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Characterization and simulation of a ground-based millimeter wave observation system for Arctic atmospheric research

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ABSTRACT

A preparatory performance and error characterization was carried out for a ground-based millimeter wave instrument designed for high Arctic atmospheric research. The instrument is a radiometer to measure rotational emission spectra of O_3, ClO, HNO_3, and N_2O, between 265 and 280 GHz, using a sensitive superconductor–insulator–superconductor detector. Forward and inverse modeling tests have been performed to assess the instrument/inversion system and to determine the sources of the most significant errors in the retrieval of each trace gas. The altitude ranges over which retrievals of concentrations can be made were found to be ~13–62 km for O_3, ~12.5–39 km for N_2O, ~12–36 km for HNO_3, and ~18–46 km for ClO. For each target species the measurement and smoothing errors calculated with an optimal estimation method (OEM) were compared to the errors calculated from inversions of 500 simulated spectra. The absolute error from these inversions agreed well the OEM results, but there were systematic differences that are attributed to nonlinearities in the forward model. The results of these nonlinearities can cause biases of the order of 5–10% of the a priori profile if they are not accounted for when averaging concentration profiles or when analyzing trends in concentration. The techniques used here can be applied to any ground-based remote sounder.

1. Introduction

Over the last three decades it has become increasingly apparent that the composition of the Earth's atmosphere is sensitive to anthropogenic perturbations and so efforts to understand the underlying physical processes have increased [1]. Remote sensing, using ground-based and satellite-borne instruments, is the predominant method of observing the middle atmosphere (stratosphere and upper troposphere). While satellites can offer near global coverage, ground-based instruments provide datasets with high temporal resolution for a particular location. These ground-based datasets are essential for determining short-term (e.g. day-to-day) and longer-term (e.g. seasonal, yearly) variations in the atmospheric composition as well as for providing validation for satellite data.

The Polar Environment Atmospheric Research Laboratory (PEARL) at Eureka, Nunavut, Canada (80.05°N, 86.42°W) [2], is a high-Arctic station housing numerous instruments for characterizing atmospheric composition and dynamics. Among the instruments focusing on stratospheric ozone chemistry, none are currently capable of making continuous measurements of stratospheric chlorine monoxide (ClO). A new millimeter wave radiometer, SPÉIR, has been designed for this purpose. Millimeter wave and microwave spectroscopy offers the advantage of high frequency resolution in measured spectra, and relatively low Doppler broadening in the atmosphere, so that altitude profiles of the atmospheric composition can be obtained from ground-based observations the using pressure broadened spectra. In particular, the highly

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sensitive receivers employed for these observations have enabled measurement of trace gases with weak spectral lines, such as ClO, from ground-based instruments [3]. A history and description of millimeter wave remote sensing of the stratosphere can be found in [4].

Instruments currently installed at PEARL to make trace gas measurements either rely on the Sun to take measurements, which means that they cannot operate in the long period of 24-h darkness during polar winter, or they observe in spectral regions in which ClO signatures are too weak or nonexistent. SPÉIR's design enables the observation of emitted radiation from rotational transitions of ozone (O_3), nitric acid (HNO_3), nitrous oxide (N_2O), and ClO in the atmosphere and provide year-round information on the altitude distribution of each gas. ClO is involved in all of the reaction sequences in which Cl, originally released from species such as chlorofluorocarbons (CFCs), catalytically destroys ozone in the stratosphere [5]. HNO_3 is a key constituent in polar stratospheric clouds. The particles of the clouds act as sites for heterogeneous chemical reactions which convert chemically inactive chlorine compounds into more labile forms that can release Cl back into the catalytic cycles [6]. N_2O is a greenhouse gas and is a precursor for NO_x ($NO+NO_2$), which catalytically destroys stratospheric ozone [7]. N_2O has also been identified as a significant threat to the ozone layer of the 21st century [8]. PEARL is located such that measurements of these species can be made inside the polar vortex during Arctic winter and spring, and as each species is involved in polar ozone chemistry their observation is essential to understanding and predicting the changes occurring in the ozone layer and their connection with future climate.

This paper describes the characterization and the observation system simulation experiments (OSSEs) carried out to assess the performance of SPÉIR operating at Eureka. An observation system is defined here as the forward model, the instrument making the measurements, and the inversion scheme used to extract the desired quantities from the measurements. The goal is to determine the feasibility of the measurement technique, to guide the instrument design, and to set requirements on the knowledge of forward model parameters, including instrument parameters, atmospheric a priori data, and physical parameters such as spectral line data [9]. Designing an observation system without such an analysis is likely to lead to problems in interpreting the data.

The remainder of this paper is laid out as follows: Section 2 outlines the instrument design, the inversion technique, and analysis tools. Section 3 describes the observation and inversion set-up for the OSSEs. Section 4 outlines the characterization of the observing system, the OSSEs, and discusses the results, and conclusions are provided in Section 5.

2. Instrument, inversion technique, and analysis tools

2.1. SPÉIR

SPÉIR (meaning "*SKY*" in Irish) is a millimeter wave radiometer that has been designed at the University of Toronto to measure electromagnetic radiation emitted from the atmosphere between 265 and 280 GHz. This spectral range was chosen as it contains signatures from rotational transitions of O_3, HNO_3, N_2O, and ClO: the target species. This spectral region has been utilized for several ground-based instruments, including Millimeter wave Radiometer 2 (MIRA 2) [10] and Radiometer for Atmospheric Measurements At Summit (RAMAS) [11], as well as those used for the first published measurements of the diurnal variation of stratospheric ClO [12], and for the first observation of enhanced lower stratospheric ClO in the Antarctic ozone hole [13,14]. The detector selected for SPÉIR is a highly sensitive superconductor–insulator–superconductor mixer, SIS. This sideband-separating detector is already in use for band 6 of the Atacama Large Millimeter Array, ALMA, and has a noise temperature of $\sim$60 K in the frequency range of interest [15]. The tests in this work assume that the instrument is using one sideband to observe one species during a measurement. In SPÉIR, the atmospheric signal is down-converted to $\sim$4 GHz at the mixer by heterodyning with a local oscillator signal, and then amplified before being digitized and transformed into the spectral domain by a Fast Fourier Transform Spectrometer (FFTS). The mixer and preamplifiers are cooled to 4 K in a cryostat for operation. The measurement bandwidth is approximately 1 GHz with a spectrometer channel resolution of 1 MHz. SPÉIR's design includes two blackbody targets for calibration, at 77 K and at ambient temperature, with S11 reflections < -65 dB observed for backscatter measurements at 300 GHz [16]. A moveable pointing mirror mounted outside the lab directs atmospheric radiation to SPÉIR's room temperature optics, which in turn directs it through a window in the cryostat where a horn antenna couples the radiation to the mixer. The local oscillator signal is coupled to the mixer in a similar way through another window in the cryostat. The windows are several millimeters thick and they are angled with respect to the signal beam to reduce standing waves. Small fans will keep air moving across the outside of the windows to prevent any condensation.

There are two main observation techniques used for microwave remote sensing: total power and balanced. The choice of which to use usually depends on the strength of the atmospheric signal. For weaker signals that are affected by nonlinearities in the gain of the receiver, the balanced technique is used [17]. This method uses the difference between the atmospheric signal and a quasi-frequency independent reference signal (e.g. from a blackbody) in order to remove the effects of gain nonlinearity in the spectrum. Measurements of O_3 and N_2O will be made by analyzing the full atmospheric signal (total power measurement). Measurements of ClO and HNO_3 will be made using the balanced technique. The reference beam for these measurements is an internal signal created by blending the blackbody emission from the two calibration targets using a rotating polarizing grid [18]. The spectrum to be analyzed will be the difference of these two signals (balanced spectrum).

In both cases, the attenuation of the signal by the atmosphere must be taken into account. For the total power measurements, this is done during the inversion (see Section 2.2). For measurements using a reference beam, the balanced spectrum will be corrected using knowledge of the opacity of the atmosphere, τ_z. The opacity of the