Biogenic O_2 detection on the Earth observed as a transiting exoplanet and perspectives with future ELTs for nearby Earth twins

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Talk based on A&A 2014 paper (published April 2014, A&A 564, A58)

L. Arnold, D. Ehrenreich, A. Vidal-Madjar, X. Dumusque, C. Nitschelm, R. R. Querel, P. Hedelt, J. Berthier, C. Lovis, C. Moutou, R. Ferlet, D. Crooker

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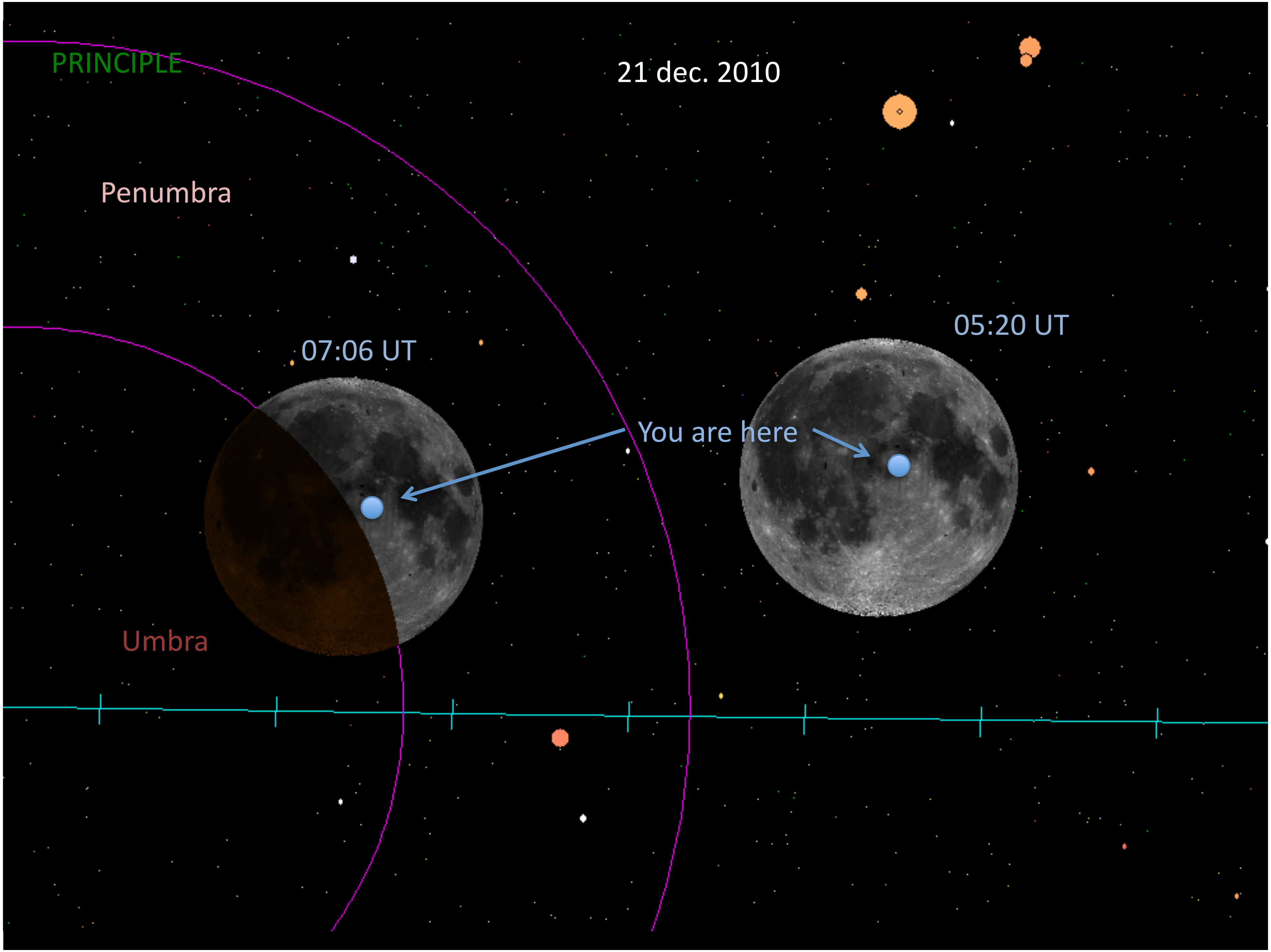
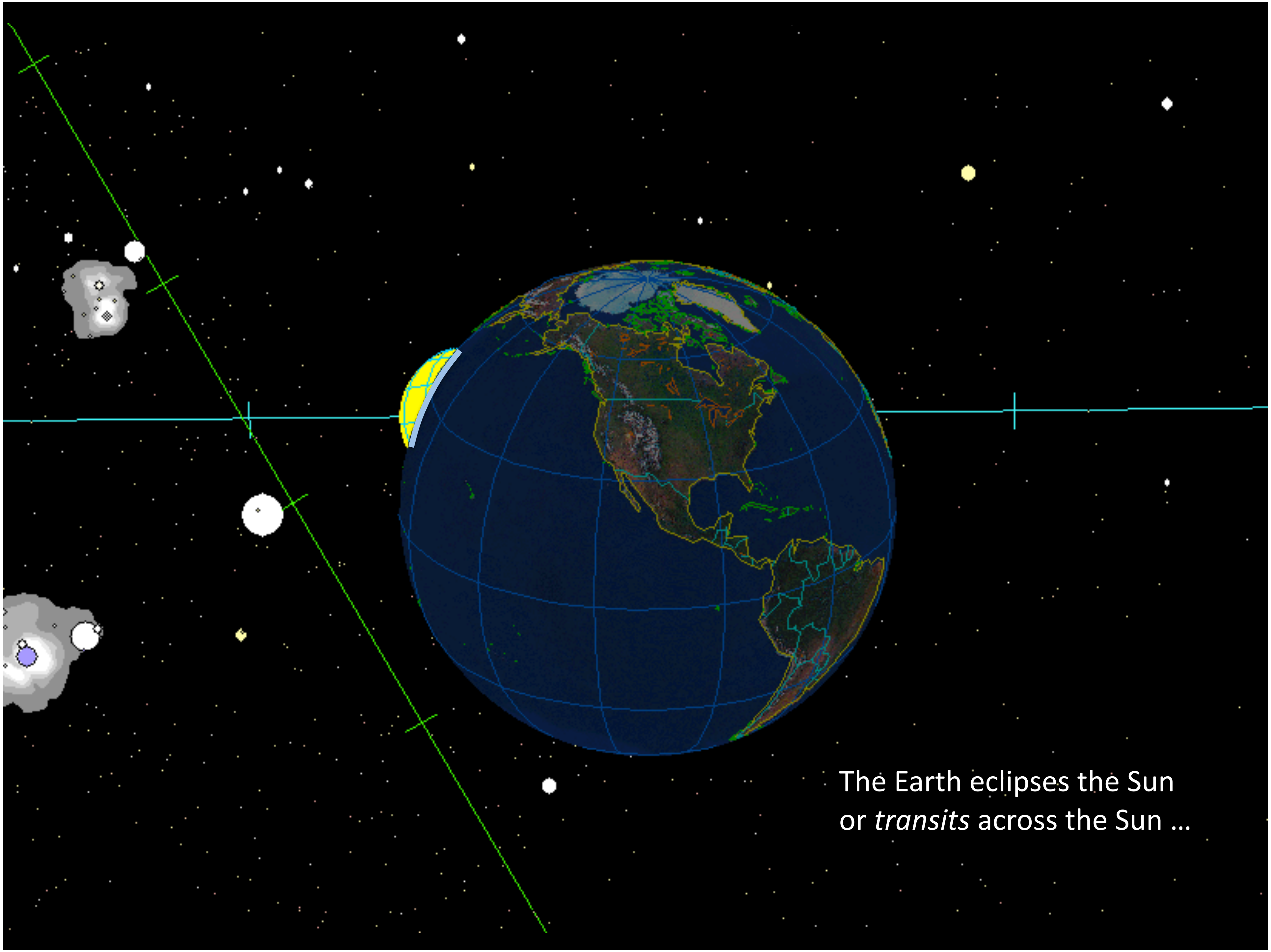
Vidal-Madjar, Arnold, Ehrenreich et al. 2010, A&A 523, A57

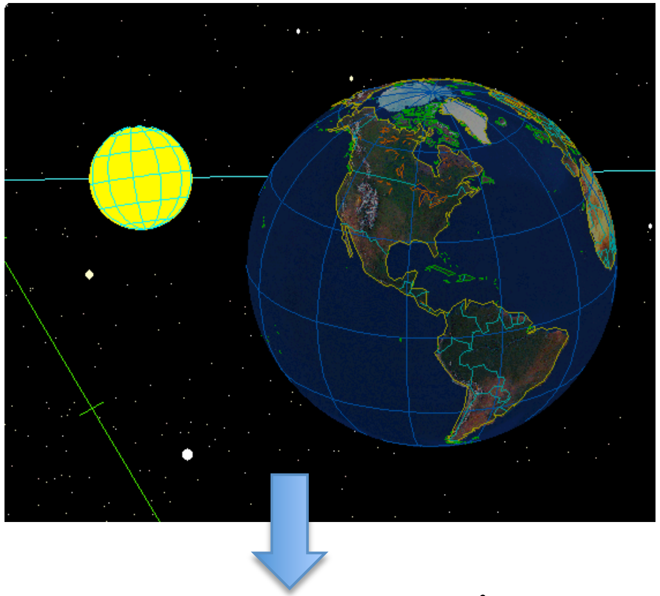
CONTEXT

- Aims:
  - Characterize the Earth seen as a transiting planet (its atmospheric signature, biogenic species, etc.)
  - Compare with / validate the model(s)
  - Provide inputs for future observations, with larger telescopes (E-ELT).

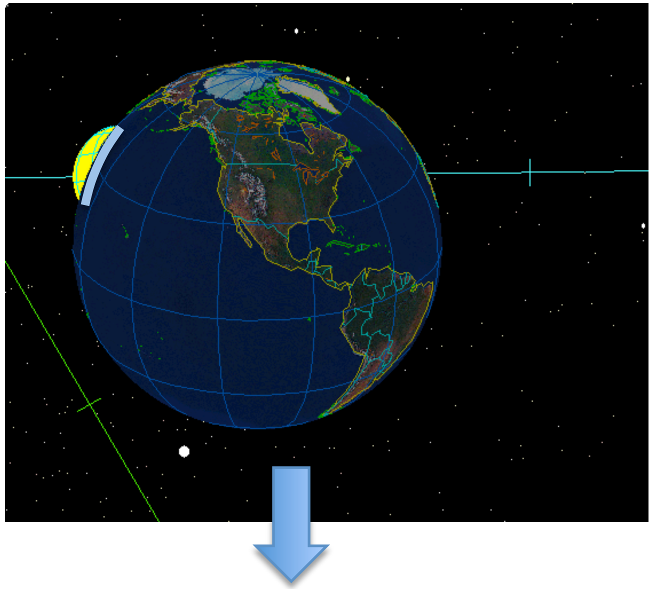
- Follow-up of first test observations with SOPHIE, August 2008 lunar eclipse (Vidal-Madjar et al 2010)
- New results from HARPS and UVES dec. 2010 lunar eclipse


PRINCIPLE
21 dec. 2010
Penumbra
07:06 UT
05:20 UT
You are here
Umbra


The Earth eclipses the Sun
or *transits* across the Sun …



Full moon spectrum $F(\lambda)$



Eclipse (penumbra) spectrum $E(\lambda)$

$$E(\lambda) = F(\lambda) \times \frac{S - L \times h(\lambda)}{S_\odot}$$

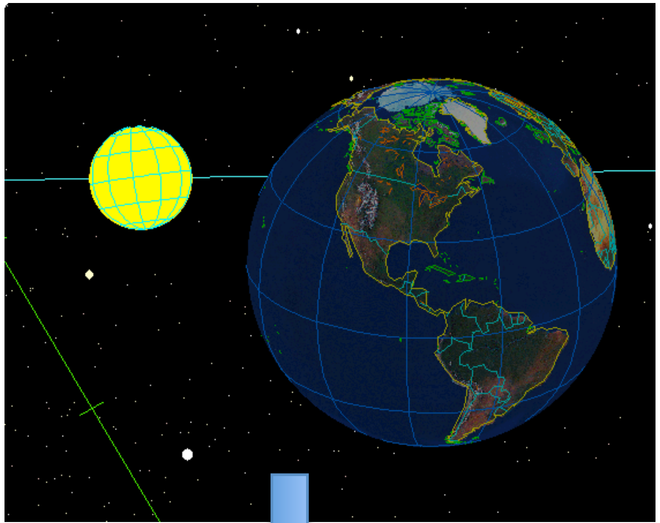
(Vidal-Madjar et al. 2010)

where $S_\odot$ = *surface of the solar disk*

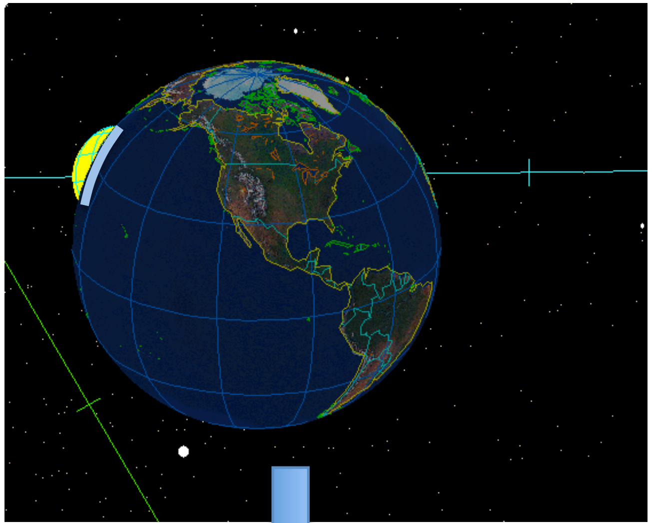
S = *surface of the solar crescent*

$L \times h(\lambda)$ = surface of the arc of Earth atmosphere in front of the Sun

-> if we are interested in $h(\lambda)$ -> we need to know S and L !



Full moon spectrum $F(\lambda)$



Eclipse (penumbra) spectrum $E(\lambda)$

S is easily retrieved from flux ratio at an unabsorbed wavelength λ_0 for which $h(\lambda_0)=0$:

$$E(\lambda_0) = F(\lambda_0) \times \frac{S}{S_\odot}$$

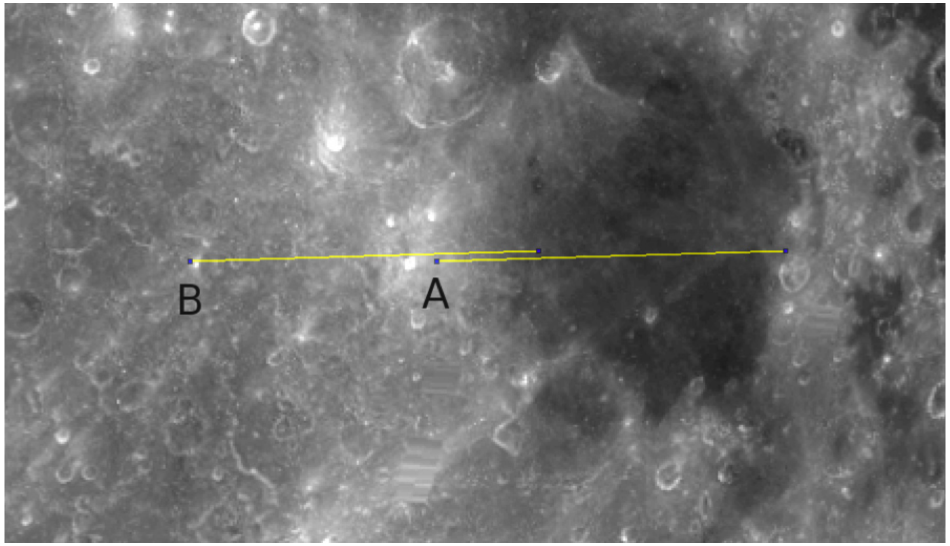
- Once S is known, the length L can be calculated

-> we are interested in $h(\lambda)$, and S and L are now known !

In practice:

- Correct *S* for Limb Darkening (even for LD(λ), Hestroffer & Magnan 1998)

- To fix the solar crescent at a given size S during the exposures, the telescope has to track neither the stars nor the Moon, but a point *attached* to the Penumbra -> the Moon shifted in front of the spectrograph -> correct *E* and *F* for moon albedo variations along the slit path with Clementine data:



Reconstructed path of HARPS fibers over the Moon during one of the exposures.

• We want to correct all spectra for the signature of the atmosphere above the telescope

$$T(\lambda) = \left[\frac{F_1^{AM_1}(\lambda)}{F_2^{AM_2}(\lambda)}\right]^{(1/(AM_1 - AM_2)}$$

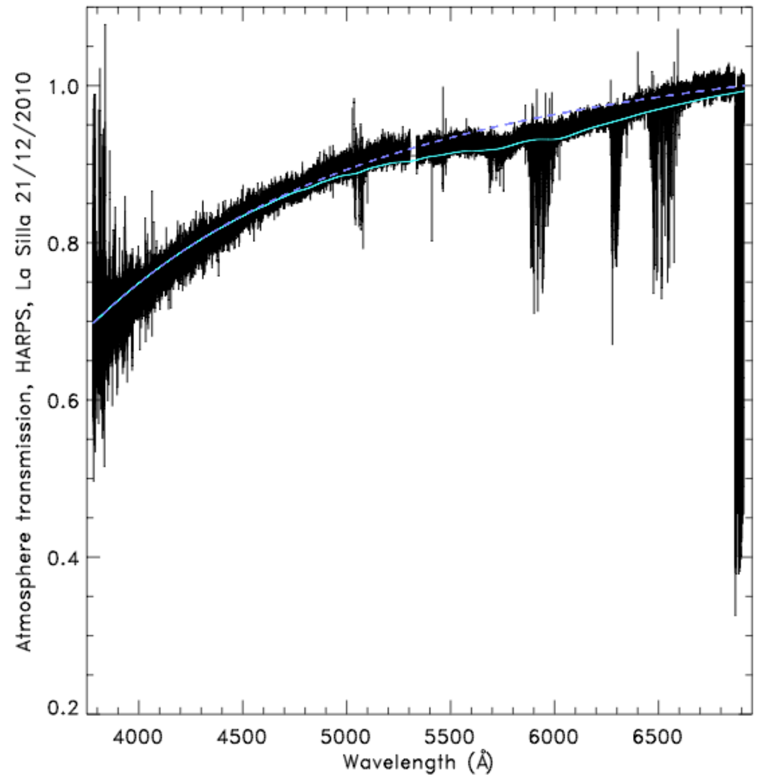


Fig. 4. La Silla atmosphere transmission function $T(\lambda)$ for $AM = 1$

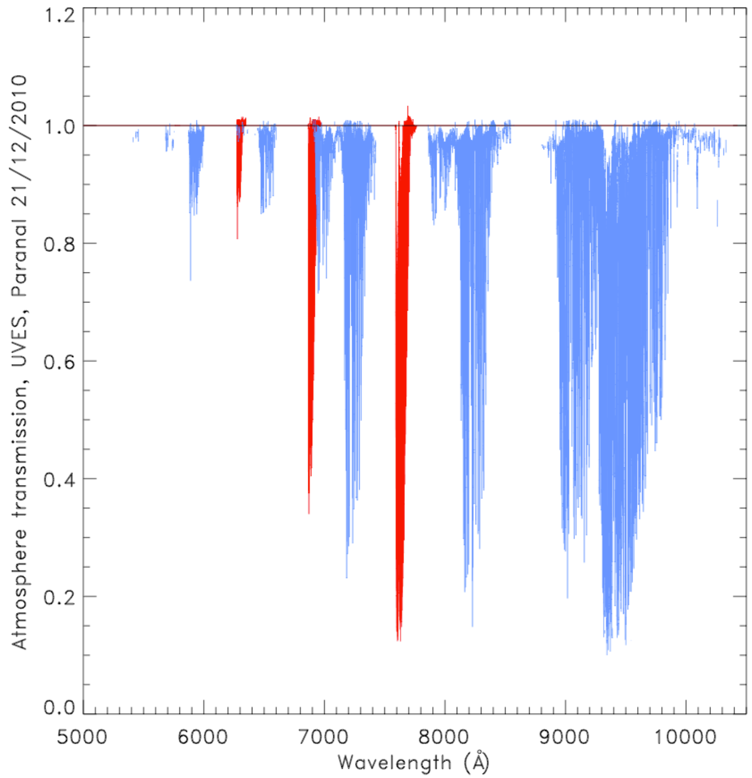


Fig. 7. Paranal atmosphere transmission function $T(\lambda)$ for $AM = 1$

Calculation of h(λ): 2 methods

- 1/ from one penumbra spectrum (Arnold et al. 2014)

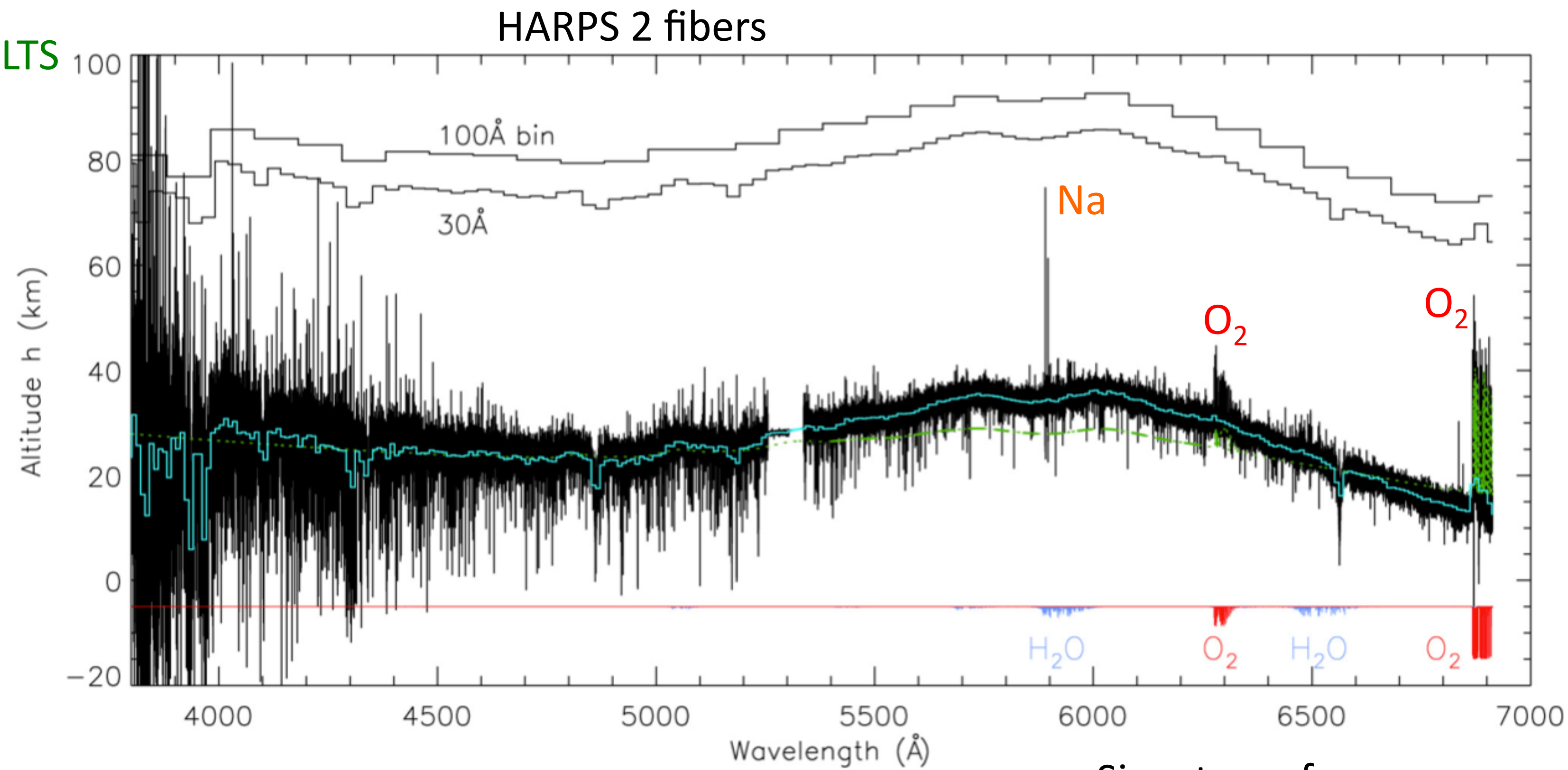
$$h(\lambda) = \left(1 - \frac{E_A(\lambda)}{E_A(\lambda_0)} \times \frac{F_A(\lambda_0)}{F_A(\lambda)}\right) \times \frac{S_A}{L_A}$$

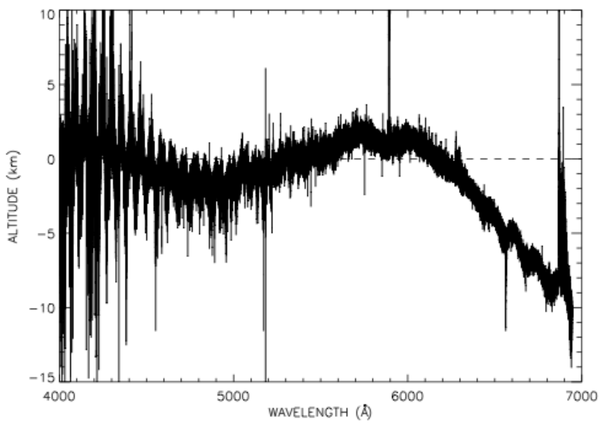
- 2/ from a pair of penumbra spectrum (SOPHIE has 2 fibers ! Vidal-Madjar et al. 2010)

$$\left(\frac{E_A(\lambda)}{E_A(\lambda_0)} \times \frac{F_A(\lambda_0)}{F_A(\lambda)} - \frac{E_B(\lambda)}{E_B(\lambda_0)} \times \frac{F_B(\lambda_0)}{F_B(\lambda)}\right) = \left(\frac{L_B}{S_B} - \frac{L_A}{S_A}\right) \times h(\lambda).$$

-> Vidal-Madjar et al. 2010 == difference between spectra gives better results

RESULTS





SOPHIE 2008 eclipse, 2 fibers
Vidal-Madjar et al. 2010

Signatures from:

- O_2
- Na
- Ozone: Chappuis band
- Rayleigh signature

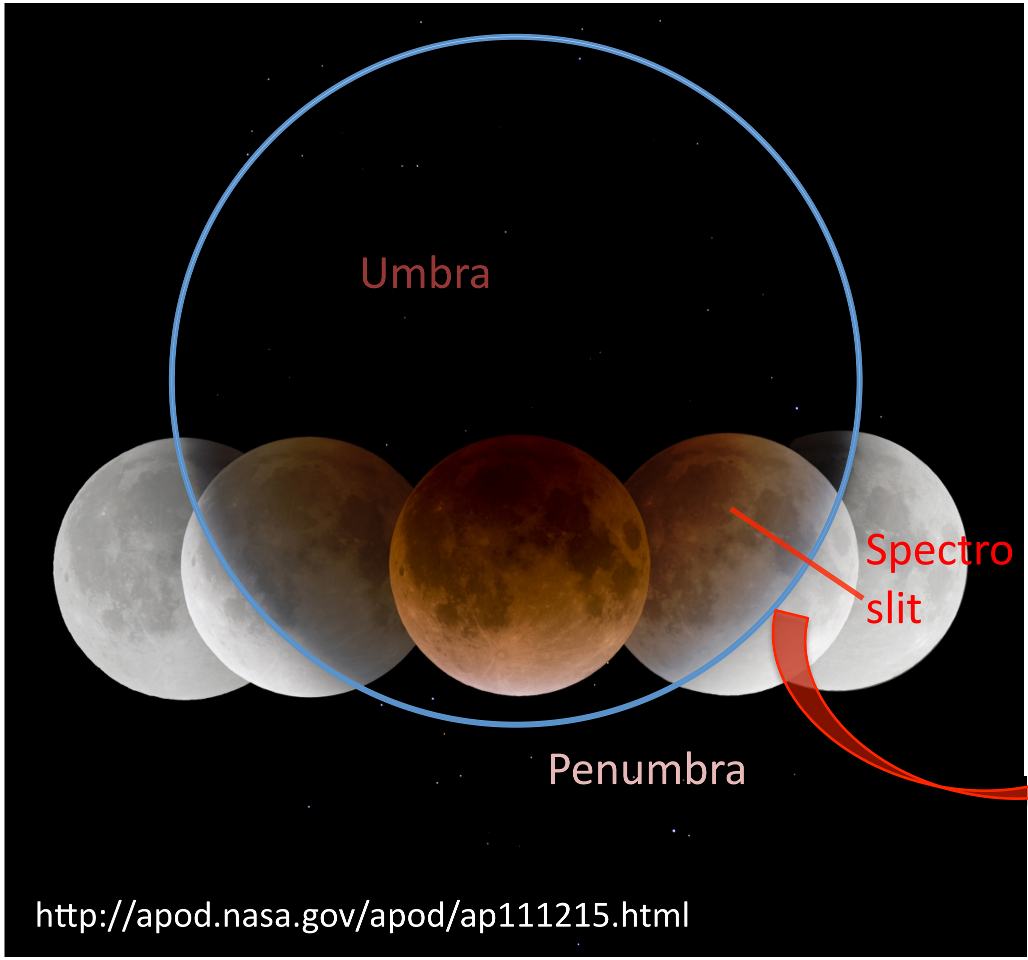
Not detected (or barely):

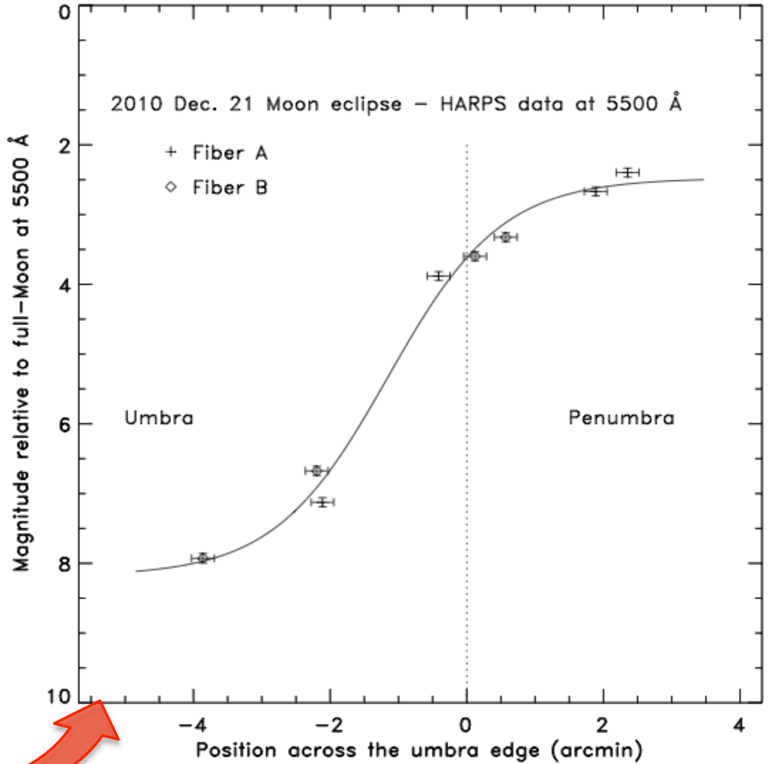
- Water vapour
- In green:

Ehrenreich et al. 2006 model

PRINCIPLE

A 3rd method: *direct measurement* of the Earth radius versus wavelength !

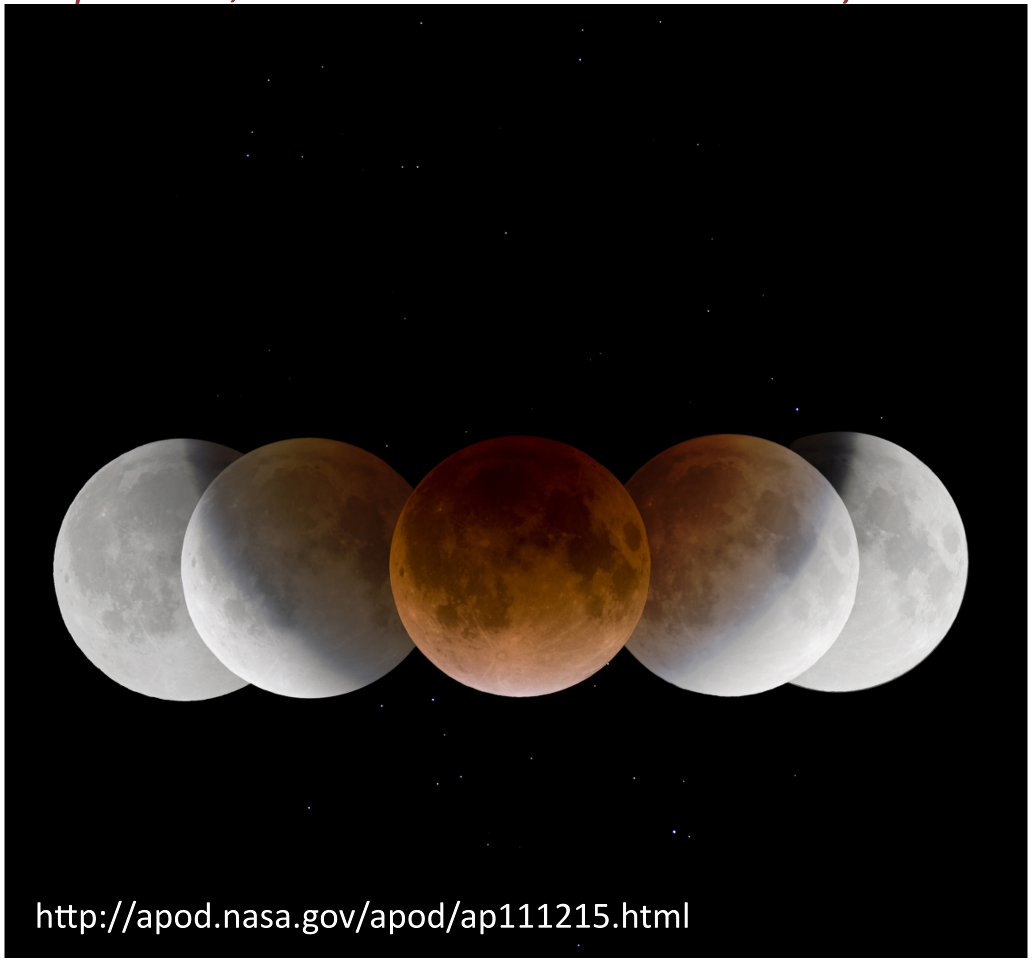


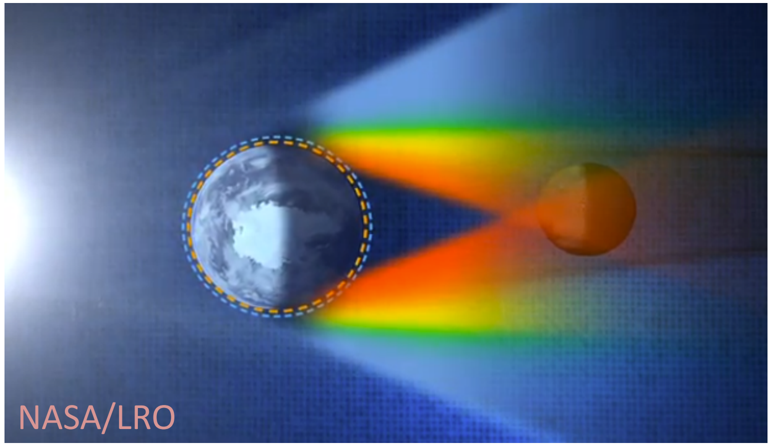


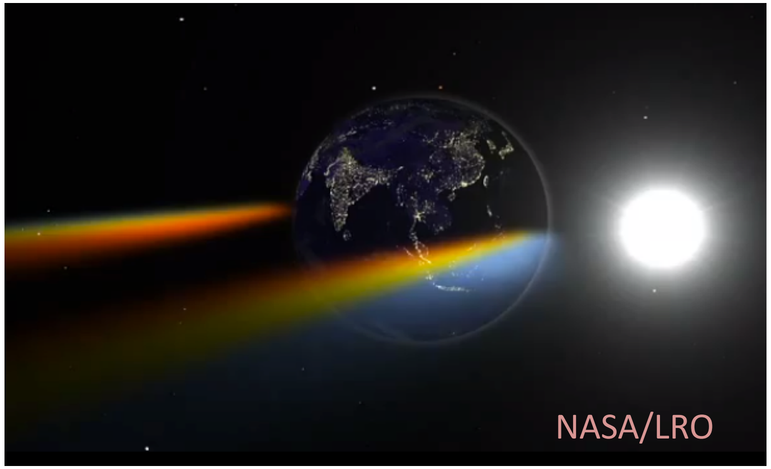
Photometry through the umbra edge

A 3rd method: *direct measurement* of the Earth radius versus wavelength !

But this method is biased by refraction (use of photons from the Umbra = refracted photons, which are lost in a real transit)





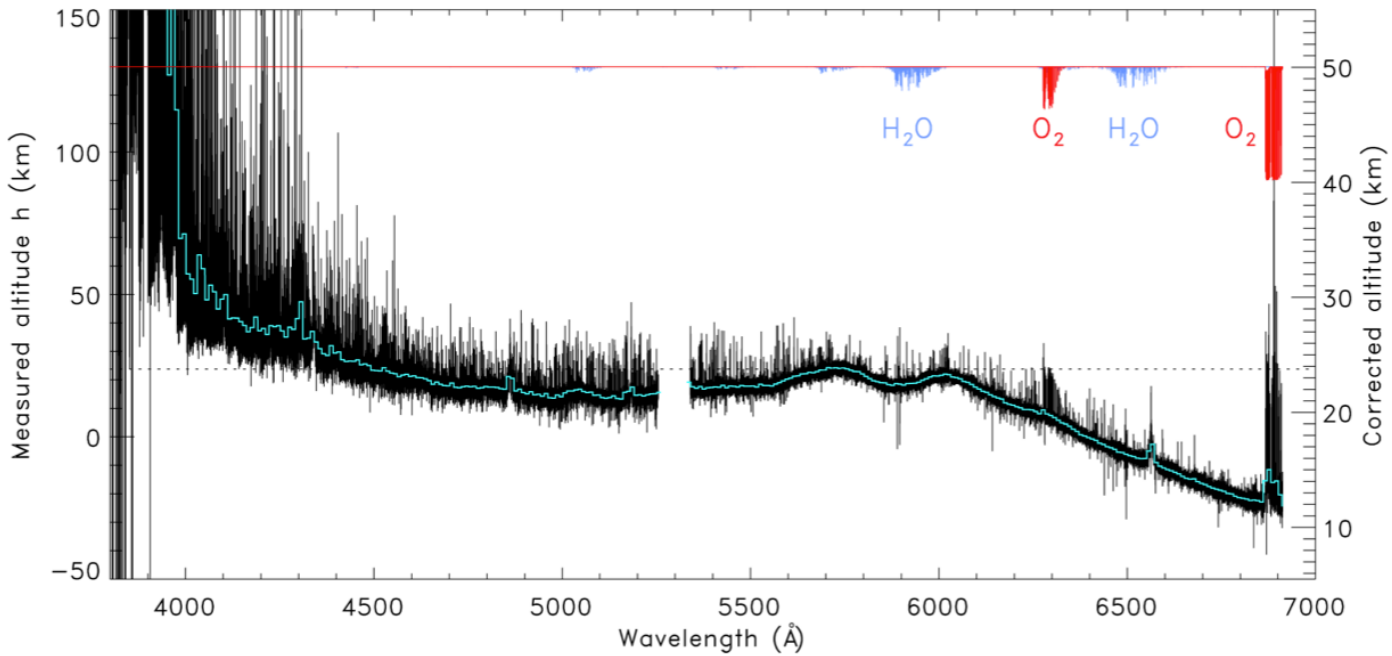


Refraction of red light in the deep atmospheric layers makes the Earth smaller than reality in the red !

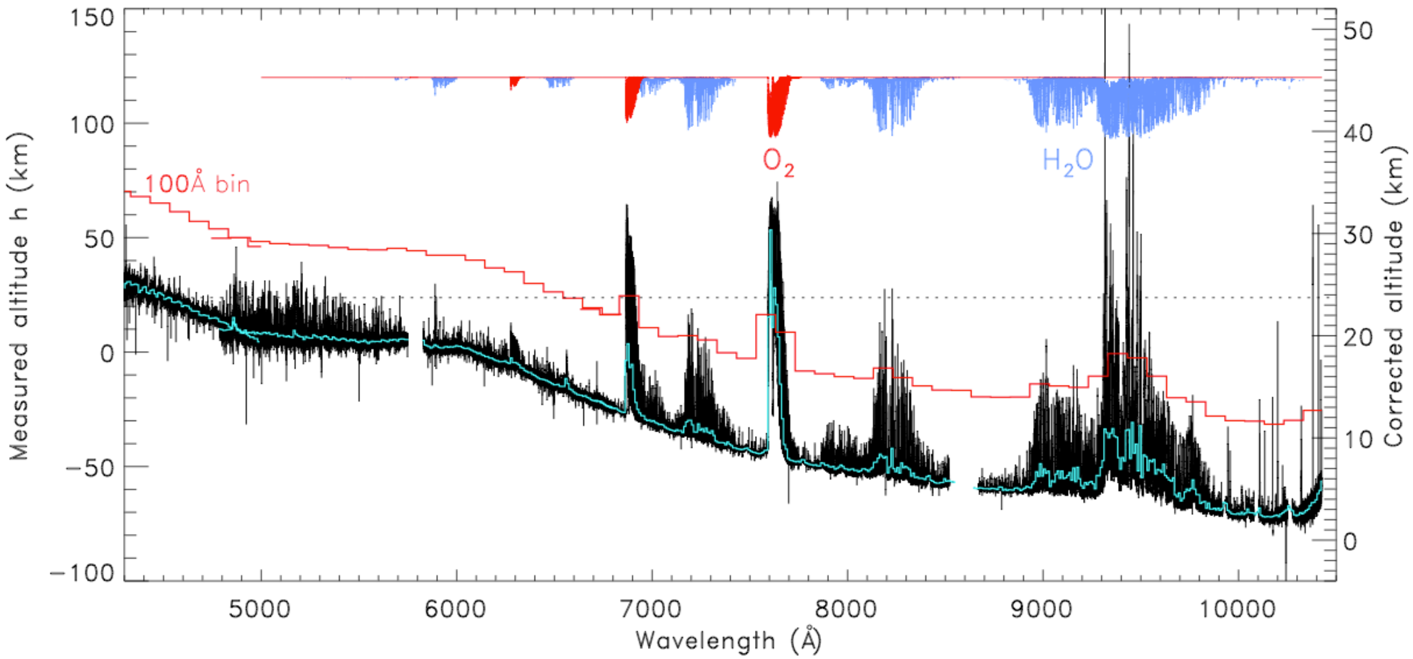
Fortunately, it can be corrected (at least partially)

RESULTS

HARPS



UVES

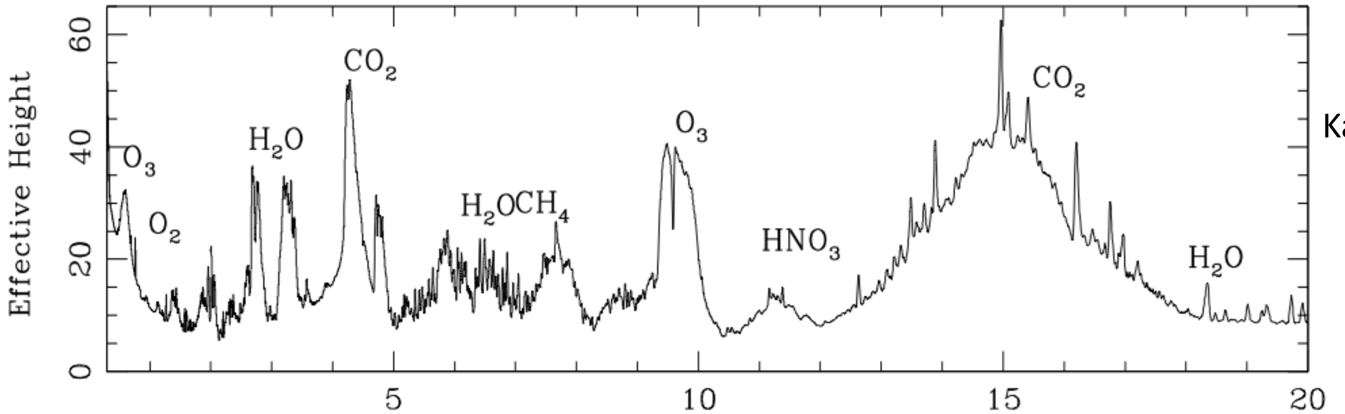


RESULTS

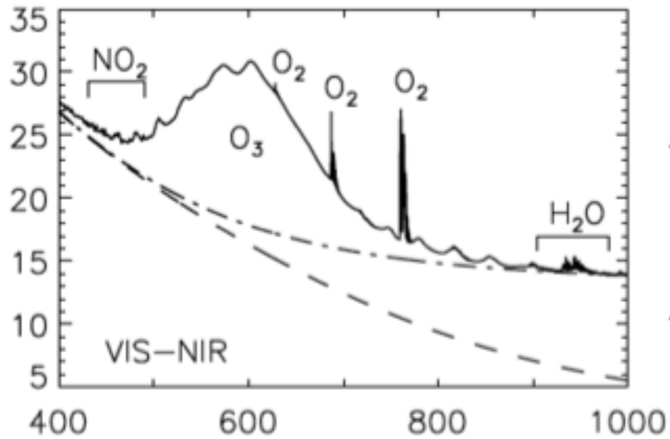
- HARPS and UVES detect O3, O2, Water (> 7000Ang), Na, Rayleigh scattering
- O2 A-band peaks at about 30 km above the continuum

DISCUSSION

- Observation in acceptable agreement with the models (Ehrenreich et al. 2006)



Kaltenegger & Traub 2009

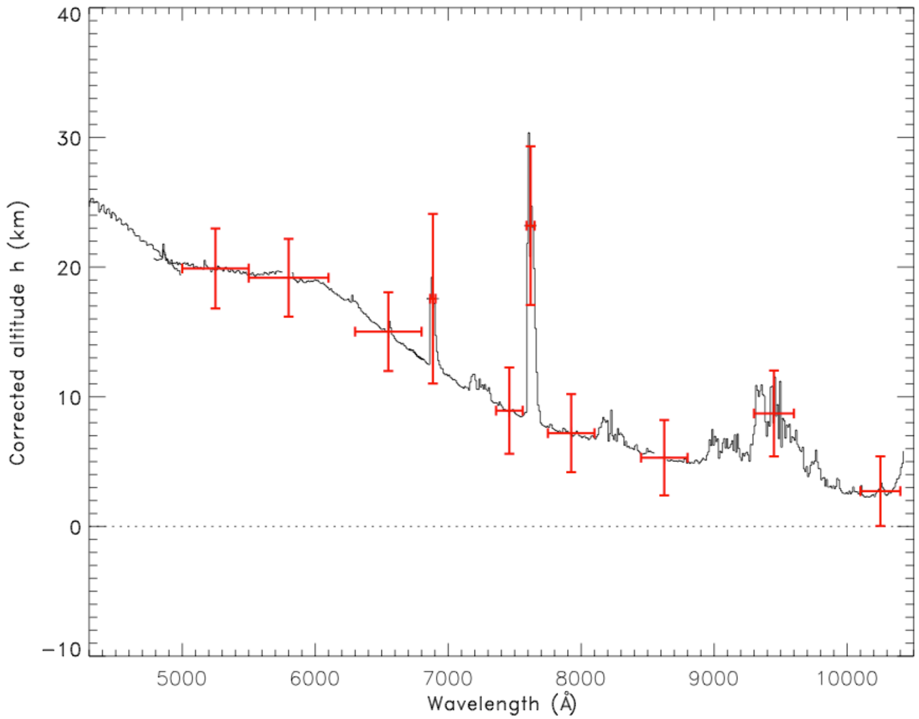


Bétrémieux & Kaltenegger 2013
Plot spectral resolution 2500

Refraction slightly *reduces* the effective height for a exoplanet transit (Bétrémieux & Kaltenegger 2014, submitted)

DISCUSSION

The big question: Will O_2 A-band (7600 Ang) be detectable with the E-ELT ?



- Model from Hedelt et al. 2013 A&A
- G2V star @ 10 pc, 1 single transit
- E-ELT 39m telescope
- Detector CCD charact. from EPICS
- Broad filters (selecting O_2-A etc.)

Assuming *perfect sky, no atmospheric perturbation*

Use High-Resolution Spectroscopy to better isolate the exo O_2 from the terrestrial O_2, and benefit from the numerous O_2 lines in the A-band (Vidal-Madjar et al. 2010, Snellen et al. 2013, Rodler & Lopez-Morales 2014, …)

DISCUSSION

TABLE 2 From Rodler & Lopez-Morales 2014

SIMULATIONS FOR E-ELT SPECTROGRAPHS IN THE VISUAL†

	UVES-like design				G-CLEF-like design			
sp. type	obs. time (h)	duty cycle	transits	time (years)	obs. time (h)	duty cycle	transits	time (yrs)
G2V	840	0.05	65	$\geq$ 65	429	0.08	34	$\geq$ 33
M1V	110	0.58	28	$\sim$ 29	67	0.71	17	$\sim$ 18
M2V	98	0.69	29	$\sim$ 23	62	0.80	19	$\sim$ 15
M3V	88	0.79	29	$\sim$ 19	57	0.87	19	$\sim$ 13
M4V	43	0.92	21	$\sim$ 8	29	0.95	14	$\sim$ 6
M5V	46	0.97	31	$\sim$ 7	31	0.98	21	$\sim$ 5
M6V	43	0.98	39	$\sim$ 6	30	0.98	27	$\sim$ 4
M7V	35	0.98	45	$\sim$ 5	24	0.98	31	$\sim$ 3
M8V	34	0.98	48	$\sim$ 4	25	0.98	36	$\sim$ 3
M9V	29	0.98	66	$\sim$ 3	22	0.98	50	$\sim$ 2

†For a velocity span of 1.2 km s^{-1} $pixel^{-1}$ (UVES-like design, left) and 0.75 km s^{-1} $pixel^{-1}$ (G-CLEF-like design, right). Numbers are given for 5 pc distance.

- Improve duty cycle
- Use Image slicer

} Reduce time from 33-65 to approx. 3 years without red noise

From Rodler & Lopez-Morales 2014:

- For red noise level = 40% white noise -> x 2 the required observing time
- Target observability constraints (airmass >2, night time etc.)

>> 10 years at least ?

CONCLUSION

- Observations of the Earth as a transiting planet confirm the model
- O_2 is detected for Earth

- Will O_2 be detectable on an nearby Earth twin around a G2V star with ground based ELTs?

- If we are lucky enough to detect a Earth-like planet around a nearby solar-like star…
- probably >>10 transits (10 years) will be needed
    - High-resolution spectroscopy O_2
    - Needed (?)
        - dedicated instrument (not CCD-based?)
        - progress in real-time atmospheric monitoring (LIDAR)