# A Water Vapor Radiometer for the CO Mapping Array Project (COMAP)

Junhan Kim(1)(7), Kieran A. Cleary(1), Sandra O'Neill(1), James W. Lamb(2), David P. Woody(2), Andrew I. Harris(3), Delaney A. Dunne(1), Morgan Catha(2), Richard Hobbs(2), Jonathon Kocz(1)(4), Timothy J. Pearson(1), Liju Philip(5), Travis W. Powell(2)(6), and Anthony C. S. Readhead(1)

(1) California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA
(2) Owens Valley Radio Observatory, California Institute of Technology, Big Pine, CA 93513, USA
(3) Department of Astronomy, University of Maryland, College Park, MD 20742, USA
(4) Department of Astronomy, University of California, Berkeley, CA 94720, USA
(5) Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
(6) Great Basin Unified Air Pollution Control District, Bishop, CA 93514, USA
(7) E-mail: junhank@caltech.edu

***Abstract*—The CO Mapping Array Project (COMAP) is a carbon monoxide (CO) line intensity mapping experiment using a 19-feed 26–34 GHz focal plane spectrometer array on a 10.4 m dish at the Owens Valley Radio Observatory. We are developing a water vapor radiometer (WVR) that continuously measures the temporal variability of the atmosphere's water vapor content along the telescope's line of sight to better calibrate the COMAP science data. The WVR is designed to monitor the rotational transition line of water vapor around 22.2 GHz, with a spectral measurement between 18 and 26 GHz and a measurement of continuum at 28–30 GHz. Here we describe the COMAP WVR instrument system.**

## I. Introduction

The CO Mapping Array Project (COMAP) is a carbon monoxide (CO) line intensity mapping experiment located at Owens Valley Radio Observatory (OVRO), California [1]. As a ground-based radio astronomy experiment, atmospheric water vapor fluctuations contribute as one of the major contaminants in observing cosmological CO line emissions. The COMAP data processing pipeline currently applies filtering to subtract dominant modes, including fluctuation due to weather conditions, from the raw data [2]. However, direct measurement of the small-scale spatial and temporal variability of water vapor content will enable improved mitigation of its effect on the COMAP data. To conduct the measurement, we have developed a water vapor radiometer (WVR). The WVR is designed to utilize much of the existing COMAP receiver signal chain by adding a separate RF frontend [3].

## II. Water Vapor Radiometer Design

We aim to measure the $H_2O$ rotational transition line at 22.235 GHz. To accurately observe the line profile, we will make a spectral measurement between 18 and 26 GHz with 2 MHz resolution using the COMAP signal processing chain and a broadband measurement of the 28–30 GHz band for the subtraction of the continuum signal using a square-law detector. Primary components of the WVR system are (1) a quasi-optical system that directs the sky signal to the feedhorn and performs calibration with a chopper, (2) a signal chain that downconverts the sky frequency to an intermediate frequency (IF) band and processes both continuum and spectral measurement, and (3) a data acquisition system.

### A. Optics

We use Gregorian dual-reflector optics for the radiometer. We designed a compact WVR unit, and the simulated FWHM beam size of the radiometer optics corresponds to 4.4 deg at 18 GHz and 3.0 deg at 30 GHz. The elements of the quasi-optical system were machined and assembled in the Cahill Radio Astronomy Lab (Fig. 1). For instrument calibration, we installed a chopper between the primary and secondary mirrors for Dicke-switching using ambient and hot loads. The WVR unit will be installed near the edge of the COMAP 10.4 m primary dish so their beams will be co-aligned on the sky.

### B. Signal Chain

The COMAP receiver operates between 26 and 34 GHz with 2 MHz resolution, using a local oscillator (LO) at 24 GHz to downconvert the RF signal to an IF of 2–10 GHz [3]. For the WVR, we use a 16 GHz LO instead, to downconvert the 18–26 GHz RF to the same IF band of 2–10 GHz (Fig. 2). From this point, the WVR spectral signal is processed in the same way as for one of COMAP receiver chains. The IF signal is split into two 4 GHz wide bands, each of which is quadrature mixed to produce an in-phase ($I$) and quadrature ($Q$) signal. Each of these $I$ and $Q$ signals are digitized using a ROACH-2 digital processing unit (CASPER Collaboration; [4]) which performs digital sideband separation. The 28–30 GHz continuum signal will be measured with a square-law detector through a coupled port.

### C. Data Acquisition

The WVR will acquire a dataset of (1) spectral measurements around the 22 GHz water line through the COMAP signal path, (2) continuum measurements (28–30 GHz) using a square-law detector, and (3) auxiliary 'housekeeping' data, including the temperature of ambient and hot calibration loads and the encoder signal from the chopper assembly. The continuum signal and housekeeping data will be collected simultaneously by a LabJack ADC.

We will synchronize the time-series dataset and calibrate the WVR data in real time to obtain an estimate of sky brightness. Then, we will convert it to precipitable water vapor by performing a fit using an atmospheric model (e.g., [5], [6]).

## III. System Test and Receiver Sensitivity

We have performed a noise measurement of the signal chain with the classical Y-factor technique using ambient and liquid nitrogen cold loads. The measured receiver noise temperature is ∼550 K, corresponding to the 400–600 K noise temperature expected from the 3.8–4.8 dB noise figure of the first RF stage amplifier (Mini-Circuits ZVA-18403G+ with 43 dB typical gain). We have also performed an Allan variance measurement by taking time-series data through the signal path, and the Allan time is in the order of 10 s. The result demonstrates that we can integrate enough samples to suppress the noise and achieve the required sensitivity.

We designed a chopper assembly with a synchronous induction motor (Oriental Motor 3SK10GN-AUL), and the chopper rotates at a period of 1.2 s (50 rpm). The WVR feedhorn gets illuminated by the sky, ambient load, sky, and hot load during a single rotation of the chopper wheel. We expect each of the four phases to take ∼230 ms, excluding the transition time due to chopper geometry. From the radiometer equation, the integration time of $\tau = 0.9$ sec (two chopper rotations for sky signal; ∼230 ms×2 × 2) and $\triangle\nu = 1$ GHz bandwidth gives $\triangle T \sim 18$ mK sensitivity without gain fluctuation. The 22 GHz water vapor line contribution to the sky brightness is in the order of 10 K, and we will be able to perform the model fit with high significance.

## IV. Conclusion and Future Work

We have developed a WVR system for COMAP in order to monitor the time and spatial variability of the atmosphere's water vapor content. We expect that the calibration of the raw data using the water vapor measurement will improve the quality of COMAP science data and help detect the cosmological CO signal.

We plan to commission the instrument on the 10.4 m dish at OVRO in Fall/Winter 2022 and start operation in parallel with the COMAP observing campaign. To achieve the plan, we will optimize the mechanical elements of the system for mounting onto the telescope and finish developing a data acquisition pipeline. The weather data will be applied to the analysis of the rest of the five-year COMAP Pathfinder survey to constrain the CO power spectrum at $z \sim 3$ [7], [8].


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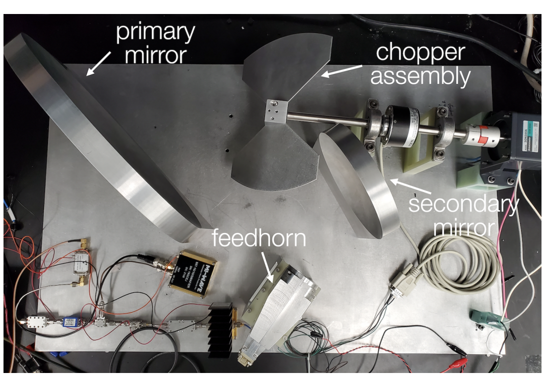


Fig. 1. The WVR assembly under test in the lab. The optical and mechanical elements comprising the WVR system are indicated. We will design a new enclosure with heated and ambient calibration loads installed for mounting onto the telescope.

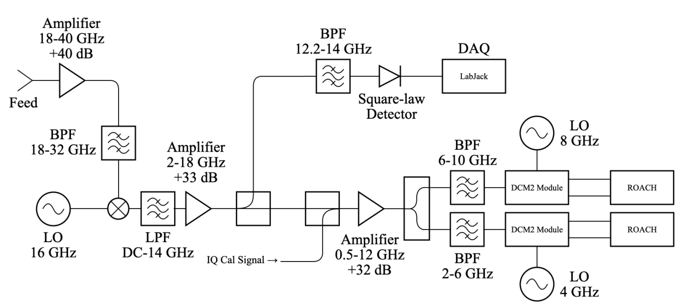


Fig. 2. Signal path for the WVR. The signals from the 18–26 GHz spectral and 28–30 GHz continuum channels are processed separately. For the detailed schematics of signal processing with the downconverter module ('DCM2'), see Fig. 2 in [3].