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## The water vapor foreign-continuum in the 1.6 $\mu\text{m}$ window by CRDS at room temperature

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### Abstract

Water vapour foreign-continuum absorption cross-sections, CF, are measured for the first time at room temperature in the 1.6  $\mu\text{m}$  transparency window, of importance for atmospheric applications. The measurements are performed by cavity ring down spectroscopy (CRDS) at 15 selected spectral data points. These data, covering the 5700-6640  $\text{cm}^{-1}$  spectral range, are derived from the variation of the absorption signal during pressure ramps of humidified air up to 1 atm with a typical 1% humidity rate. The foreign-continuum absorption was obtained as the excess of the measured loss rate compared to the sum of the loss rate measured with dry air, the local water monomer contribution and the self-continuum absorption. CF values were derived from the linear dependence of the foreign-continuum absorption with the product of the partial pressures of water vapour and air. The semi-empirical MT\_CKD CF values are found significantly underestimated in the centre of the window. The temperature dependence is discussed using high temperature measurements available in the literature.

<b>Keywords</b>	Water vapor; foreign-continuum; MT_CKD model; CRDS; transparency window; atmosphere
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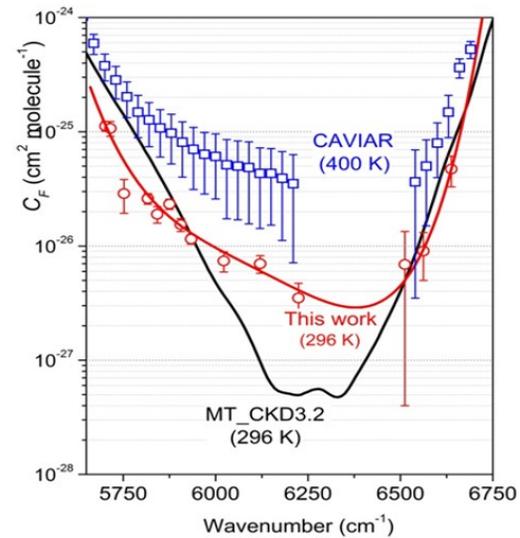
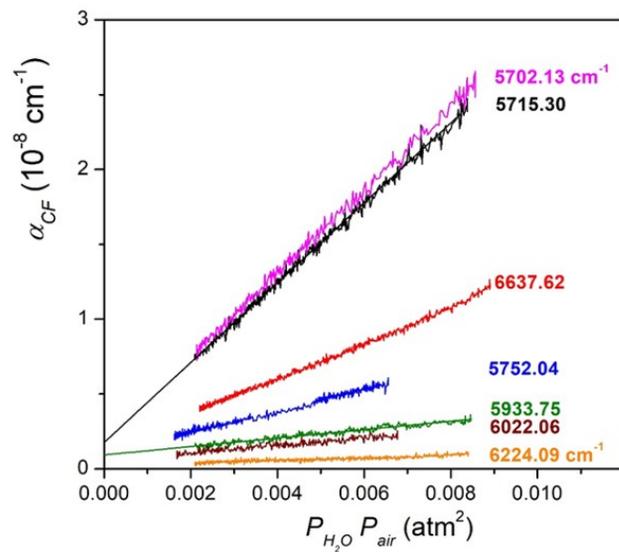
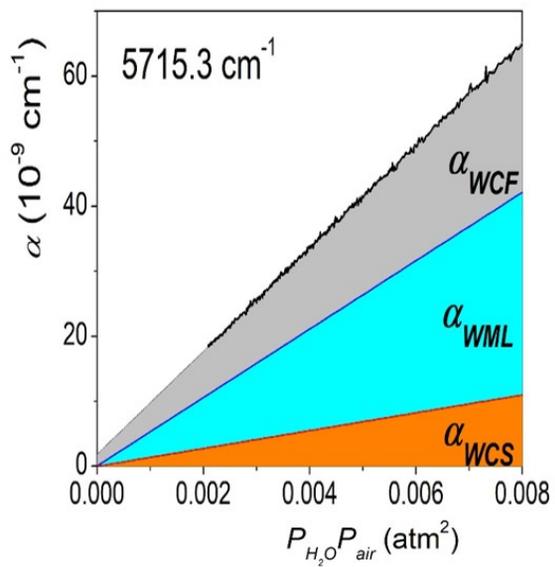
*St Martin d'Hères, the 21<sup>st</sup> of January 2020*

Dear Sir,

Please find attached the version of our paper entitled: *The water vapor foreign-continuum in the 1.6  $\mu\text{m}$  window by CRDS at room temperature* by D. Mondelain, S. Vasilchenko, S. Kassi, A. Campargue, submitted to JQSRT.

Best regards  
Didier Mondelain

- First water vapour foreign-continuum measurements at 296 K in the 1.6  $\mu\text{m}$  window
- CRDS loss rates were measured during pressure ramps of humidified air
- Cross-sections are provided for 15 spectral points between 5700 and 6750  $\text{cm}^{-1}$
- Derived foreign cross-sections are larger than the semi-empirical MT\_CKD values





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### Abstract

Water vapour foreign-continuum absorption cross-sections,  $C_F$ , are measured for the first time at room temperature in the 1.6  $\mu\text{m}$  transparency window, of importance for atmospheric applications. The measurements are performed by cavity ring down spectroscopy (CRDS) at 15 selected spectral data points. These data, covering the 5700-6640  $\text{cm}^{-1}$  spectral range, are derived from the variation of the absorption signal during pressure ramps of humidified air up to 1 atm with a typical 1% humidity rate. The foreign-continuum absorption was obtained as the excess of the measured loss rate compared to the sum of the loss rate measured with dry air, the local water monomer contribution and the self-continuum absorption.  $C_F$  values were derived from the linear dependence of the foreign-continuum absorption with the product of the partial pressures of water vapour and air. The semi-empirical MT\_CKD  $C_F$  values are found significantly underestimated in the centre of the window. The temperature dependence is discussed using high temperature measurements available in the literature

## 63 1. Introduction

64 Water vapour is known to strongly absorb the infrared radiations in the Earth's atmosphere  
65 and thus to play a key role in its radiative budget [1]. In addition to the usual absorption by  
66 water rovibrational lines, water vapour is responsible for an absorption slowly varying with  
67 wavenumber, the so-called water vapour continuum. Paynter and Ramaswamy studied the  
68 impact of this continuum in the atmospheric radiative transfer using their own empirical  
69 continuum model (BPS continuum) [2] and the semi-empirical MT\_CKD model [3,4]. These  
70 models exhibit differences which can be particularly important in the mid- and shortwave IR  
71 regions leading to significant changes (up to  $1 \text{ Wm}^{-2}$ ) of the atmospheric absorption. It is thus  
72 important to produce accurate experimental absorption cross-sections to test and validate  
73 these empirical models, in particular in the transparency windows where the relative impact of  
74 the continuum is the largest. Since now one decade, large experimental efforts have been  
75 performed to complete the pioneer works of Burch [5,6,7], using different techniques: Fourier  
76 transform spectroscopy (FTS) [8,9,10,11], cavity enhanced absorption spectroscopy (CEAS)  
77 [12,13,14,15,16,17,18,19,20,21], calorimetric interferometry [22,23] and photo-acoustic  
78 spectroscopy [24]. This is particularly true for the self-continuum absorption due to the  
79 interaction between two water molecules. As a result, the latest version (3.2) of the MT\_CKD  
80 self-continuum has been recently constrained in the 4.0, 2.1, 1.6 and 1.25  $\mu\text{m}$  windows [25],  
81 taking into account most of the CEAS cross-sections of Refs. [16,17,18,19,21].

82 In the case of the foreign-continuum arising from interactions between water molecules and  
83 molecular oxygen and nitrogen, scarce experimental data are available [26], in particular at  
84 room temperature. This includes in-band continuum measurements in the  $3500\text{--}4000 \text{ cm}^{-1}$   
85 spectral range by direct absorption spectroscopy [7] and between  $1300$  and  $7500 \text{ cm}^{-1}$  by FTS  
86 [27]. As concerned the transparency windows, cross-sections provided by FTS [28,29,30] in  
87 the mid-IR windows and by cavity ring down spectroscopy (CRDS) in the  $2.1 \mu\text{m}$  window  
88 [19] have led to a significant increase of the MT\_CKD foreign-continuum since the 2.8  
89 version [25]. Note that FTS data were reported by the CAVIAR consortium at high  
90 temperature ( $350\text{--}430 \text{ K}$ ) over the wide  $1.1 - 5.0 \mu\text{m}$  spectral range thus including the  $1.6 \mu\text{m}$   
91 window of present interest [31]. Additional measurements by CRDS are available at  $10.6 \mu\text{m}$   
92 [13], in the  $0.94 \mu\text{m}$  absorption band [32] and, very recently, in the  $2.1 \mu\text{m}$  window by our  
93 group [20]. This latter work compared with [31] at high temperature shows a weak positive  
94 temperature dependence of the foreign continuum also reported in the infrared in the  $296\text{--}363$   
95  $\text{K}$  range [28,29] and in the  $260\text{--}360 \text{ K}$  range near  $183 \text{ GHz}$  [33].

96 Note that these experimental investigations, in particular the temperature dependence, may  
97 provide insights on the origin of the continuum which can be due to different processes like  
98 the far wings of the rovibrational lines, water dimers (in the case of the self-continuum) and  
99 collision-induced absorption (CIA) [34,35].

100 The present work is part of an extensive study that we conduct since several years to better  
101 characterize the water vapour continuum absorption in the short-wave and mid-infrared  
102 transparency windows [14,15,16,17,18,19,20,21]. The self-continuum including its  
103 temperature dependence was investigated by CRDS in these references. Because of the  
104 weakness of the signal to be measured, the experiment is particular challenging in the 1.6  $\mu\text{m}$   
105 window. This applies in particular for the foreign-continuum measurements which require  
106 relatively large changes in the gas pressure which may affect the optical alignment. In the  
107 following part 2, we will present the experimental procedure adopted for the determination of  
108 the foreign-continuum cross-sections at room temperature at 15 selected spectral points of the  
109 1.6  $\mu\text{m}$  window. Data acquisition by CRDS and data treatment as well as the error budget will  
110 be discussed in part 3 and the resulting data will be compared to experimental data available  
111 in the literature and to the MT\_CKD model in part 4.

## 112 **2. Experimental**

### 113 *2.1 The CRDS setups*

114 Measurements were performed using two cavity ring down spectrometers. As described in  
115 [36], a distributed feedback (DFB) laser diode (either from Eblana Photonics or NEL) is  
116 coupled into a high finesse cavity fitted by two mirrors with highly reflective coatings. Our  
117 two spectrometers used mirrors optimized for the 1500-1700 nm and the 1730-1840 nm  
118 spectral regions. The output mirror of the cavity is mounted on a piezoelectric transducer to  
119 periodically change the cell length allowing covering one free spectral range (FSR) of the  
120 cavity and thus achieving resonance between the laser light and one longitudinal mode of the  
121 cavity. After a build-up time necessary to fill the cavity with photons at resonance, the  
122 injection of laser light is stopped thanks to an acousto-optic modulator and the purely  
123 exponential decay time of photons leaking from the cavity (*i.e.* the ring down (RD) time,  $\tau$ ) is  
124 measured with a photodiode. The fitted RD time is directly related to the absorption  
125 coefficient of the absorbing gas,  $\alpha(\nu)$ , through equation (1).  
126

$$127 \quad \alpha(\nu) = \frac{1}{c\tau(\nu)} - \frac{1}{c\tau_0(\nu)} \quad (1)$$

128 With  $c$  the speed of light,  $\nu$  the laser frequency and  $\tau_0$  the ring down time with the optical  
129 cavity empty or filled with a non-absorbing gas.

130 To measure the laser frequency, a part of the laser light was directed via a fibre either to an  
131 optical interferometer-based wavelength meter (model 621-A IR from Bristol,  $\pm 1.5 \times 10^{-3} \text{ cm}^{-1}$   
132 accuracy or model WA-1650 from Burleigh,  $\pm 1.1 \times 10^{-3} \text{ cm}^{-1}$  accuracy) or to a Fizeau  
133 wavelength meter (High Finesse WS-U-30 IR,  $6.6 \times 10^{-4} \text{ cm}^{-1}$  accuracy) depending on the  
134 selected data point and on the availability of the instrument.

135 A 1000 mbar pressure gauge (model 622AB from MKS instruments) was installed on the  
136 cavity to continuously measure the total pressure with an accuracy of 0.15% between 100 and  
137 1000 mbar. A temperature sensor (TSic 501 from IST,  $\pm 0.1 \text{ K}$  accuracy) was fixed on the  
138 external wall of the cavity and enveloped by thermal insulation foam to continuously record  
139 the temperature.

## 140 *2.2. Data acquisition*

141 Foreign continuum cross-sections were determined for 15 spectral points between  $5700 \text{ cm}^{-1}$   
142 and  $6640 \text{ cm}^{-1}$  (see **Table 1**). Each spectral point corresponds to the frequency of the radiation  
143 delivered by a distributed feedback (DFB) laser diode. Some measurements were repeated  
144 several times to check the repeatability. The spectral points were selected because they are  
145 located in spectral intervals mostly free of absorption lines and thus correspond to weak local  
146 monomer contribution. The following procedure was adopted to derive the foreign cross-  
147 section value at each selected spectral point.

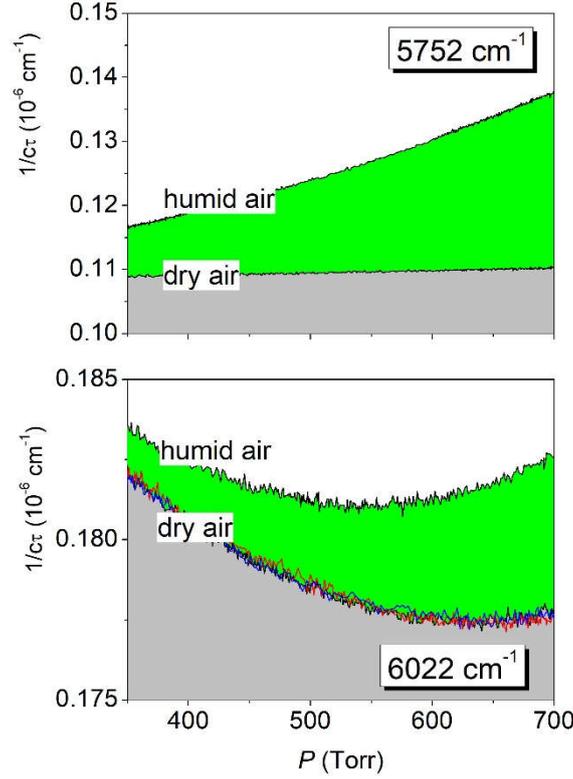
148 The high finesse cavity was first flushed with dry air (Alphagaz 2 from Air Liquide, purity  $>$   
149  $99.9999\%$ ) at a total pressure of 700 Torr, regulated with a solenoid valve and a proportional  
150 integral software based loop acting on the gas flow. A spectrum, including at least one  
151 isolated water line reported in HITRAN2016 [37] with an accuracy between 1% and 2%  
152 (called the reference line, hereafter), was recorded to check the low residual water vapour  
153 concentration (typically on the order of 100 ppmv). The loss rate,  $\frac{1}{c\tau_0(\nu)}$ , at the laser frequency  
154 fixed to one of the selected spectral points was measured during pressure ramp of dry air  
155 decreasing from 700 Torr to 350 Torr (**Figure 1**). The typical duration of the pressure ramp  
156 was a few minutes.

157 As mentioned above a major difficulty of the experiment is that the amplitude of the pressure  
158 variation required to measure the foreign-continuum induces significant changes in the optical  
159 alignment of the CRDS cavity. As illustrated in the dry air recordings of **Fig. 1**, the pressure  
160 induced variation of the loss rate is mostly negligible on the edges of the window but, in the  
161 centre of the window, reaches values on the order of the additional losses due to water in the  
162 humidified air recordings. This would prevent foreign-continuum determination if the

163 observed pressure induced variation were not repeatable. In fact, as illustrated in the  
164 superimposed traces of the dry air recordings presented in **Fig. 1**, the pressure effect on the  
165 optical alignment was checked to be highly repeatable allowing to use dry air pressure ramps  
166 as zero absorption baseline of the humidified air pressure ramps.

167 After the dry air recording, the cell was evacuated and filled with humidified air up to 700  
168 Torr using a home-made humidifier [20]. Humidified air was flushed until a constant water  
169 vapour concentration of typically 1% was achieved (Above this value, the water concentration  
170 was not stable enough. In order to check the stability of the water partial pressure, a series of  
171 consecutive CRDS spectra, including the reference water line, was recorded. For each  
172 spectrum, the concentration was deduced from a fit to the water absorption line using a Voigt  
173 profile. Once the water relative concentration in the cell was stabilized within better than 1%  
174 (typically after 60 min), the injection of humidified air was stopped and the loss rates were  
175 measured at the selected spectral point, during pressure ramp decreasing from 700 to 350 Torr  
176 (**Figure 1**). An additional spectrum around the reference line was recorded at 350 Torr to  
177 check that the water vapour concentration has remained unchanged during the ramp.

178 For this type of measurements, the stability of the ramp is essential. This is why we checked  
179 carefully both the short-term and long-term stability of our set-up by recording several  
180 decreasing and increasing dry air ramps consecutively and comparing dry air ramps recorded  
181 at several hours of distance and/or at different days for a given spectral point. We observed a  
182 very good repeatability with no detectable changes on the short term scale (**Figure 1**) and  
183 changes of  $5 \times 10^{-10} \text{ cm}^{-1}$  (offset) at maximum on the long term scale (over days) which  
184 represents between 2% and 50% of the maximum measured absorption of the foreign-  
185 continuum, depending on the considered spectral point. Let us mention that pressure ramps  
186 were restricted to the 350 - 700 Torr range as a small hysteresis, probably caused by changes  
187 in the mirror alignment, was observed when the cell was fully evacuated. Note that the  
188 procedure described here based on pressure ramps at fixed frequency was adopted because it  
189 is less time consuming than that applied in reference [20], where spectra of air with different  
190 water vapour concentrations were recorded.



191

192 *Figure 1. Variation of the CRDS loss rate for humidified and dry air pressure ramps on the low*  
 193 *energy edge (5752 cm<sup>-1</sup>) and near the center (6022 cm<sup>-1</sup>) of the 1.6 μm window. Note the variation of*  
 194 *the loss rate of the dry air recordings with pressure due to a change of the mirrors alignment. This*  
 195 *variation is checked to be repeatable by the superposed results obtained here for three dry air*  
 196 *pressure ramps at 6022 cm<sup>-1</sup> (lower panel). Note the different amplitude of the losses due to water*  
 197 *vapor (green) at 5752 cm<sup>-1</sup> and 6022 cm<sup>-1</sup>*

### 198 3. Analysis and resulting $C_F$ cross-sections

#### 199 3.2 Data analysis and $C_F$ cross-sections retrieval

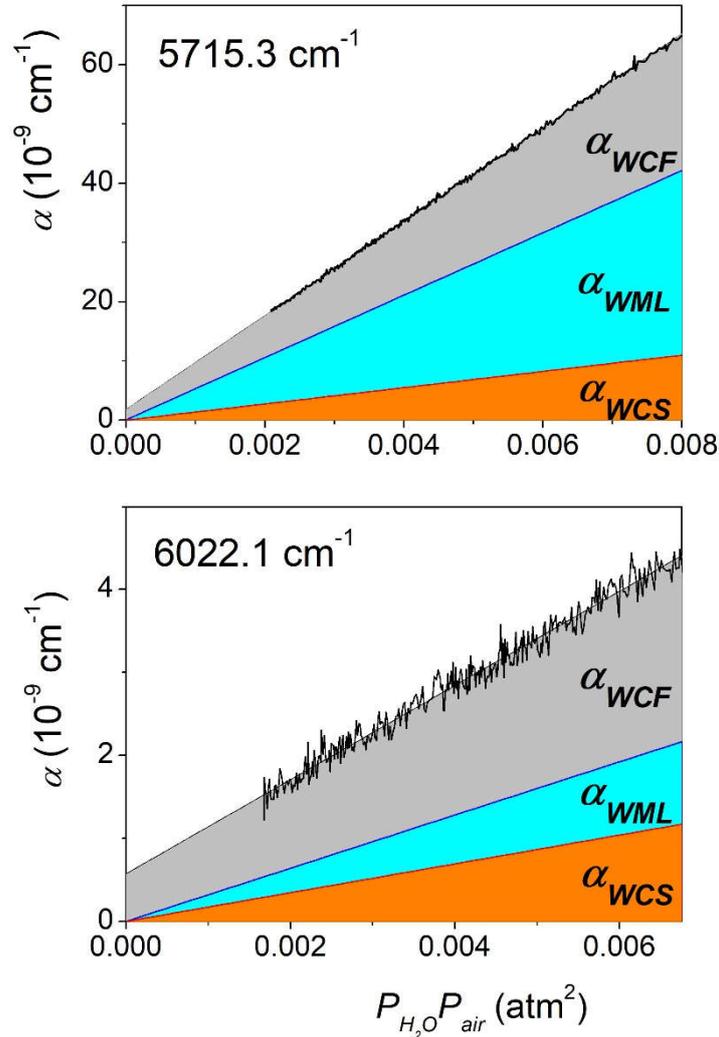
200 In a mixture of water vapor in air, the total absorption coefficient can be expressed as the sum  
 201 of four terms:

$$\begin{aligned}
 202 \quad \alpha_{tot}(\nu, T) &= \alpha_{cavity} + \alpha_{WML} + \alpha_{WCS} + \alpha_{WCF} \\
 203 \quad &= \alpha_{cavity} + \alpha_{WML} + \frac{1}{kT} C_S(\nu, T) P_{H_2O}^2 + \frac{1}{kT} C_F(\nu, T) P_{H_2O} P_{air} \quad (2)
 \end{aligned}$$

204 where  $\alpha_{cavity}$ ,  $\alpha_{WML}$ ,  $\alpha_{WCS}$  and  $\alpha_{WCF}$  are the contributions due to the cavity, water vapor  
 205 “monomer local lines” (WML), water vapor self-continuum (WCS) and foreign-continuum  
 206 (WCF), respectively.  $C_S$  and  $C_F$  cross-sections are expressed in cm<sup>2</sup> molecule<sup>-1</sup> atm<sup>-1</sup>.

207 From Equation (2), the foreign continuum absorption for a total pressure  $P = P_{air} + P_{H_2O}$ , is thus  
 208 obtained by subtracting three contributions from the measured humidified air absorption  
 209 ( $\alpha_{tot}$ ): the dry air signal ( $\alpha_{cavity}$ ) for the same total pressure,  $P$ , corresponding to the losses of  
 210 the cavity in absence of water vapor, the contribution of the air-broadened rovibrational  
 211 lines,  $\alpha_{WML}$ , and the water vapor self-continuum absorption at the  $P_{H_2O}$  partial pressure. Note

212 that at a total pressure of 700 Torr, losses due to Rayleigh scattering in dry air and in air  
 213 humidified with 1% water concentration differ by a negligible quantity of  $2 \times 10^{-11} \text{ cm}^{-1}$   
 214 calculated from [38].

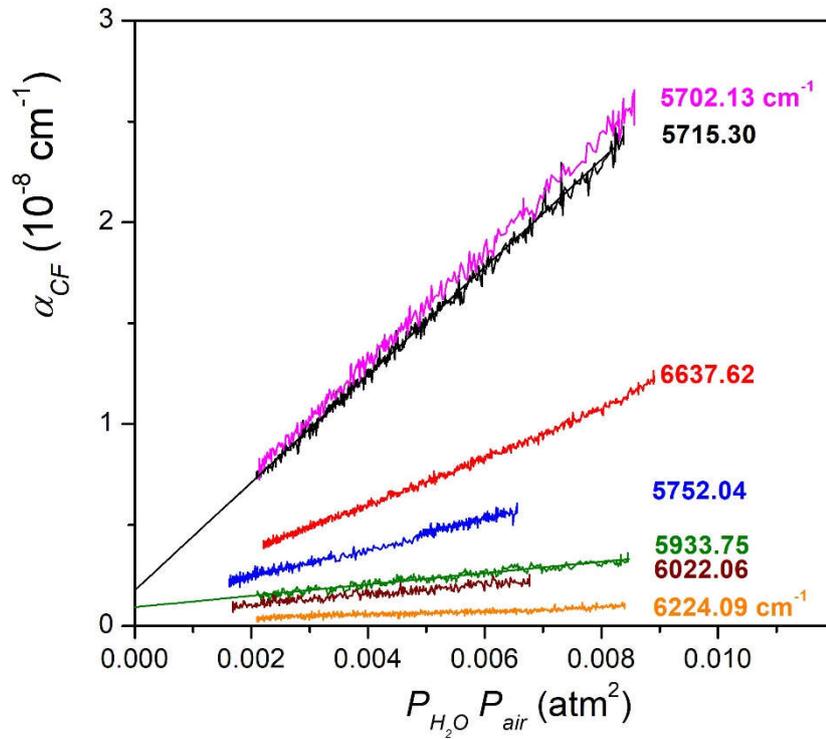


215  
 216 *Figure 2. Humidified air pressure ramp recorded at  $5715.30 \text{ cm}^{-1}$  (left panel) and  $6022.06 \text{ cm}^{-1}$  (right*  
 217 *panel) after subtraction of the dry air ramp (black solid line). The water monomer local contribution*  
 218 *( $\alpha_{WML}$ ), the self- ( $\alpha_{WCS}$ ) and the foreign-continuum contributions ( $\alpha_{WCF}$ ) are also plotted. The water*  
 219 *relative concentration,  $P_{H_2O}/P_{air}$ , on the order of 1% was maintained constant during the pressure*  
 220 *ramp.*

221 After subtraction of the baseline, the quantity  $\alpha_{tot} - \alpha_{cavity} = \alpha_{WML} + \alpha_{WCS} + \alpha_{WCF}$  shows  
 222 a linear dependence with  $P_{H_2O}P_{air}$  as illustrated in **Figure 2**. In particular, note the linearity of  
 223  $\alpha_{tot} - \alpha_{cavity}$  achieved at  $6022.1 \text{ cm}^{-1}$  confirming that the pressure effects on the mirror  
 224 alignment, although important (see lower panel of **Figure 1**), is corrected by using the dry air  
 225 measurements. The lines contribution was simulated at the selected spectral points, for total  
 226 pressures of 350, 500, 600 and 700 Torr and the  $P_{H_2O}$  partial pressure fixed to its measured  
 227 value (corresponding to about 1% concentration). Simulations were performed using the

228 HITRAN2016 line list [37], using a Voigt profile and the standard  $[-25 \text{ cm}^{-1}, +25 \text{ cm}^{-1}]$   
 229 convention cut-off for the line wings [9]. The selected spectral points,  $\nu_i$ , being located at  
 230 frequency values far from line centers, the pressure dependence of  $\alpha_{WML}$  is proportional to  
 231  $P_{H_2O}P_{air}$ . The pressure dependence of the simulated  $\alpha_{WML}$  values were thus fitted with a  
 232 second order polynomial which was used to subtract the local line contribution over the  
 233 pressure ramp (**Figure 2**). The self-continuum contribution was calculated using the self-  
 234 continuum cross-sections from [20]. As the pressure ramps were performed at constant  
 235 humidity rate ( $P_{H_2O}/P_{air} \approx 1\%$ ),  $\alpha_{WCS}$  is also proportional to  $P_{H_2O}P_{air}$ . The relative  
 236 contributions of the local monomer and of the self- and foreign-continuum, to the total  
 237 absorption are provided in **Table 1**.

238 **Figure 3** shows the achieved linear dependence of  $\alpha_{WCF}$  versus  $P_{H_2O}P_{air}$  for different  
 239 selected spectral points. The change of the slope illustrates the frequency dependence of the  
 240 foreign-continuum cross-sections which were derived from a linear fit (Eq.2). A small  
 241 positive offset is observed at null pressure. The origin of this offset is not clear. After several  
 242 tests, we only observed that the slope seems not being affected by a change of the offset  
 243 value. No offset of this sort was observed in our previous measurements in the  $2.3 \mu\text{m}$   
 244 window [20].



245  
 246 *Figure 3. Absorption coefficient of the foreign-continuum for pressure ramps obtained for different*  
 247 *selected spectral points. Two linear fit are also added to show the small observed offsets.*

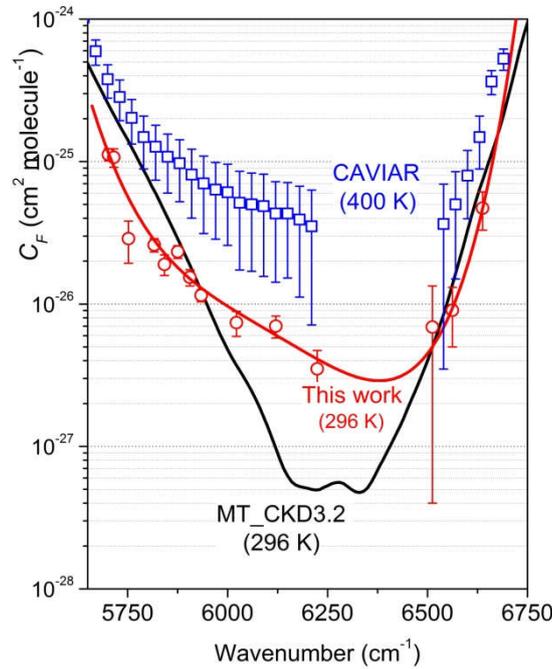
248 The  $C_F$  values derived from the procedure described above are listed in **Table 1** and presented  
 249 in **Figure 4**. A 5<sup>th</sup> order polynomial fit of the  $C_F$  cross-sections (weighted by their  
 250 uncertainties) is also shown in **Figure 4** and was used to provide  $C_F$  cross-sections every 10  
 251  $\text{cm}^{-1}$  between  $5700 \text{ cm}^{-1}$  and  $6640 \text{ cm}^{-1}$  as Supplementary Material.

252 *Table 1. Foreign-continuum cross-sections in the 1.6  $\mu\text{m}$  window and their  $1\sigma$  estimated uncertainties*  
 253 *in units of the last digit (in parenthesis). The relative contributions of the “local line monomer”, self-*  
 254 *and foreign continuum to the total absorption are also given in the three last columns. During the*  
 255 *whole period of measurements temperature varied between 296 K and 298.5 K.*  
 256

$\nu$ $\text{cm}^{-1}$	$C_F$ $\text{cm}^2 \text{ molecule}^{-1} \text{ atm}^{-1}$	$\alpha_{WML}/\alpha_{tot}$ %	$\alpha_{WCS}/\alpha_{tot}$ %	$\alpha_{WCF}/\alpha_{tot}$ %
5702.13	$1.12(11)\times 10^{-25}$	48.5	17.9	33.6
5715.30	$1.07(16)\times 10^{-25}$	49.1	17.3	33.6
5752.04	$2.88(95)\times 10^{-26}$	61.0	21.3	17.7
5816.60	$2.60(28)\times 10^{-26}$	29.4	37.3	33.3
5842.20	$1.61(30)\times 10^{-26}$	28.8	39.7	31.5
	$1.90(30)\times 10^{-26}$			
	$2.20(30)\times 10^{-26}$			
5875.20	$2.42(24)\times 10^{-26}$	30.5	29.3	40.2
	$2.33(24)\times 10^{-26}$			
5905.72	$1.33(20)\times 10^{-26}$	25.5	37.1	37.4
	$1.76(20)\times 10^{-26}$			
	$1.53(20)\times 10^{-26}$			
5933.75	$1.03(10)\times 10^{-26}$	21.3	41.5	37.2
	$1.21(10)\times 10^{-26}$			
	$1.14(10)\times 10^{-26}$			
	$1.17(10)\times 10^{-26}$			
	$1.17(10)\times 10^{-26}$			
	$1.15(10)\times 10^{-26}$			
	$1.18(10)\times 10^{-26}$			
6022.06	$7.4(15)\times 10^{-27}$	25.9	30.6	43.5
6120.45	$7.0(12)\times 10^{-27}$	14.6	34.0	51.4
6224.09	$3.5(12)\times 10^{-27}$	17.9	36.6	45.5
6369.00 <sup>a</sup>	$<5\times 10^{-27}$			
6511.97	$6.9(65)\times 10^{-27}$	85.4	5.9	8.7
6562.18	$9.1(40)\times 10^{-27}$	79.4	8.0	12.6
6637.62	$4.7(14)\times 10^{-26}$	71.8	6.9	21.3

257

258 <sup>a</sup> Due to the large estimated uncertainty, only an upper limit value can be given at  $6369 \text{ cm}^{-1}$ .



259

260 *Figure 4. Overview of the foreign-continuum cross-sections,  $C_F$ , in the 1.6  $\mu\text{m}$  window obtained in this*  
 261 *work and found in the literature. The red solid line corresponds to the fit of our data with a 5<sup>th</sup>*  
 262 *polynomial. Note that for comparison purposes, the  $C_F$  values are density normalized and are given in*  
 263  *$\text{cm}^2 \text{ molecule}^{-1}$ .*

### 264 3.3 Error budget

265 Uncertainties on the derived  $C_F$  values have been calculated with the error propagation  
 266 approach using Eq. 2 and assuming uncorrelated variables. As discussed earlier, the baseline  
 267 stability was evaluated to be below  $5 \times 10^{-10} \text{ cm}^{-1}$ . Temperature and total pressure are measured  
 268 with accuracies of 0.1K and 0.15%, respectively. Their contributions are almost negligible.  
 269 The uncertainties on  $C_S$  values used here are reported in [20].

270 The knowledge on the water vapour partial pressure is the main contributor to the error budget  
 271 through the monomer contribution which is proportional to  $P_{\text{H}_2\text{O}}$  and the self-continuum  
 272 contribution proportional to  $P_{\text{H}_2\text{O}}^2$ . The partial pressure is derived from the fitted area of well-  
 273 isolated  $\text{H}_2\text{O}$  lines with intensities reported in HITRAN2016 with uncertainties better than 2%  
 274 [37]. This value is adopted as the uncertainty on  $P_{\text{H}_2\text{O}}$  considering that the quality figure of the  
 275 fits, defined as the ratio between peak signal and *rms* fit residuals, of several hundred, limits  
 276 the error on the fitted area below 1%.

277 The monomer contribution uncertainties were determined by taking into account the error  
 278 bars on the line intensities, self-broadening, air-broadening coefficients and water vapour  
 279 pressure. Four simulations,  $\delta_i(\nu)$ , were performed, each of them with either, the intensities,

280  $\gamma_{self}$ ,  $\gamma_{air}$  coefficients or  $P_{H_2O}$  values increased by their error bar. The uncertainty on  $\alpha_{WML}$  was  
281 obtained from:  $\delta\alpha_{WML}(\nu) = [\sum_{i=1}^4 \delta_i(\nu)^2]^{1/2}$ .

282 The uncertainties detailed above are of type-B. To quantify statistical (type-A) uncertainties  
283 we recorded consecutively six decreasing pressure ramps of humidified air at the selected  
284 spectral point of  $5933.75 \text{ cm}^{-1}$  chosen because of a limited impact of the uncertainty on  $P_{H_2O}$ .  
285 Between each ramp, the cell was filled again with humidified air from 350 Torr to 700 Torr  
286 and two CRDS spectra were recorded to check the stability of the water concentration and  
287 determine this concentration. All the ramps were base line corrected using the same dry air  
288 ramp recorded just before. Nevertheless, a dry air ramp recorded just after exactly superposed  
289 to the ramp used. A relative standard deviation of 2.1% was obtained on the derived  $C_F$  values  
290 showing the very good short term repeatability. Two months before a  $C_F$  value 13% lower  
291 than the averaged value on the 6 ramps was measured for the same spectral point with the  
292 other CRDS spectrometer used in this work showing that largest statistical uncertainties have  
293 to be considered. We also achieved measurements at  $5842.24 \text{ cm}^{-1}$ ,  $5905.72 \text{ cm}^{-1}$  and  $6369.00$   
294  $\text{cm}^{-1}$  done each time at three different days. From these data we extended to each spectral  
295 point a statistical uncertainty that we chosen inversely proportional to the ratio between the  
296 value of  $\alpha_{WCF}$  at  $0.08 \text{ atm}^2$  (i.e. the maximum of the pressure ramps) and the minimum  
297 detectable absorption coefficient  $\alpha_{min}$  for the pressure ramp.  
298 Combining the type-A and type-B uncertainties, we obtained the final uncertainties reported  
299 in **Table 1** for each spectral point.

300

#### 301 **4 Comparison to literature data**

302 To our knowledge, the only previous determinations of foreign-continuum cross-sections  
303 available in the  $1.6 \mu\text{m}$  window have been reported in [31] by the CAVIAR consortium at  
304 high temperature. In this work,  $C_F$  values were derived from spectra recorded at a single  
305 pressure value, with a Fourier transform spectrometer coupled to a White cell providing a  
306  $17.7 \text{ m}$  optical path length. To increase the absorption continuum signal, the cell was heated  
307 between  $350 \text{ K}$  and  $430 \text{ K}$  allowing for water vapour partial pressure to be increased up to  $266$   
308  $\text{mbar}$  and  $600 \text{ mbar}$ , depending on the cell temperature. No temperature dependence of the  
309 foreign-continuum could be evidenced in the  $350\text{-}430 \text{ K}$  temperature interval of the FTS  
310 measurements. The spectrally smoothed CAVIAR  $C_F$  values reported at  $400 \text{ K}$  [31] are  
311 plotted in **Figure 4** with their corresponding error bars ranging between about 25% and 120%  
312 on the edges and near the centre of the window, respectively. Overall, the CAVIAR  $C_F$  values

313 (density normalized) at 400 K are larger than our cross-sections by factors between  $\sim 3$  and  $\sim 8$ ,  
314 on the edges and near the centre of the window, respectively. Such important increase  
315 between 296 K and 400 K is significantly larger than the FTS error bars [31] (see **Figure 4**).  
316 Nevertheless, the fact that no clear temperature dependence was evidenced between the  
317 CAVIAR measurements at 350 K and 430 K questioned the correctness and amplitude of the  
318 positive temperature dependence between 296 K and 400 K. Note that in the  $2.3 \mu\text{m}$  window  
319 [20], a constant  $C_F$  ratio of  $\sim 3$  was observed over most of the window between the CAVIAR  
320 and CRDS cross-sections (density normalized). Again, the significance of this variation close  
321 to the  $1\sigma$  error bar of the FTS  $C_F$  values, remains to be confirmed.

322 Finally, let us recall that the foreign-continuum temperature dependence in the windows is by  
323 no means similar to that of the self-continuum which exhibits a clear negative temperature  
324 dependence (see for example [9,17]).

325 Foreign-continuum provided by the latest version of the MT\_CKD model (MT\_CKD3.2) is  
326 included in **Figure 4** for comparison purposes. No temperature dependence is provided for the  
327 MT\_CKD foreign cross-sections. For the low energy edge of the window, the MT\_CKD  $C_F$   
328 values are significantly larger than our measurements in contrast with the values in the centre  
329 of the window which are smaller by a factor of  $\sim 9$ . Nevertheless, near the centre of the  
330 window, the foreign continuum is very weak and the experimental uncertainty reaches almost  
331 100%. More accurate measurements are thus required to be conclusive in the very centre of  
332 the window, near  $6300 \text{ cm}^{-1}$ .

333 Finally, let us consider the humidified measurements by calorimetric interferometry reported  
334 by Bicknell [22]. In the  $2.3 \mu\text{m}$  window where the continuum is larger, we could calculate the  
335 self-contribution to Bicknell's continuum using our determination of the  $C_F$  values and  
336 obtained a good agreement with our  $C_S$  value [20]. In the considered  $1.6 \mu\text{m}$  window,  
337 Bicknell reported a total (self+foreign) continuum absorption coefficient of  $3.2 \times 10^{-8} \text{ cm}^{-1}$  at  
338  $6150 \text{ cm}^{-1}$  for a mixture of 18.75 Torr of  $\text{H}_2\text{O}$  in  $\text{N}_2$  with a total pressure of 760 Torr (see [10]  
339 for details). For the same experimental conditions, we calculate an absorption coefficient of  
340  $\sim 1 \times 10^{-8} \text{ cm}^{-1}$  when using our present  $C_F$  determination of  $5.4(9) \times 10^{-27} \text{ cm}^2 \text{ molec}^{-1} \text{ atm}^{-1}$  and  
341 a  $C_S$  value of  $4.9(7) \times 10^{-25} \text{ cm}^2 \text{ molec}^{-1} \text{ atm}^{-1}$  from Ref. [20]. This difference by a factor of 3 is  
342 outside the combined error bars and difficult to interpret on the basis of the scarce  
343 experimental information provided in Ref.[22] (see [39] for discussion). Note that our  $C_F$   
344 determinations rely on careful study of the pressure dependence of the continuum signal while  
345 Bicknell's measurements were performed at a single pressure [22].

346 **5. Conclusion**

347 Water vapor foreign-continuum cross-sections have been obtained at room temperature in the  
348 1.6  $\mu\text{m}$  window. The corresponding small cross-sections were derived from CRDS  
349 measurements during pressure ramps recorded at fixed spectral points between  $5700\text{ cm}^{-1}$  and  
350  $6640\text{ cm}^{-1}$ . Fifteen spectral points were selected to sample the window at frequencies  
351 corresponding to small contribution of the water monomer lines. The CAVIAR measurements  
352 at high temperature in the same window are larger in amplitude but show a similar  
353 wavelength dependence.

354 The foreign-continuum absorption is very weak at room temperature, in particular, in the very  
355 centre of the window. For instance, the absorption coefficient to be measured is on the order  
356 of  $10^{-9}\text{ cm}^{-1}$  for 1 atm of humidified air with 1 % of water vapor ( $\approx 7$  Torr). Measurements in  
357 this central region were made possible thanks to the very good repeatability of the loss rates  
358 of our CRDS set up. Although the dry air CRDS loss rates were found to be sensitive to the  
359 pressure variation during the pressure ramp, their dependence was found highly repeatable  
360 allowing us to use dry air recordings as baseline of the humidified air recordings.

361 Two factors could help to decrease the  $C_F$  relative uncertainties which range between 10%  
362 and 100%. Firstly, our home-made humidifier provides humidified air with stable water vapor  
363 relative concentration limited to 1% at most, corresponding to a relative humidity of 33% at  
364 296 K. The increase by a factor of two of the water vapor partial pressure could help to  
365 decrease the relative uncertainties. Secondly, the uncertainty on the water vapor partial  
366 pressure (or concentration) is the main contributor to the final uncertainties through the self-  
367 continuum and the water monomer subtracted contributions. At the moment, a 2% uncertainty  
368 is achieved on the knowledge of the water concentration in the used humidified air, mainly  
369 due to the uncertainty on the intensity reported in HITRAN2016 for the water reference line  
370 used to derive the water partial pressure. Alternative techniques as dew point mirror  
371 hygrometers are considered to improve the determination of the water vapor partial pressure  
372 by at least a factor of two and thus the accuracy of the reported  $C_F$  values, in particular near  
373 the centre of the window.

374

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**A. Campargue**: Data analysis, Writing the paper