# A First Look at Inverse Problems for the Atmospheres of M and G Earth-like Planets

M. Vasquez, F. Schreier, S. Gimeno Garcia, and T. Trautmann

## Introduction

This work addresses the main question regarding how much can we learn from spectroscopic observations of Earth-like exoplanets along with what can we identify in terms of atmospheric conditions and biosignatures that may be present on the planet and serve as evidence of life. Since, in reality, there is limited information in the measured spectra of distant planets and scarce a priori knowledge, it is essential to determine which atmospheric parameters can be retrieved in preparation to characterize the atmospheres of small size planets. Using a high resolution infrared radiative transfer model, we calculate the emission spectra of Earth-like exoplanets and their partial derivatives with respect to the unknowns of the inverse problem (i.e. the so-called Jacobians). The analysis of the Jacobians, the (ill-) conditioning of the problem, and the correlation of the parameters allows to identify an optimal set of parameters that can be retrieved despite the limited quality of measured spectra.

## Scenarios and Input

- Earth-like planets around different host stars: G2V and M4.5V:
  - Atmospheric profiles from Kitzmann et al. A&A 2010 (See Fig. 1)
- HITRAN Molecular spectroscopic database: $CO_2$, $H_2O$, and $O_3$

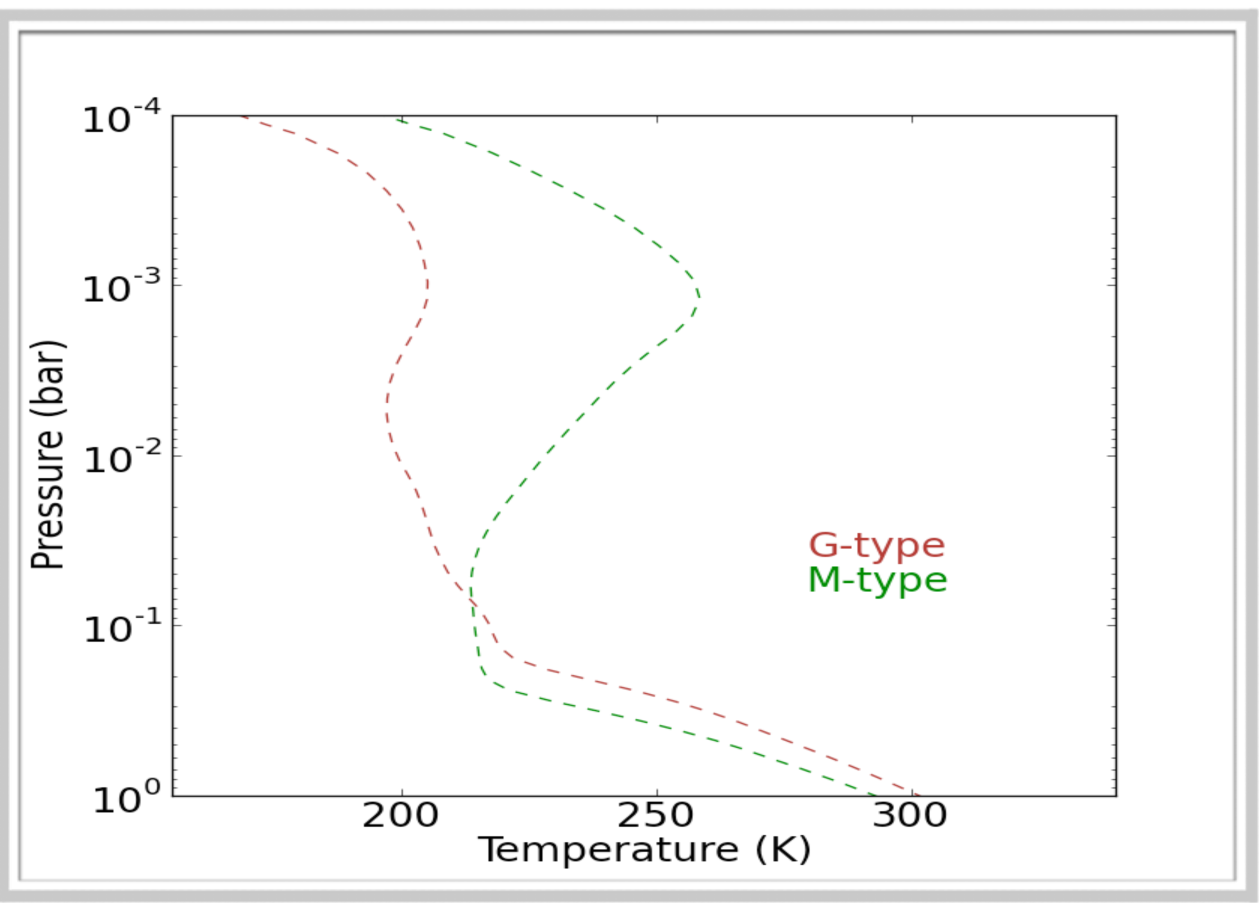


Figure 1: Atmospheric profiles of Earth-like planets around G and M stars.

## Jacobian Matrices

Sensitivity analysis based on Jacobians can reveal which parameters can be retrieved independently and which parameters have to be set a priori, depending on the type of observation and spectral domain. This also allows to determine which atmospheric parameters can be considered to be more reliable for retrievals. Fig. 2 shows Jacobians for the G and M star planets. The Jacobian for each derivative *i* is calculated from the numerical expression:

$$J_i(x) = \frac{y(x+\delta x_i) - y(x)}{\delta(x_i)}$$

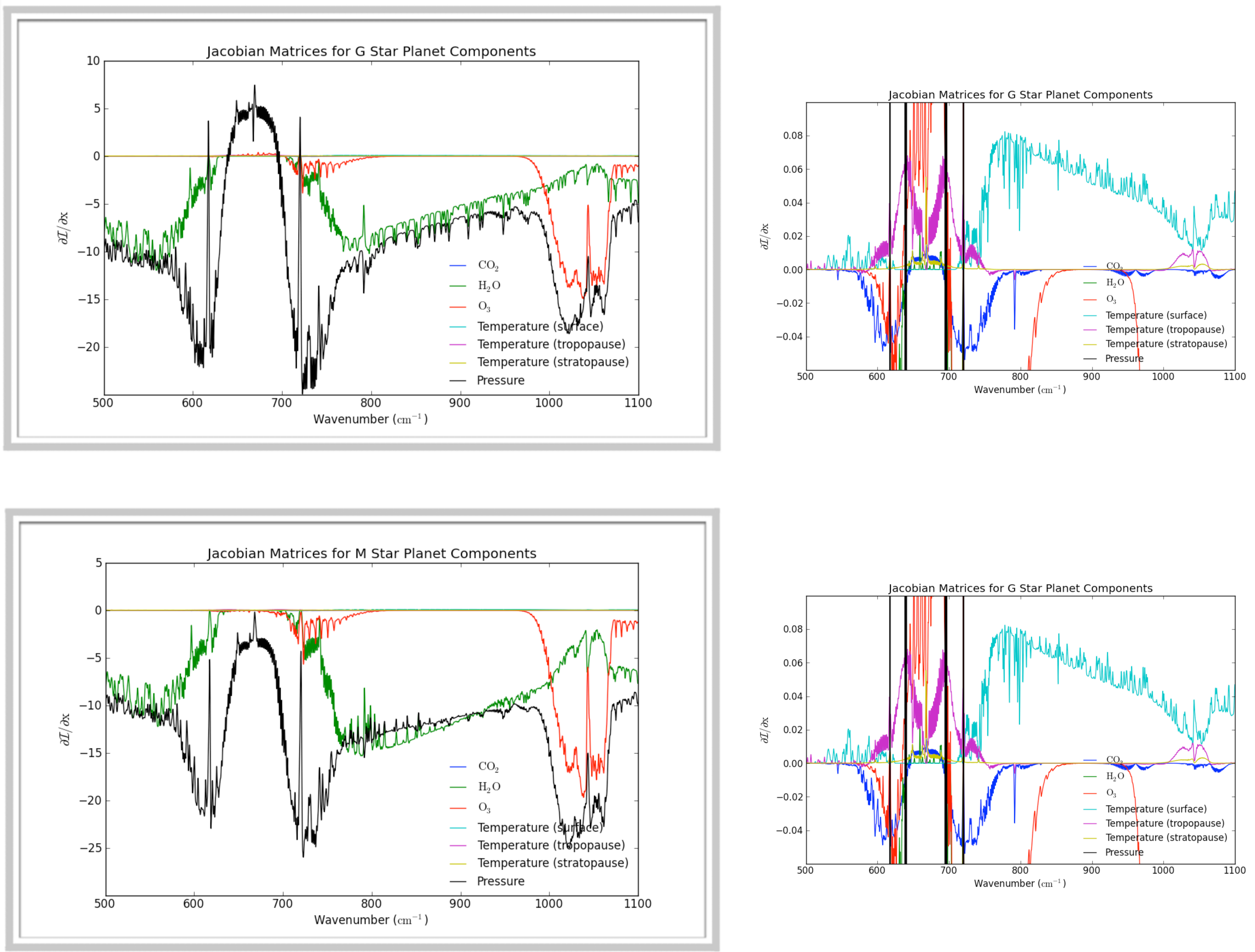


Figure 2: Jacobian matrices of Earth-like planets around G and M stars.

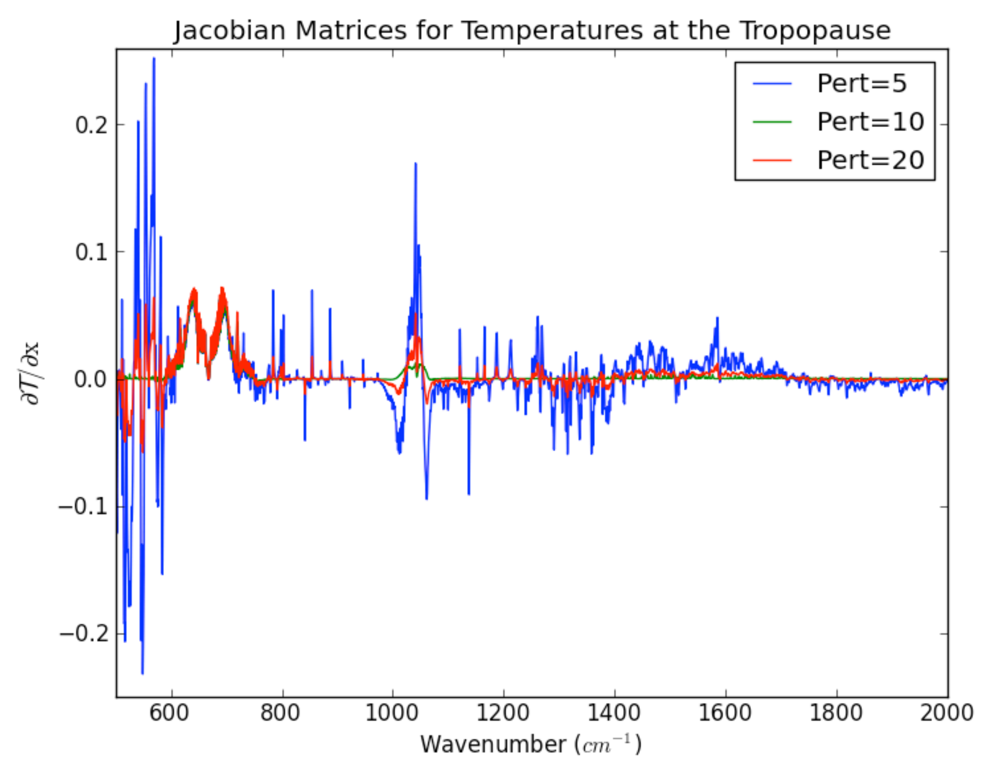


Figure 3: Jacobians with different perturbation values. A perturbation value of 10 was chosen for the calculations.

## Correlation Matrices

Correlation matrices have also been computed (see Fig. 4) to assess the statistical properties of the calculated Jacobians. The correlation coefficient is defined as:

$$Corr_{[i,k]} = \frac{Cov_{[i,k]}}{\sqrt{Cov_{[i,i]} Cov_{[k,k]}}} \qquad -1 \leq Corr_{[i,k]} \leq 1$$

where *Cov* is the covariance describing the linear relationship between two random variables. Correlations of zero values indicate non-linear relationships.

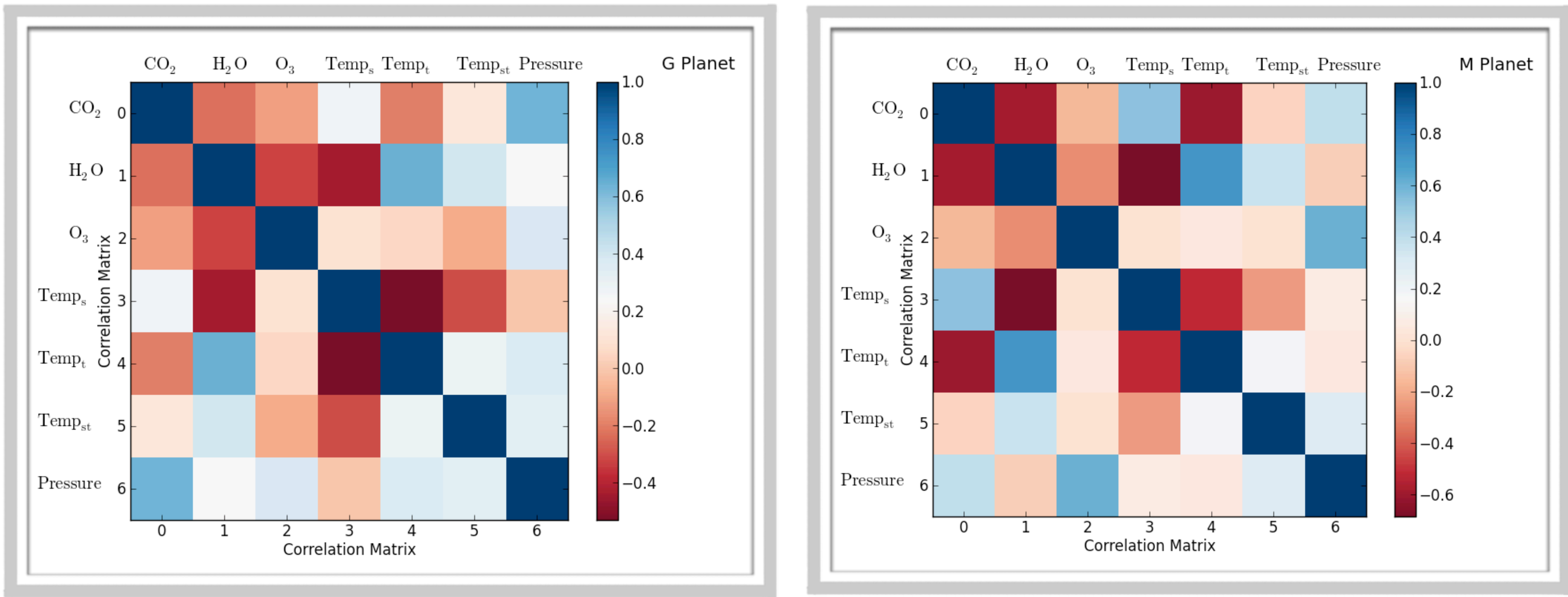


Figure 4: Correlation matrices of the Jacobians of Earth-like planets around G and M stars for various molecules, surface temperature ($Temp_s$), temperature at the tropopause ($Temp_t$), temperature at the stratopause ($Temp_{st}$), and pressure. $CO_2$ and $H_2O$ are highly correlated. The surface temperature and $H_2O$ also show large correlations.

## Sensitivity to Noise Level

A sensitivity study has been performed in order to assess the feasibility of retrieving $CO_2$ and $H_2O$ molecular concentrations from an observed spectrum with a 1% noise level (see Fig. 5).

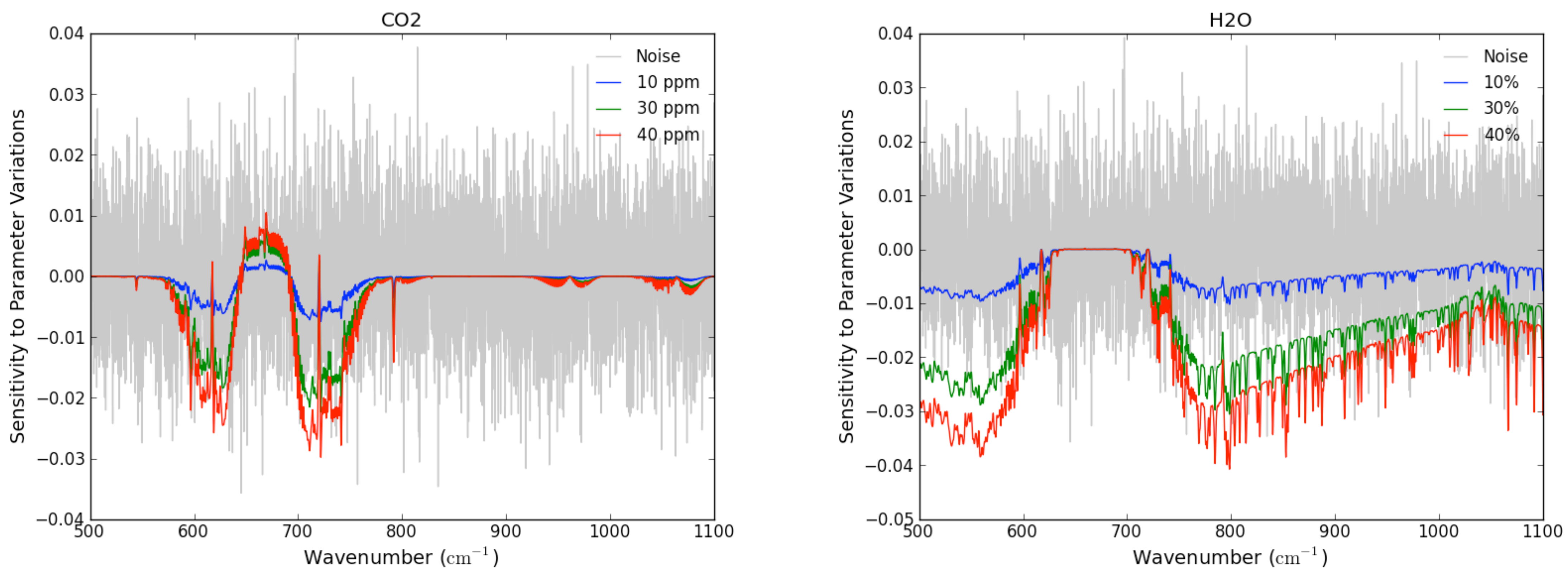


Figure 5: Sensitivity analysis of the Jacobians for the G star planet.

## Results

- First results indicate that the atmospheric parameters are more suitable to be retrieved from different spectral regions. For example, in case of $O_3$, the Jacobians show that its molecular concentrations in the atmosphere could be estimated from roughly 1041 $cm^{-1}$ (9.6 µm), where the molecule presents strong absorption. In case of $CO_2$, it is more reliable to derive its mixing ratios from about 700 $cm^{-1}$ (15 µm).
- Correlation values for the M star planet are larger. Main differences arise due to the temperature profile with missing inversion in the stratosphere of the M star planet. A different spectral range may be more suitable to retrieve if correlations are lower.
- From a measured spectrum with a noise level of 1%, it is possible to retrieve variations of 30 ppm $CO_2$ and 10% $H_2O$.

INSTITUT FÜR METHODIK DER FERNERKUNDUNG