Assessing the impact of telluric contamination on near-infrared RV measurements with IRD

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Summary

- Contaminations from the Earth's atmosphere on the observed stellar spectrum are one of the major limitations for precise radial velocity measurements.
- We investigated their error budget on RV measurements in the exoplanet survey with the InfraRed Doppler (IRD), a fiber-fed high-resolution spectrometer for the Subaru 8.2-m telescope.
- This study focused on forward modeling RV measurements at NIR. The impact of telluric lines there has not yet been well explored.
- We found that the residuals around telluric lines in the corrected spectrum seem to be insignificant (<1%).
- However, these residuals could cause RV variations of 1-2 m/s.

RV analysis pipeline of IRD

To correct for the impacts of time variable telluric lines and "instrumental profiles" (IPs) of IRD, we use a forward modeling technique (eq. (1), Hirano et al. 2020).

RV Pipeline

Stellar template spectrum S
(1) Removing telluric absorptions by Rapid Rotator (RR) or Telluric model (telluric standard star)

Telluric T
(2) Using Telluric model

RV fitting

$$f_{obs}(\lambda) = k(\lambda)\left[S\left(\lambda(1 - v_{obs}/c)\right)T(A; \lambda - v_{tell}/c)\right] * IP \quad (1)$$

Observed spectrum of the Target $f_{obs}(\lambda)$

There are two telluric removal steps in this RV pipeline, and two types of telluric models are used.

(1) Creating a stellar template spectrum
A template spectrum is created from observed spectra of targets by removing telluric lines. For this removal, we observe a rapid rotator as a telluric standard star, if possible, otherwise, we use a model telluric.

(2) RV fitting with a model target spectrum
We fit the observed target spectra with a model spectrum which is created by multiplying a doppler-shifted stellar spectrum and a model telluric. Model telluric is generated by interpolation of telluric spectra on the (W, A) grid, with optimizing A simultaneously.

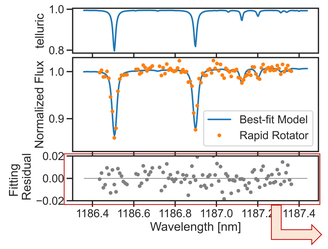
A) Rapid Rotator (RR) (Telluric standard star): Because the absorption lines of the star are broadened by its high-speed rotation, telluric features appear predominantly in the spectrum. It is observed ideally within a few hours of observing the target to make both have similar conditions and telluric features.

B) Model telluric: We use the theoretical transmission spectra generated by the Line By Line Radiative Transfer Model (LBLRTM: Clough et al. 2005). Models are generated in a 4×4 grid of $\mathbf{A} = (W, A)$.
W: water vapor content ($1.0\text{mm} < W < 5.0\text{mm}$)
A: target airmass ($1.0 < A < 2.9$)

Telluric model v.s. Rapid Rotator spectrum

~How well does the model telluric agree with real observations?~

[Method]
1. In RV fitting (eq. (1)), set a template ($\boldsymbol{S}$) to a featureless (1 at all λ) and a telluric ($\boldsymbol{T}$) to a RR observed spectrum.
2. Perform the fitting with a model telluric as usual.
3. Check the fitting residuals (Fig. 1)

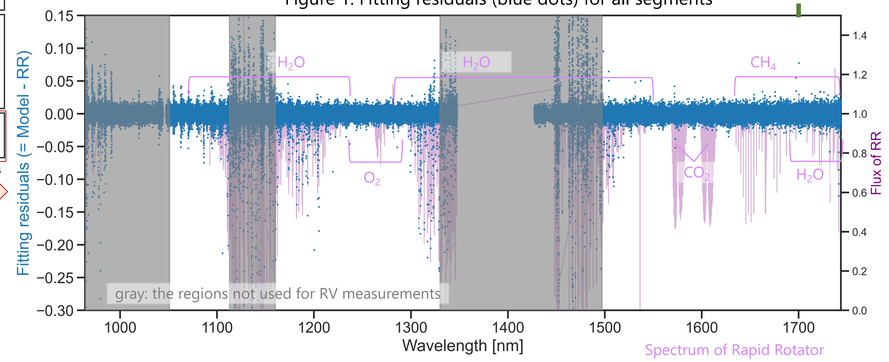


RV fitting is performed in each "segment" ($\Delta\lambda \sim 1$nm)

[Results]
- Residuals (i.e. difference between RR and model telluric) are typically ~1% in each segment.

Previous studies looking at NIR:
- ~ 4% in O_2 region (Ulmer-Moll et al. 2019)
- ~ 2% by comparing Molecfit and RR (Samesima et al. 2018)

Figure 1: Fitting residuals (blue dots) for all segments

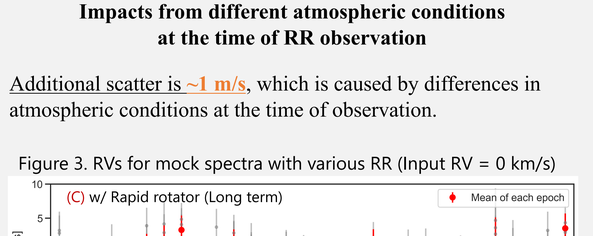


[Problem]
Shallow models being fitted to shallow telluric

- Observed with small airmass and PWV values
- The lack of a deep absorption line in a segment

[Estimated cause]
We found that among the fitted parameters, the telluric line shift in wavelength direction v_{tell} (in eq. (1)) have a large uncertainty. Therefore, this problem seems to be caused as shown in Fig. 4;

Figure 4. Images of the fitted lines for shallow line and deep line



[Solution?] *Not yet found...*
We have tried to improve the fitting process to solve this problem, but without good results.

- Fix parameters of airmass and PWV to known values
  → Worse outcomes ×
- Change priors of some parameters
  → Works well only in some wavelength ranges (Fig. 5) △

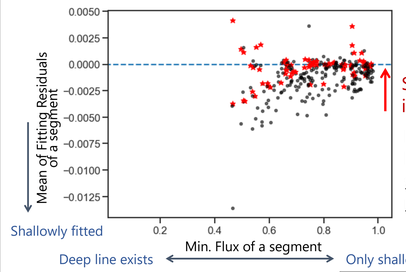


Figure 5.
Result for segments in strong H_2O absorption regions (1166 – 1188 nm)

Impact on RVs

~How much RVs change due to residuals of telluric removal~

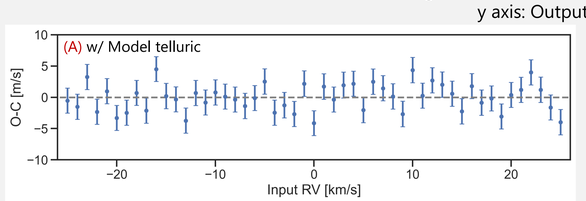
Phoenix 3,000 K spectrum + Model telluric | **Mock spectrum** | Phoenix 3,000 K spectrum + Rapid Rotator spectrum

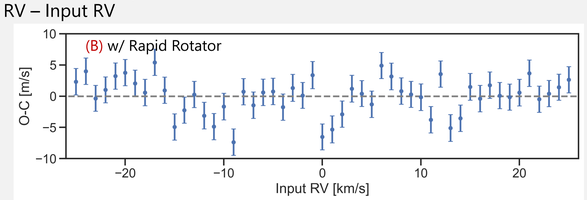
RV fit with model telluric
for -25 km/s ≦ RV ≦ +25 km/s

Fitting residuals exist around telluric absorption lines (see Fig. 1)

Results

Figure 2. RV measurements for mock spectra
y axis: Output RV – Input RV





- The standard deviation of (Output RV – Input RV) tends to be smaller than the mean of internal errors as expected (e.g., (A), with > 970 nm in Table 1).
- The standard deviation of (Output RV – Input RV) is larger than the mean of internal errors.
- Additional scatter is ~ 2 m/s, which is likely to be caused by the difference between RR and model telluric.

Mock spectrum	Wavelength range used	Internal error $\sigma_{internal}$ [m/s]	Std σ_{RV} [m/s]	$\sqrt{\sigma_{RV}^2 - \sigma_{internal}^2}$ [m/s]
(A) w/ Model telluric	> 1051.5 nm	2.02	2.17	0.81
	> 970 nm (incl. weak LFC region)	1.86	1.82	--
(B) w/ Rapid Rotator	> 1051.5 nm	2.11	2.91	2.00
	> 970 nm (incl. weak LFC region)	1.95	2.64	1.77
(C) w/ Rapid Rotator (Long term)	> 1051.5 nm	2.28 (2.05~3.38)	2.47	0.95 (< 1.38)

Table 1. Internal errors and RV scatter of RV measurements for mock spectra

Impacts from different atmospheric conditions at the time of RR observation

- Additional scatter is ~1 m/s, which is caused by differences in atmospheric conditions at the time of observation.

Figure 3. RVs for mock spectra with various RR (Input RV = 0 km/s)