness owing to its monolithic design, making the SHS particularly apt for space applications.

2 Determination of Temperature

The temperature of the atmosphere is obtained by measuring the intensity ratios of eight lines of the fine structure of the oxygen atmospheric band (A-band) at about 762 nm, as Fig. 3 illustrates. The lifetimes of the corresponding rovibrational states are of the order of several seconds, assuring the necessary thermalization. In contrast to other methods, only intensity ratios have to be measured, making calibration procedures for absolute intensity measurements unnecessary. The spectrometer, the SHS, is described in the next section.

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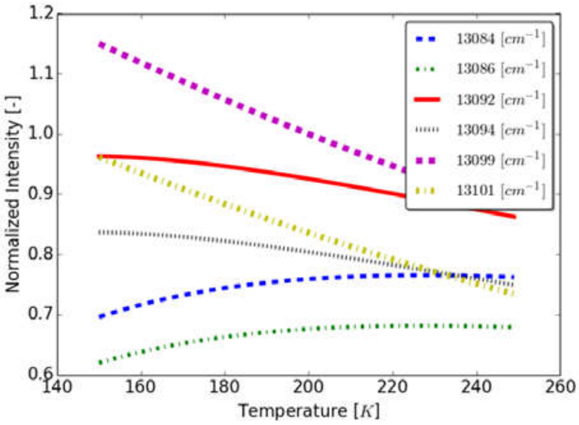

Fig. 3 *Atmospheric temperature dependence of the six A-band lines chosen for this experiment. Measuring the intensity ratios of the lines allows the temperature reconstruction.*

3 The Spatial Heterodyne Spectrometer

Originally devised by Pierre Connes (SISAM), an SHS is similar to a Michelson interferometer in design, only with the mirrors replaced by diffraction gratings, see Fig. 4. Owing to the dispersion of the gratings, incoming light waves will show a wavefront tilt depending on the wavelength, giving rise to interference fringes. In this way, the (temporal) frequency of the light is translated into a corresponding spatial frequency, whose intensity can be determined by a Fourier transform.

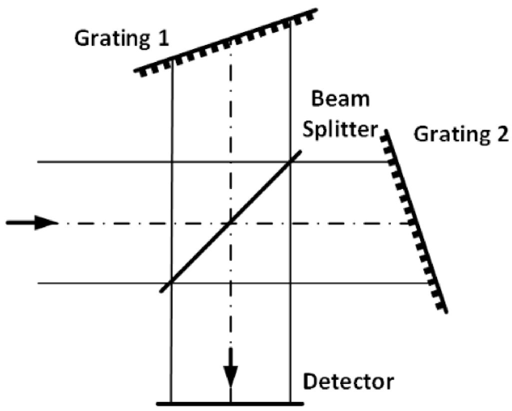

Fig. 4 *Principle of an SHS. Depending on the wavelength of the incoming light, the SHS generates a tilt between the wavefronts of object and reference arm. In this way, a fringe pattern is formed with a spatial frequency characteristic for the wavelength.*

Contrary to the schematic setup shown in Fig. 4, the SHS is designed in a focused geometry: the atmosphere, regarded as infinitely far away, is imaged onto the gratings, which are themselves imaged onto the detector. In this way, the direction perpendicular to the grating structures acts as spectral domain, whereas the parallel direction encodes the height information. The front and detector optics have been designed to show minimal aberrations despite the space constraints on board of the satellite. The assembly, in particular the gluing, is monitored live, with a tunable laser playing the part of the atmosphere.

4 The Rexus project

The first test of the system has been within the REXUS project 2017, a joint project between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB), in collaboration with the European Space Agency (ESA). Concieved as a programme for students, the SHS flew on board of a sounding rocket which achieved a maximum height of 84.3 km, and then fell back to the earth, guided by parachutes. Due to an accident while separating the payload from the booster section, the rocket unfortunately started tumbling very fast, such that none of the images was exposed to a stable atmospheric scene. Figure 5 shows one of the acquired images, while Fig. 6 displays the corresponding spectrum. Because of the fast tumbling, the data cannot be used to draw conclusions about temperature. Nevertheless, the mission was a success, verifying the capability of the system to measure atmospheric temperature.

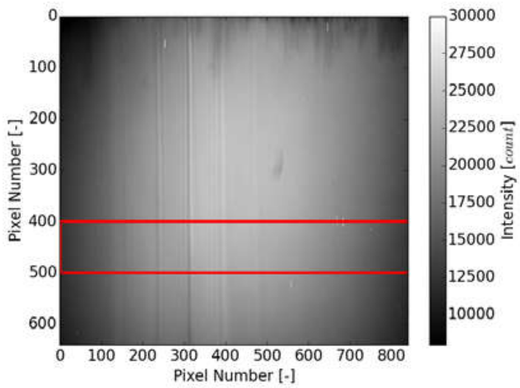

Fig. 5 *An interferogram obtained with the SHS from the atmosphere of the earth. The indicated area was used to calculate the spectrum.*

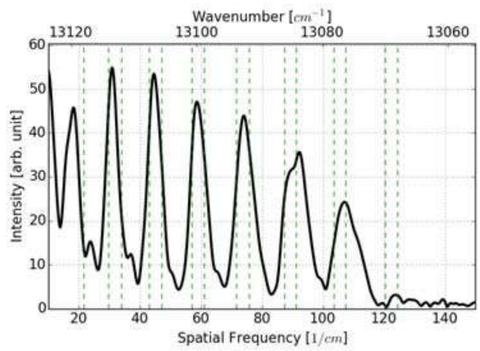

Fig. 6 *The spectrum resulting from the interferogram.*

Future research includes a generalization of the SHS concept to measure the Doppler shift of the spectral lines, giving information about wind systems.

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