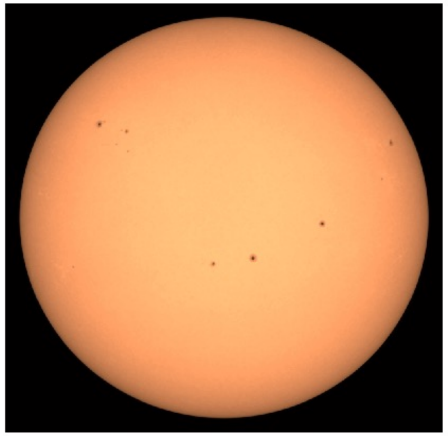
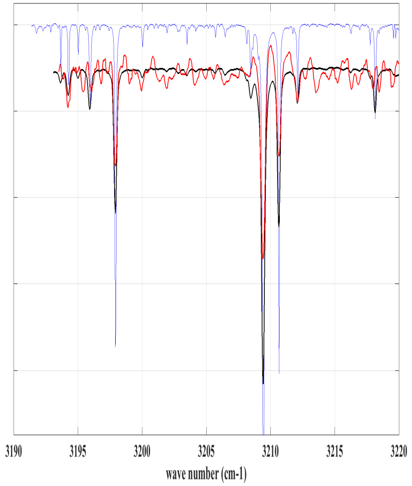





# High-resolution solar spectrum in the 0.7-1.7 µm domain obtained from TGO observations shows solar lines unreached from ground

**Abdanour Irbah**(1), **Luc Damé** (1), Jean-Loup Bertaux(1), Franck Montmessin(1), Alexander Trokhimovskiy(2), Oleg Korablev(2) and Anna Fedorova(2)

(1) LATMOS/IPSL/CNRS/UVSQ, France (2) IKI Space Research Institute, Moscow

**2023 Sun-Climate Symposium – October 16-20, 2023 – Flagstaff, Arizona**

# *Outline*

**I –** Overview of the NIR spectrometer and calibration data

**II –** Data processing method to build the solar spectrum

**III –** Use of off-center order images to reconstruct the spectral bands of each diffraction order

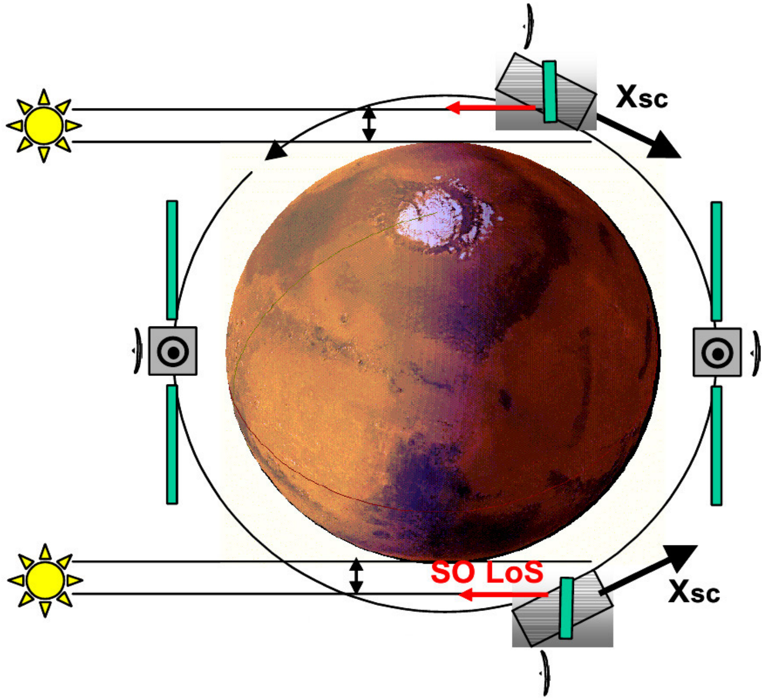
**IV –** New ACS-NIR solar spectrum and comparison with Toon's reference spectrum

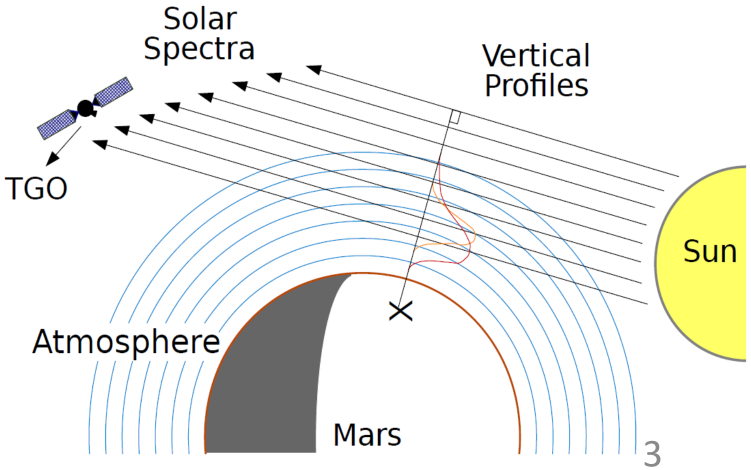
# **I -** ACS-NIR spectrometer aboard TGO

- **Trace Gas Orbiter (TGO)** is **in orbit around Mars** to study the **presence** and **origin of gases in its atmosphere.**
  **TGO is in orbit** since **October 2016**
  **Observations available** since **2018**

- **Payload of TGO** is composed of **several instruments** including **spectrometers observing in the infrared placed on the ACS platform:** <u>among them</u> the **NIR (Near InfraRed) spectrometer**

- **Solar spectrum** in the **0.7-1.7 µm domain can be measured** when the **Light-of-Sight** of **ACS-NIR** is **above the atmosphere**



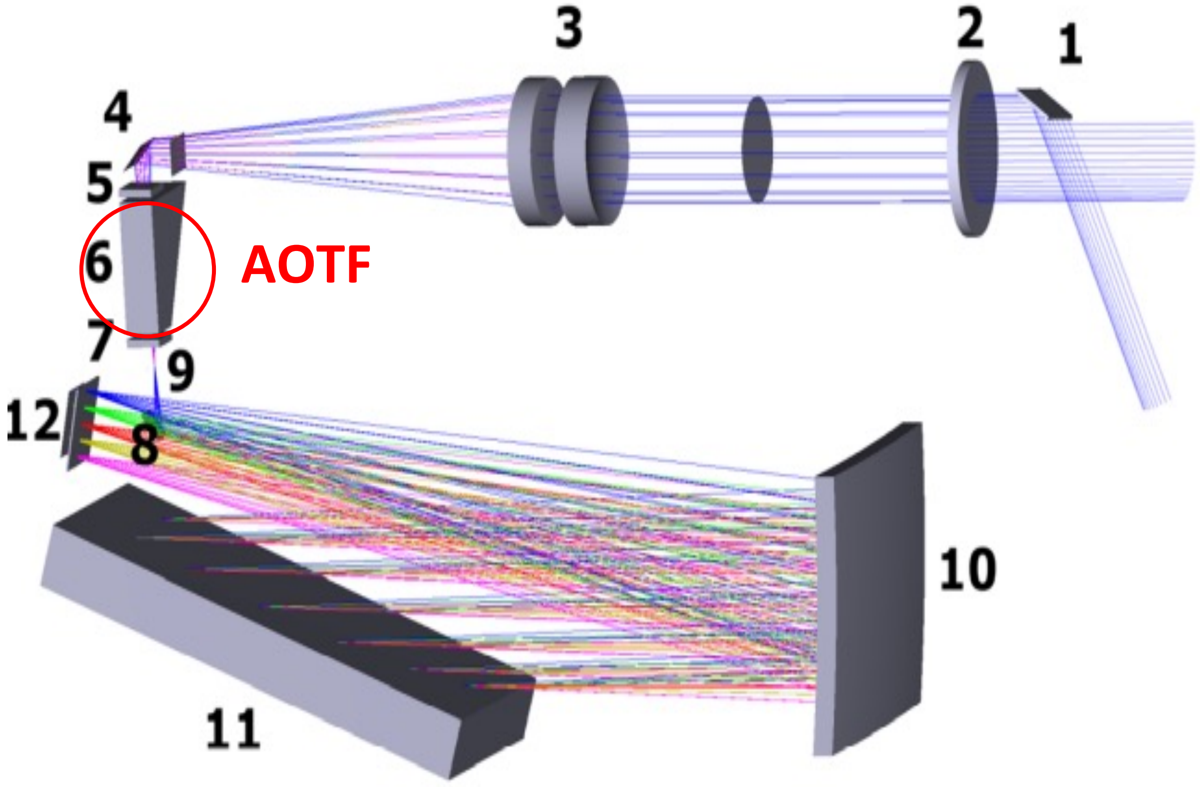



# Simplified optical scheme of the ACS-NIR photometer (*)

The ***spectrometer slit*** (**9**) selects a **narrow part of the solar images** formed by the telescope (**3**) through the ***AOTF*** (**Acousto-Optic Tunable Filter**) (**6**).

The selected spectral light of the image part is then **diffracted** by the ***grating*** (**11**) and the **diffraction orders** are **formed** on the ***2D detector*** (**) (**12**).

***Frequency control of the AOTF*** allows ***to select*** the ***diffraction orders***.




(*) *A simplified optical scheme of the NIR channel. 1 - solar periscope; 2 - blocking filter; 3 - entry telescope; 4, 8 - folding mirrors; 5, 7 - polarizers; 6 - AOTF crystal; 9 - slit; 10 - collimating mirror; 11 - diffraction grating; 12 - detector array. (Korablev et al., Space Sci. Rev., 2018)*

(**) ***InfraRed camera*** *module* ***XSW-640*** *from Xenics based on a thermo-electrically cooled (Peltier element) InGaAs array* (***512 x 640 pixels***).

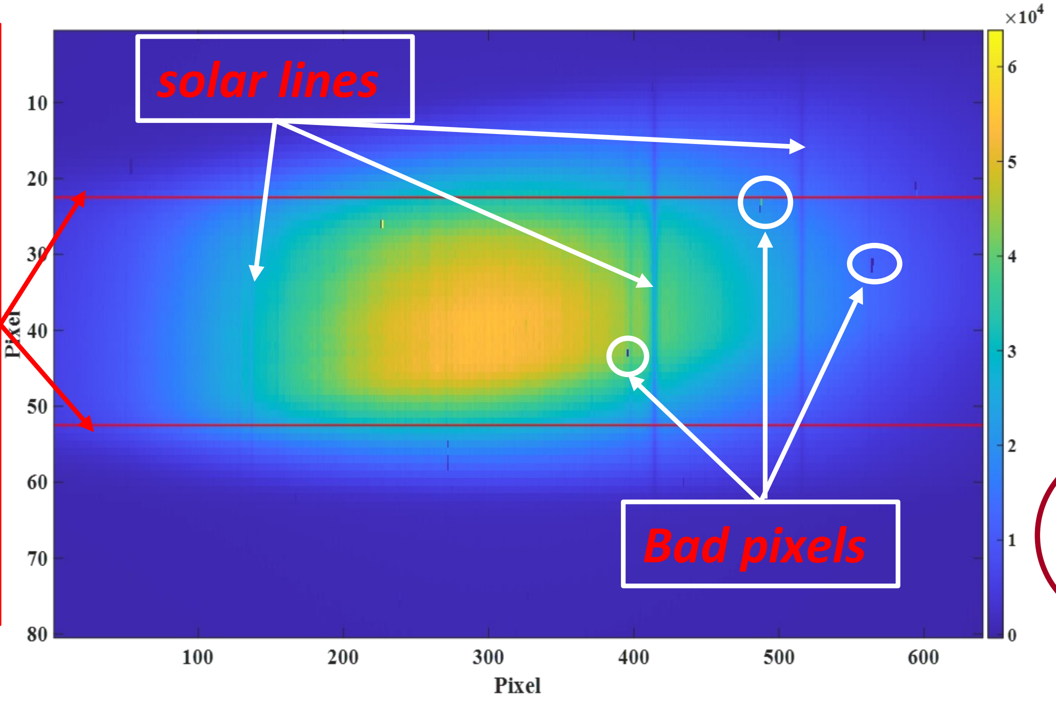
# Overview on calibration data

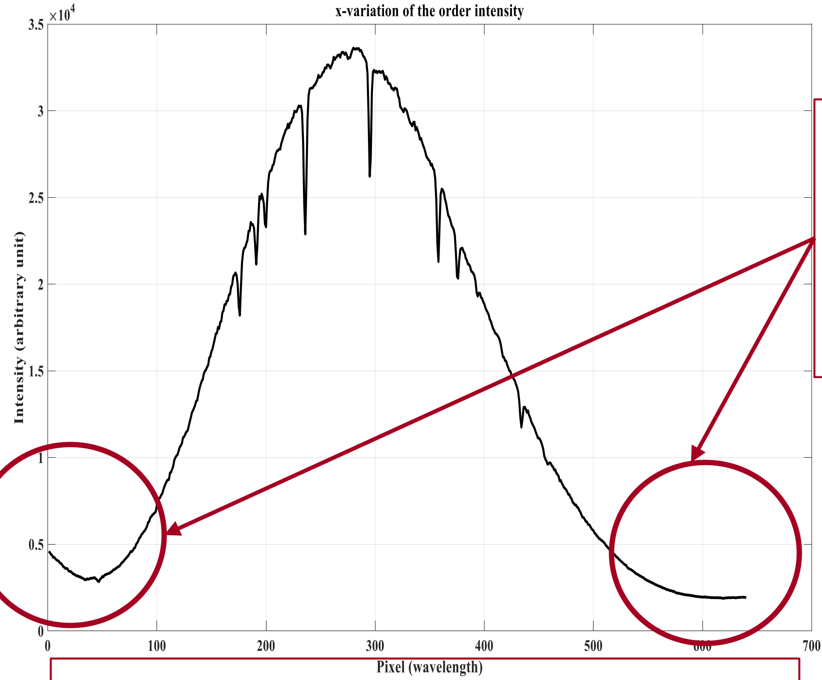
**Data** acquired to **estimate** the **solar spectrum** and carry out **calibration studies** are ***images of all diffraction orders*** of **NIR** (ranging from *45* to *103*) obtained by ***continuously varying the AOTF frequency*** (from *64 MHz* to *160 MHz* by step of *0.1 MHz*).

There are about ***31280 images of 80 x 640 pixels*** acquired during ***10 months*** (10/2020-08/2021)

**Sample of a diffraction order of ACS-NIR**

**Lines delimiting the region** used to calculate the **spectrum** (here, case of the whole Sun)

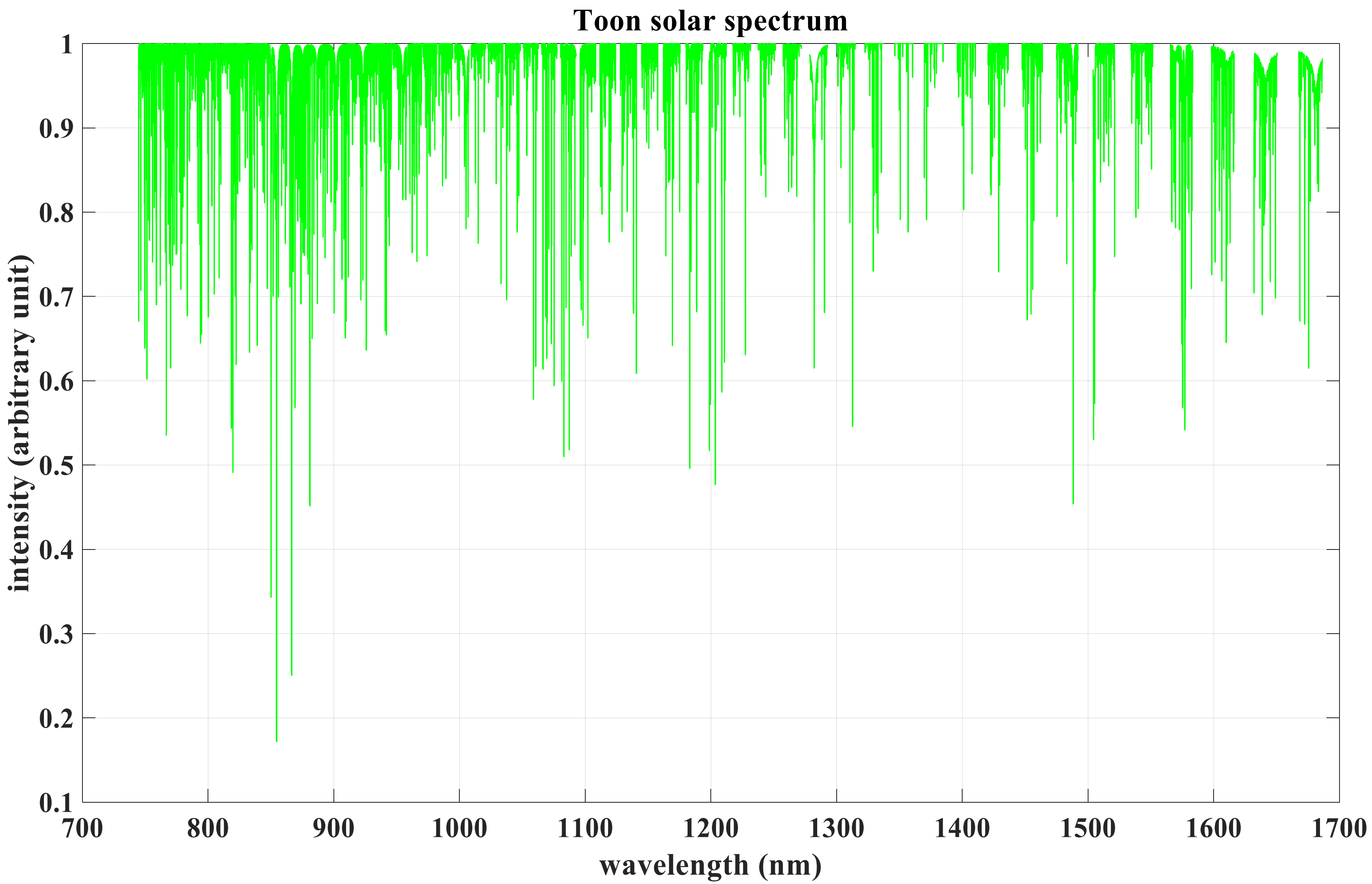



Regions of poor line detection and contamination

x-variation of order intensity

# The Toon solar spectrum on the 0.7-1.7 μm domain (*)




**The solar pseudo-transmittance spectrum** calculated by **G. Toon** is taken as **reference** to **compare** the obtained **NIR solar spectrum**

It was **set to the same spectral sampling of the NIR one**

(*) https://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html

# II - Data processing to build the solar spectrum

# Extraction of the spectral bands from diffraction order images

- ➢ ***First step***: order is corrected from **flat field**, **stray light** & **bad pixels**
- ➢ ***Second step***: extraction of the **spectral band** of the **order image**

**An integration region in the order image is chosen**

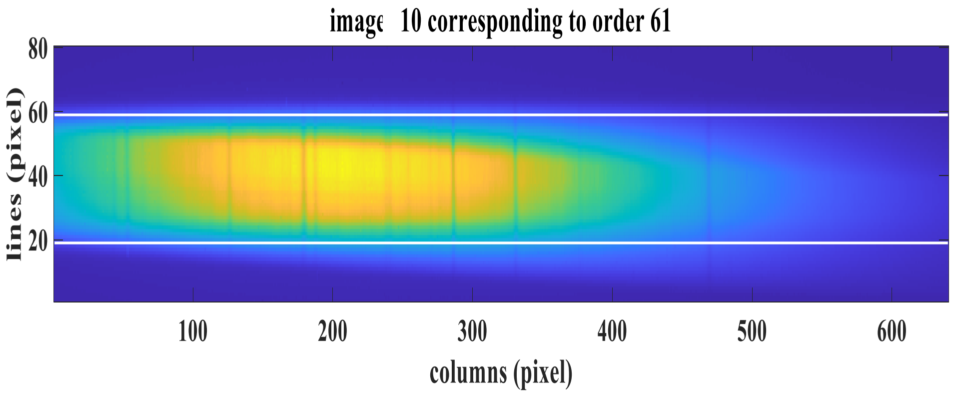
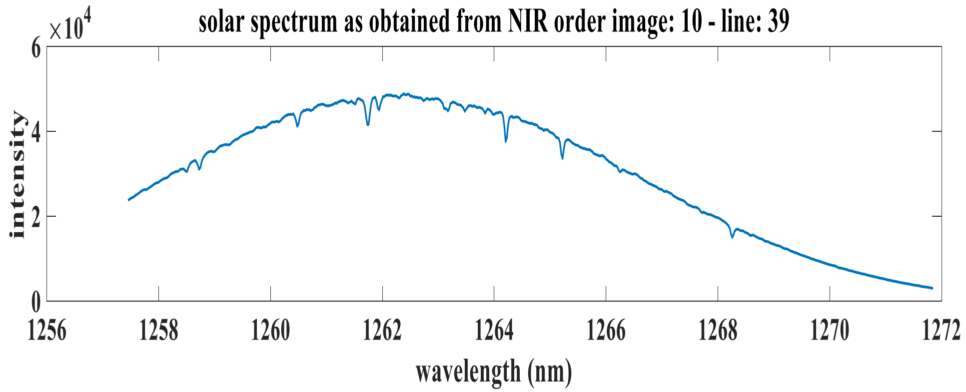
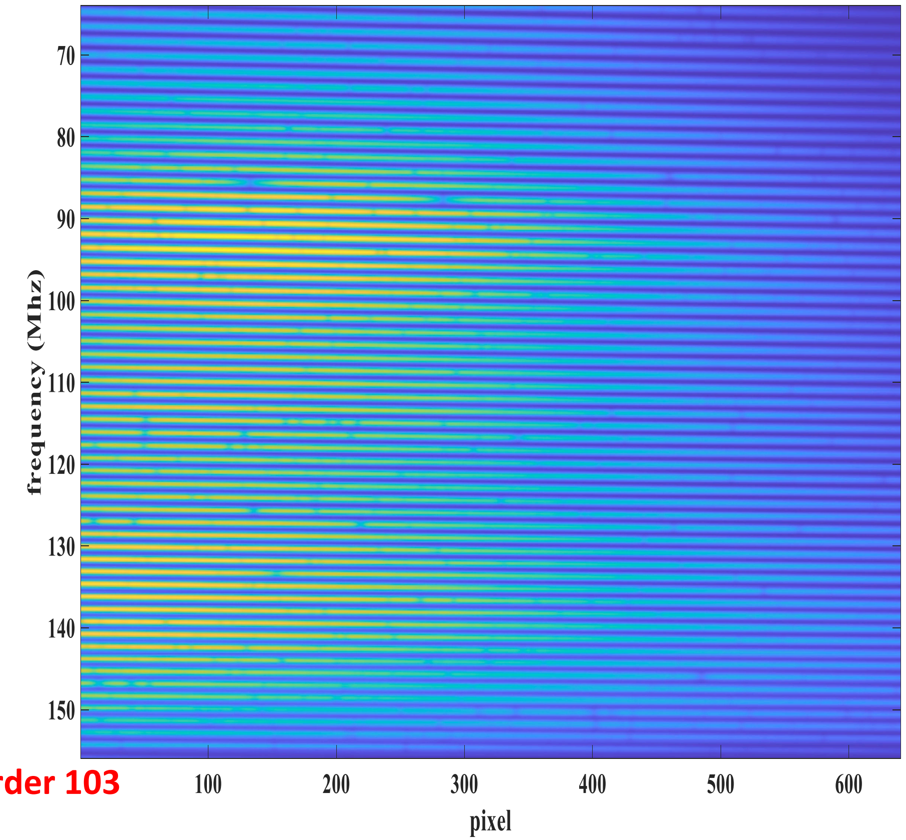



**Image lines in this region are added to obtain** the **spectral band** corresponding to the **diffraction order**




**Each line** corresponds to a **spectral band associated** to its **AOTF frequency**

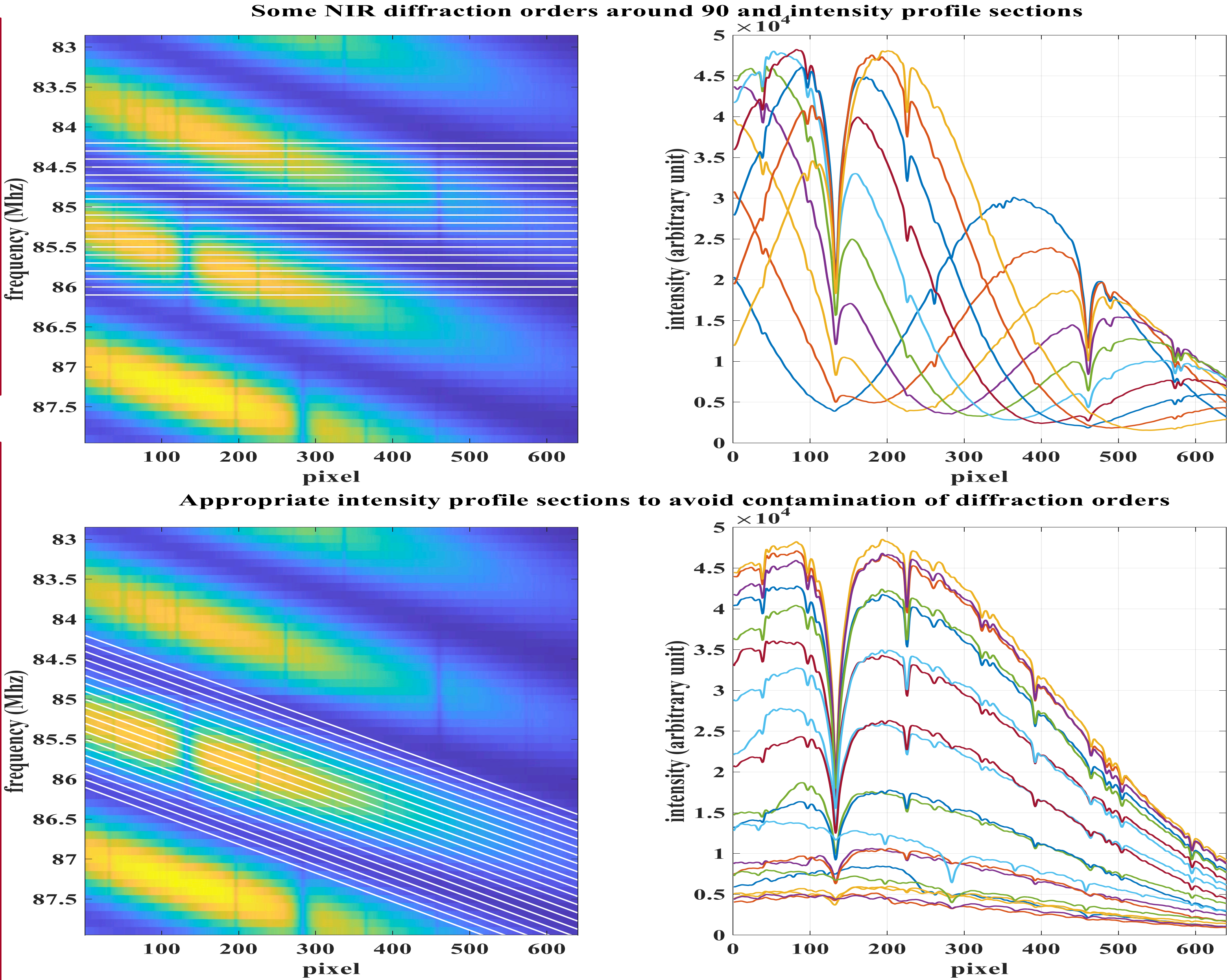



- ➢ ***Third step***: **processing** applied to **all diffraction order**

# Zoom on the previous figure: wavelength drift with frequency

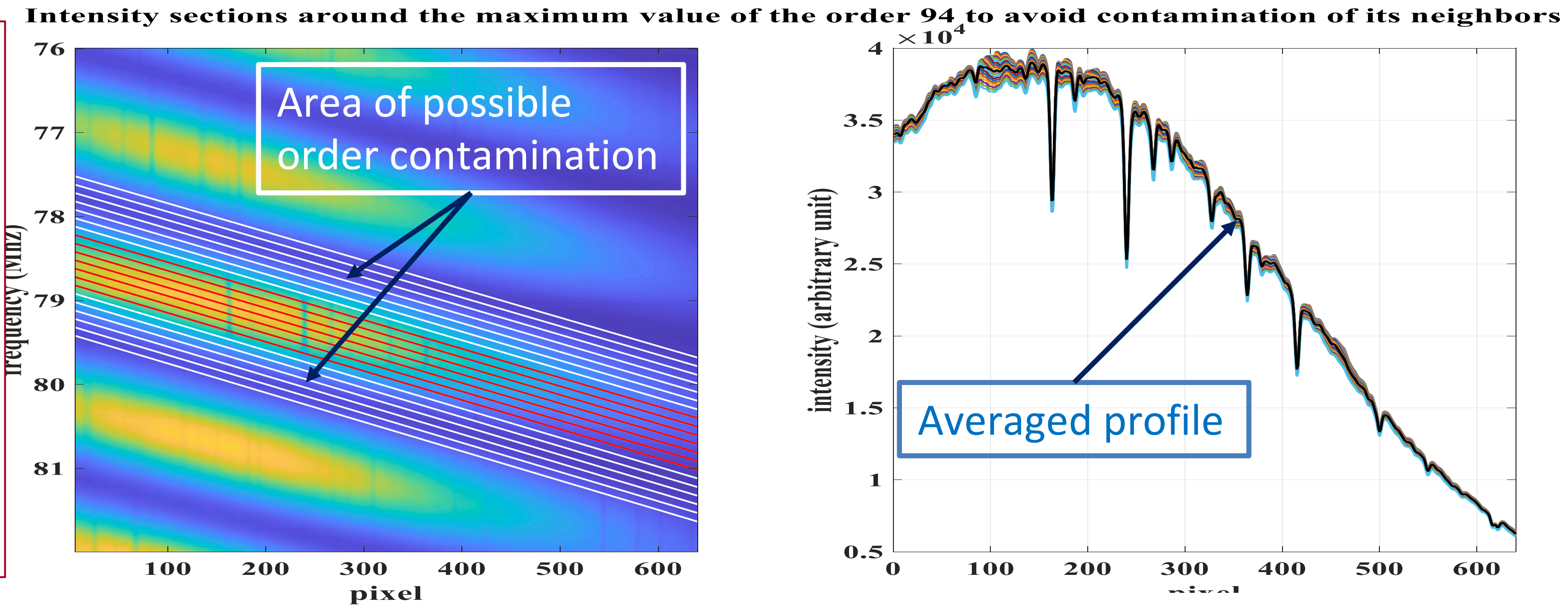
- There is a **wavelength drift** (pixel axis) of the orders with the **AOTF frequency**
- **2 or more orders** may be **affected** for a **given AOTF frequency**

- **Slices** in the **spectral image** following the **wavelength drift** are taken in the **frame [AOTF frequency, wavelength]**
- Most of **the solar lines** are in their **correct locations** when we plot **intensity (slice) profiles**.



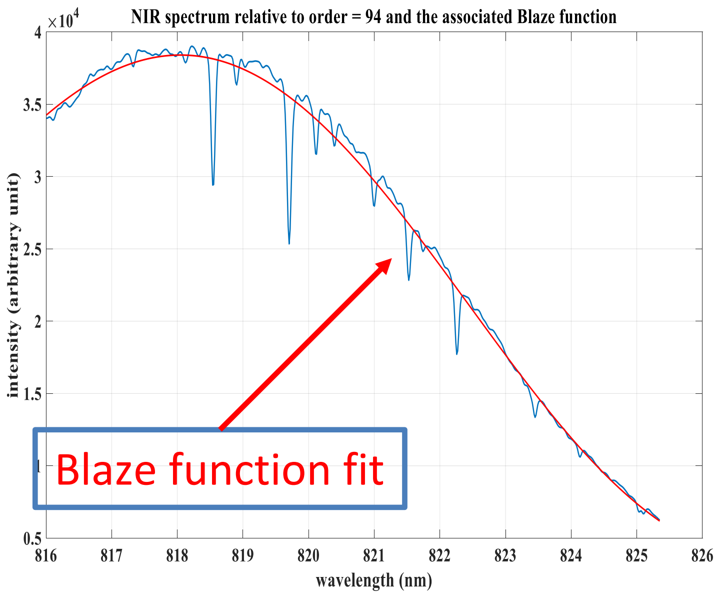
# Solar spectral bands versus AOTF frequencies

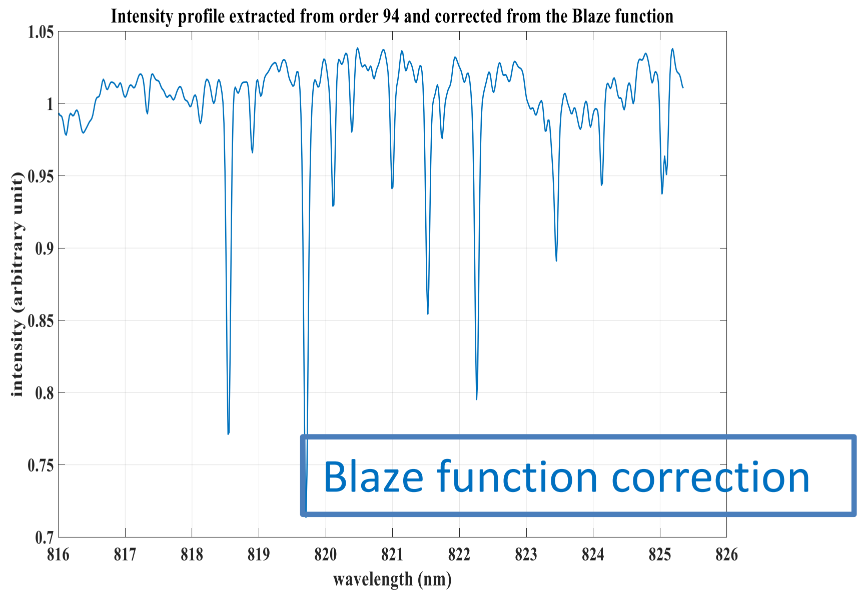
**Intensity profiles** are **only taken** in the **area around the maximum intensity** of the diffraction order (**red straight lines**) to **avoid contamination** from neighbors, then **the average is calculated**.



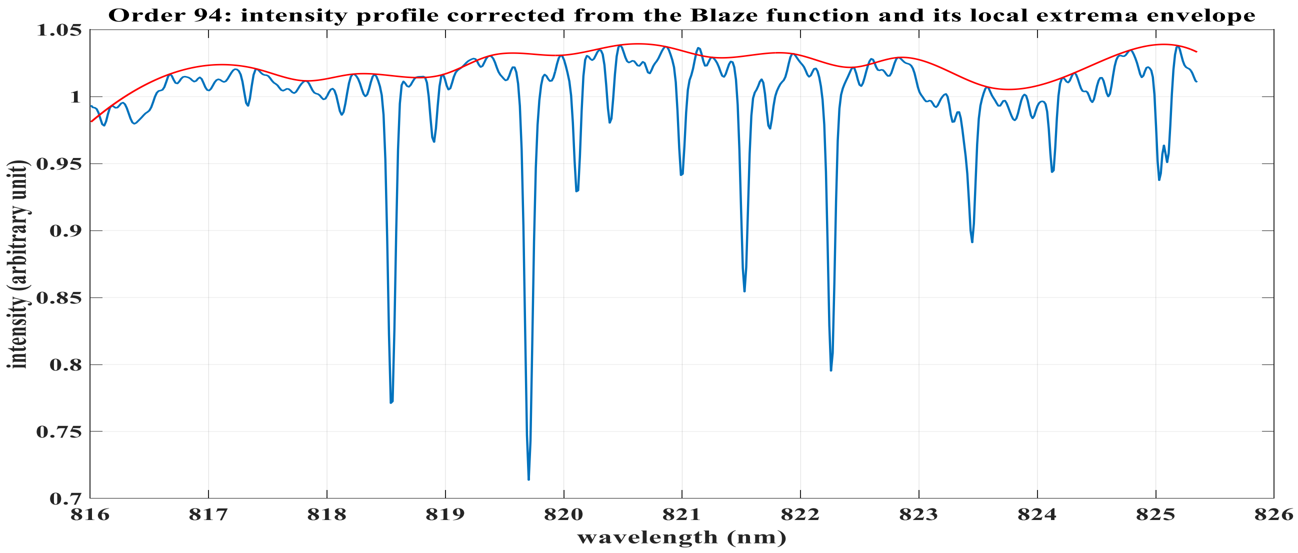

- The **averaged profile** of **each diffraction order** is **well fitted** by the corresponding **Blaze function**

- The **Blaze function** is used to correct **each mean profile** of its **intensity variation along x**



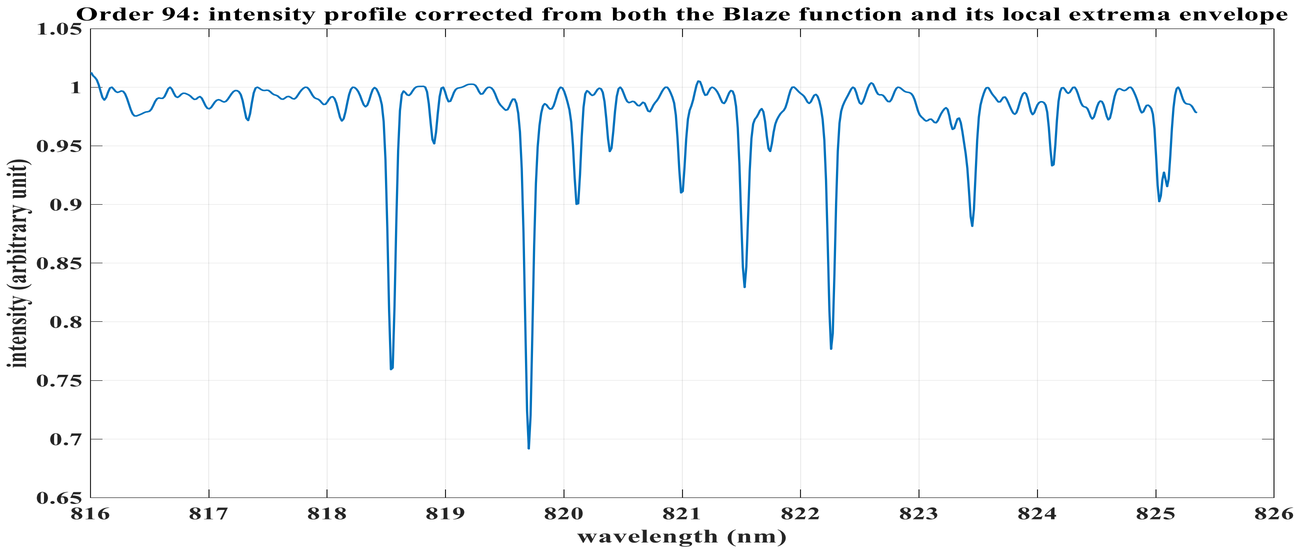



# Intensity profile corrected from the Blaze function then from its local extrema curve




**Residual fluctuations are then reduced.**

<u>To do this</u>, we ***detect the envelope*** (**red curve**) defined by the ***local extrema*** of the fluctuations and we ***use it for this for correction***.




***All mean intensity profiles of each order*** are ***corrected*** for **both** their ***Blaze function fits*** and their **envelope** of ***residual fluctuations***.

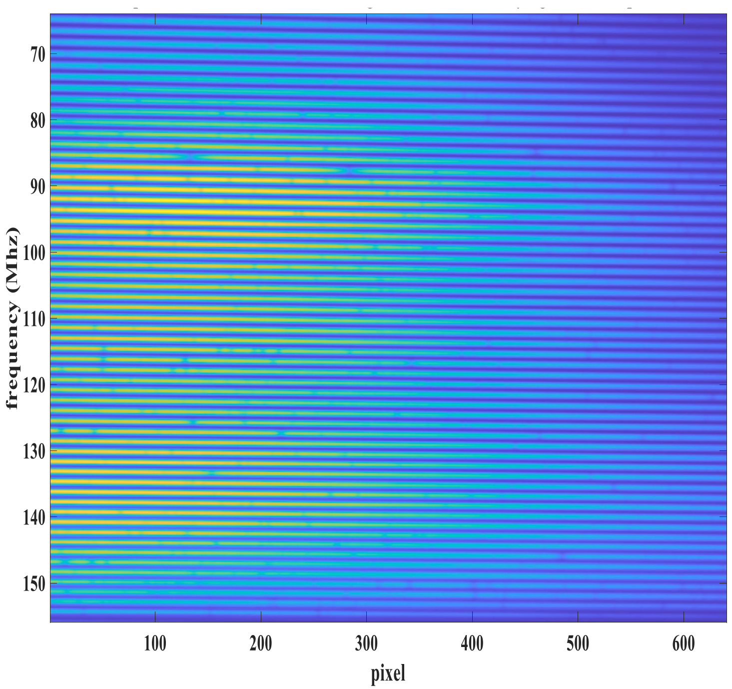
***The solar continuum is set arbitrary to 1***

∴ <u>At this stage</u>, the **solar spectrum can be constructed** but the **interpolation** needed to extract the **oblique slices** in the **spectral band image** introduces **spectral filtering**: **additional improvements are required**

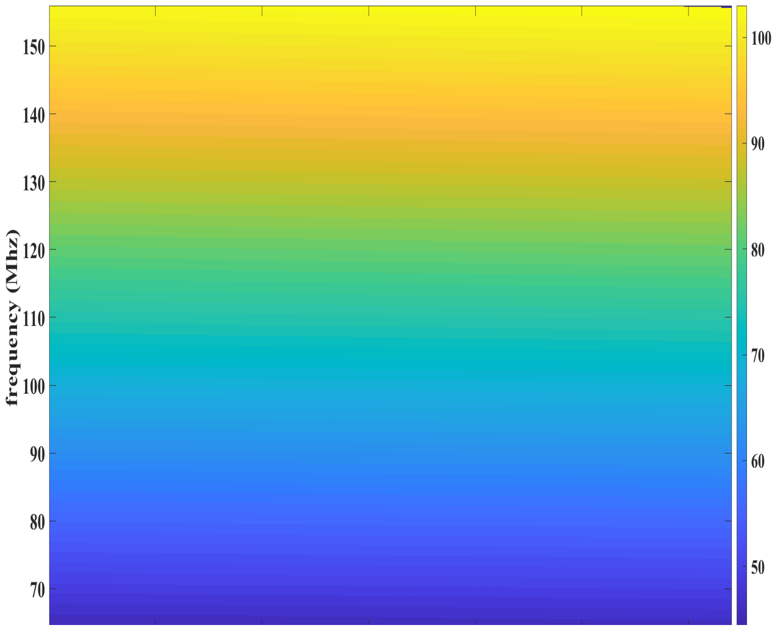
# III – Use of off-center images to reconstruct the spectral band of each diffraction order

The **previous method is valid in case of continuous variation of AOTF frequency but** **what about spectral contamination when using few constant AOTF frequencies?**

The **spectral contamination matrix** can be deduced from this method if we **encode** the **spectral band of the diffraction orders** with **their order number**.



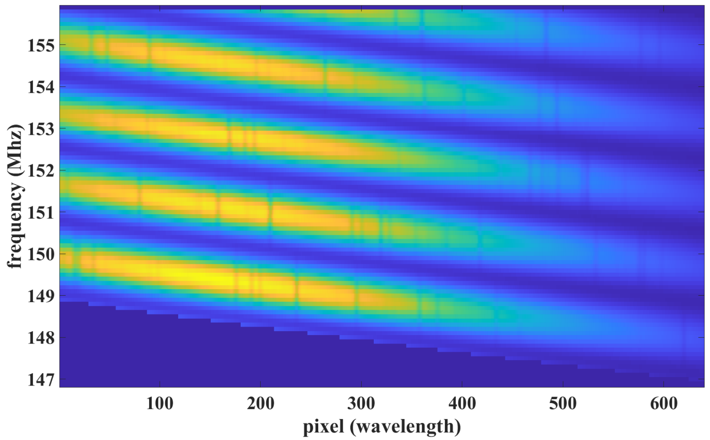

All spectral bands obtained from orders

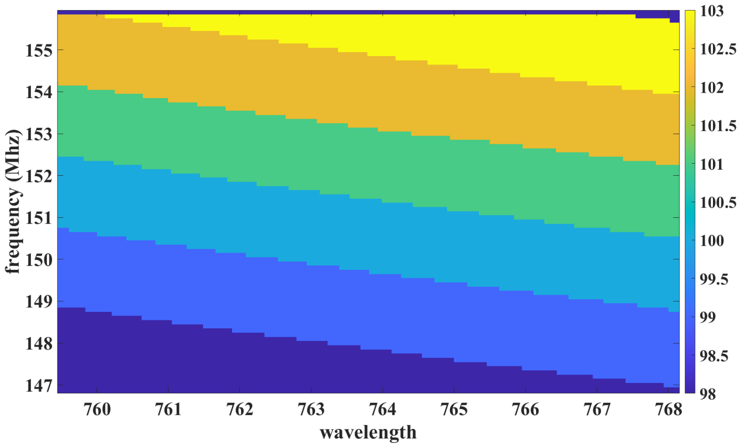



Spectral bands ***encoded*** with ***order numbers*** ***define*** **the** ***contamination matrix***

# ***Example***

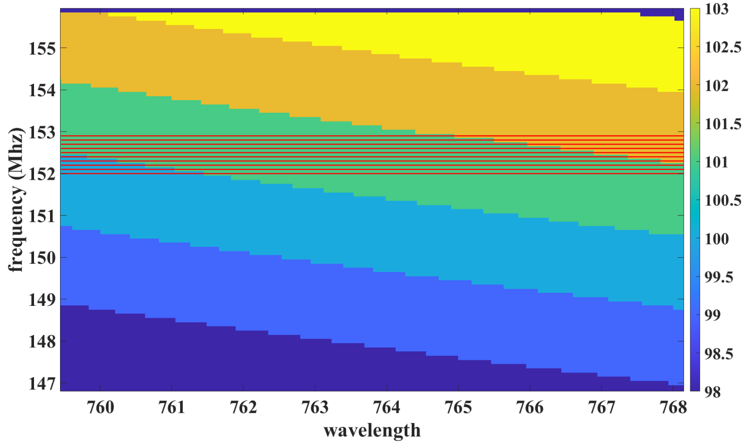
Successive spectral bands near **order 101**

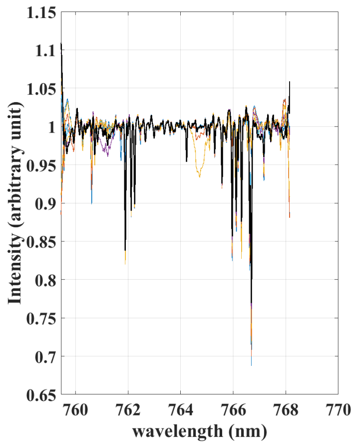


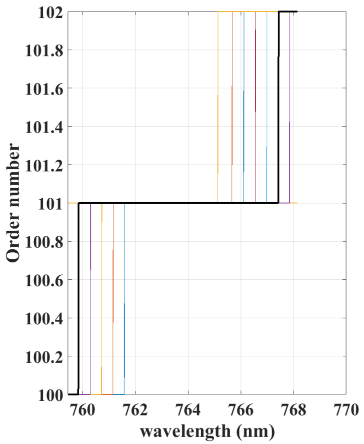




Successive orders near **order 101** encoded with order numbers.

Slices in the encoded image in case of **constant AOTF frequencies**

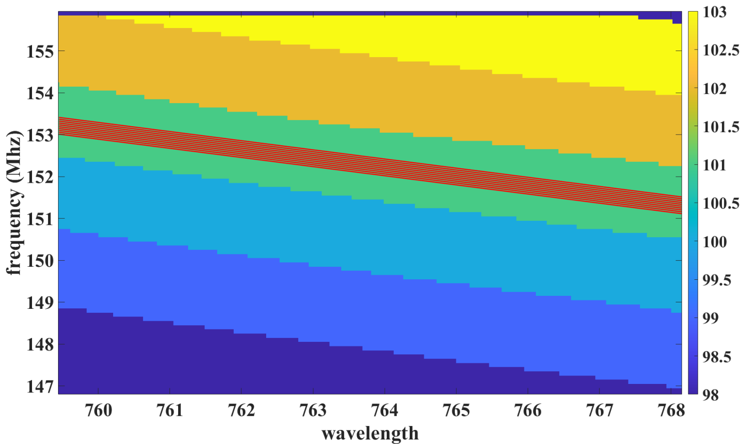


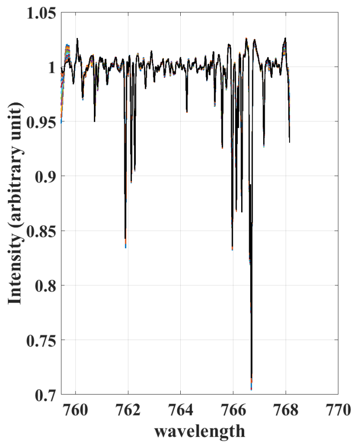



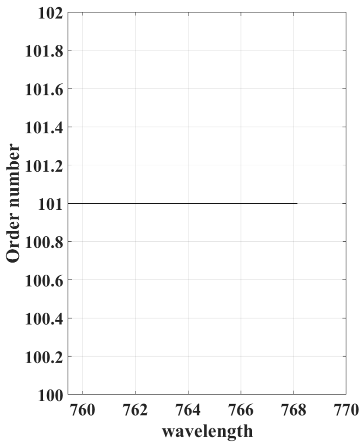




Corresponding intensity profiles and orders involved.
The **frequency that minimizes** the **order contamination** is used in **nominal mode** (***black line***).

**Oblique slices** in the encoded image




Only **one order involved**.

# How to avoid spectral contamination between orders?

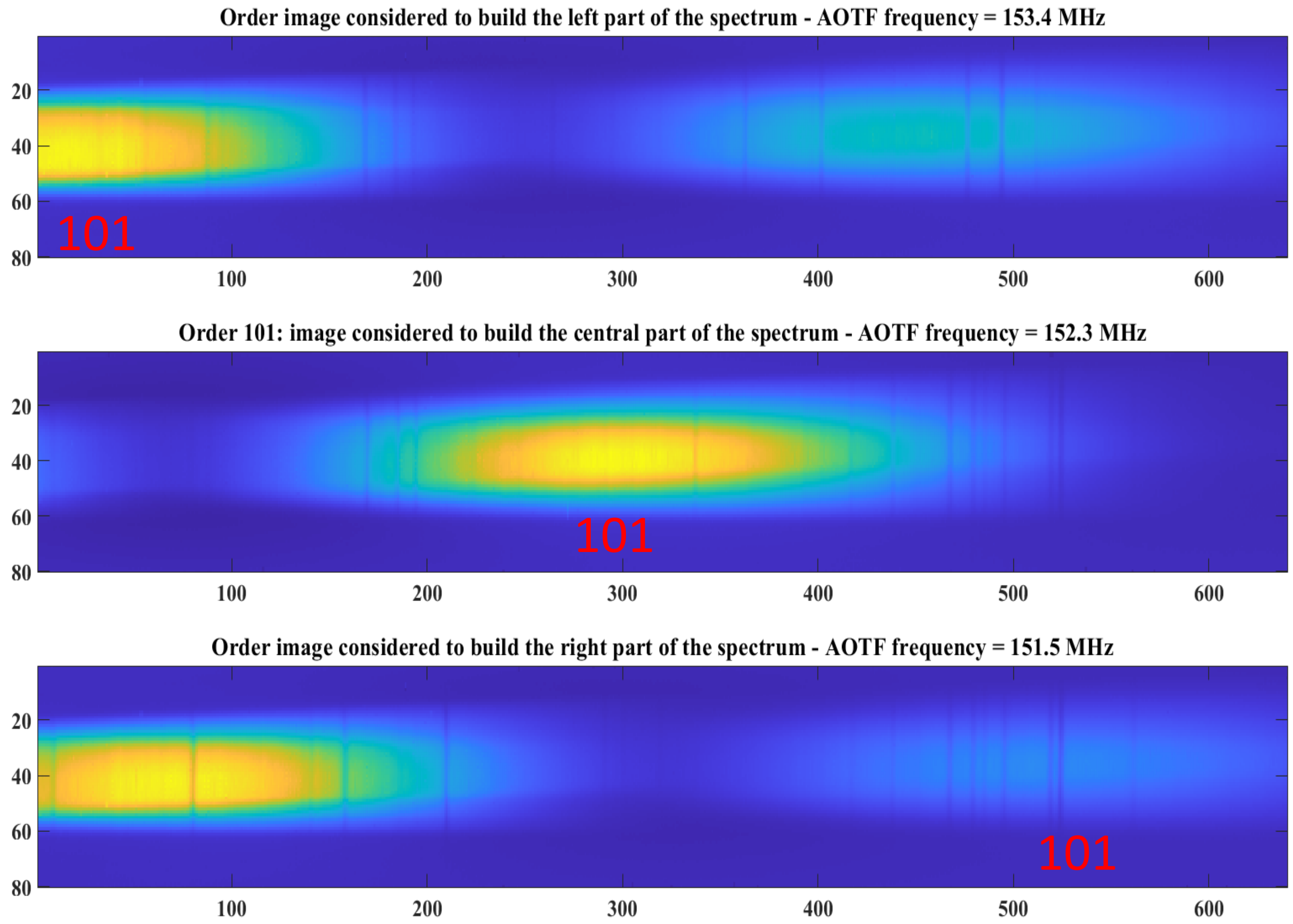
***Image pieces extracted from 3 off-center images of the same order obtained with 3 AOTF frequencies are combined to reconstruct the spectral band without contamination***.

This ***solution*** also has the ***advantage*** of having ***higher intensity at the order ends***, therefore a ***better detection of spectral lines*** there.

# Spectral bands obtained from combination of image regions

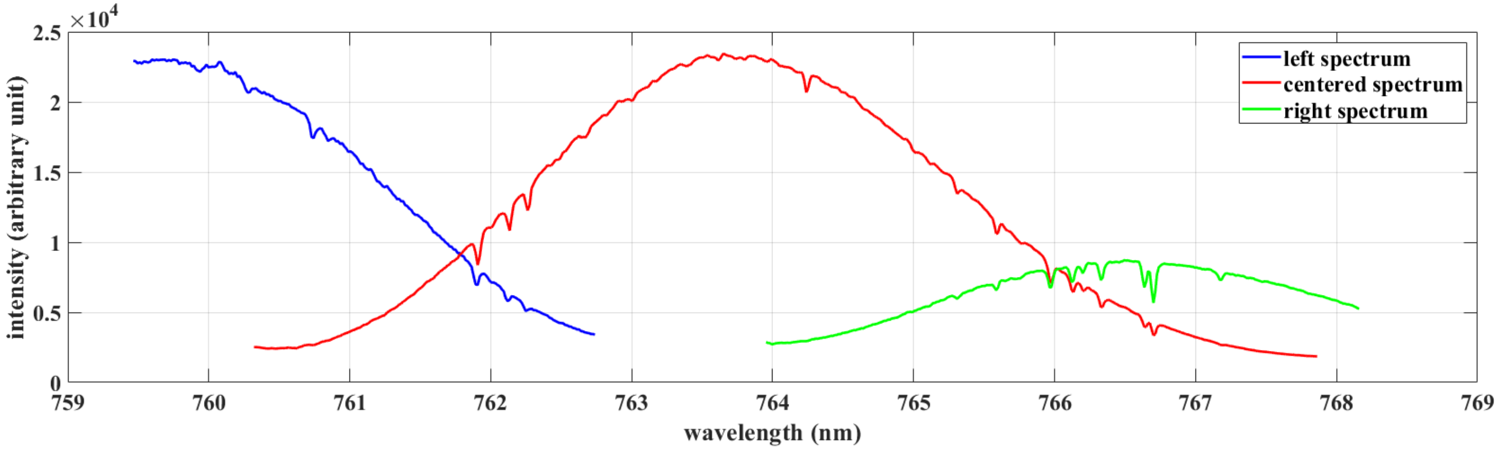
Choose of ***3 off-center images*** of the ***same diffraction*** order (here **order 101**).

The ***contamination matrix*** makes it possible to ***find*** the ***best image candidates*** i.e. the ***most off-center images*** with ***maximum intensity at the ends***.

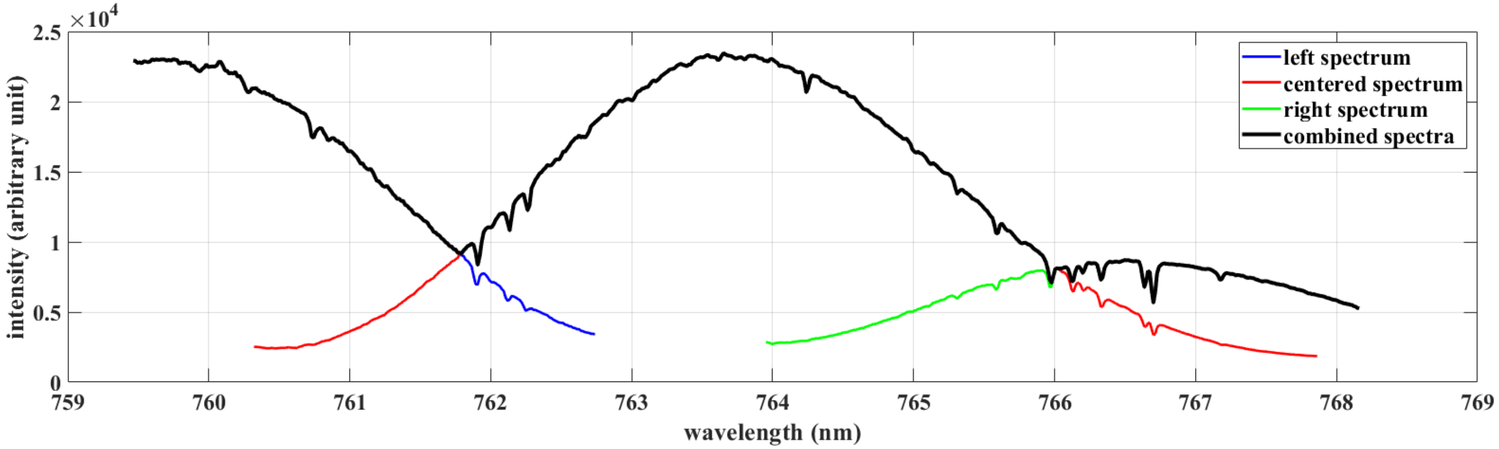


# Spectral bands obtained from combination of image regions

The 3 extracted spectral bands from off-center images of the same order.
***Blue***: left image
***Red***: middle image
***Green***: right image




They are then combined (***black***) and the result is used to reconstruct the spectral band of the considered order

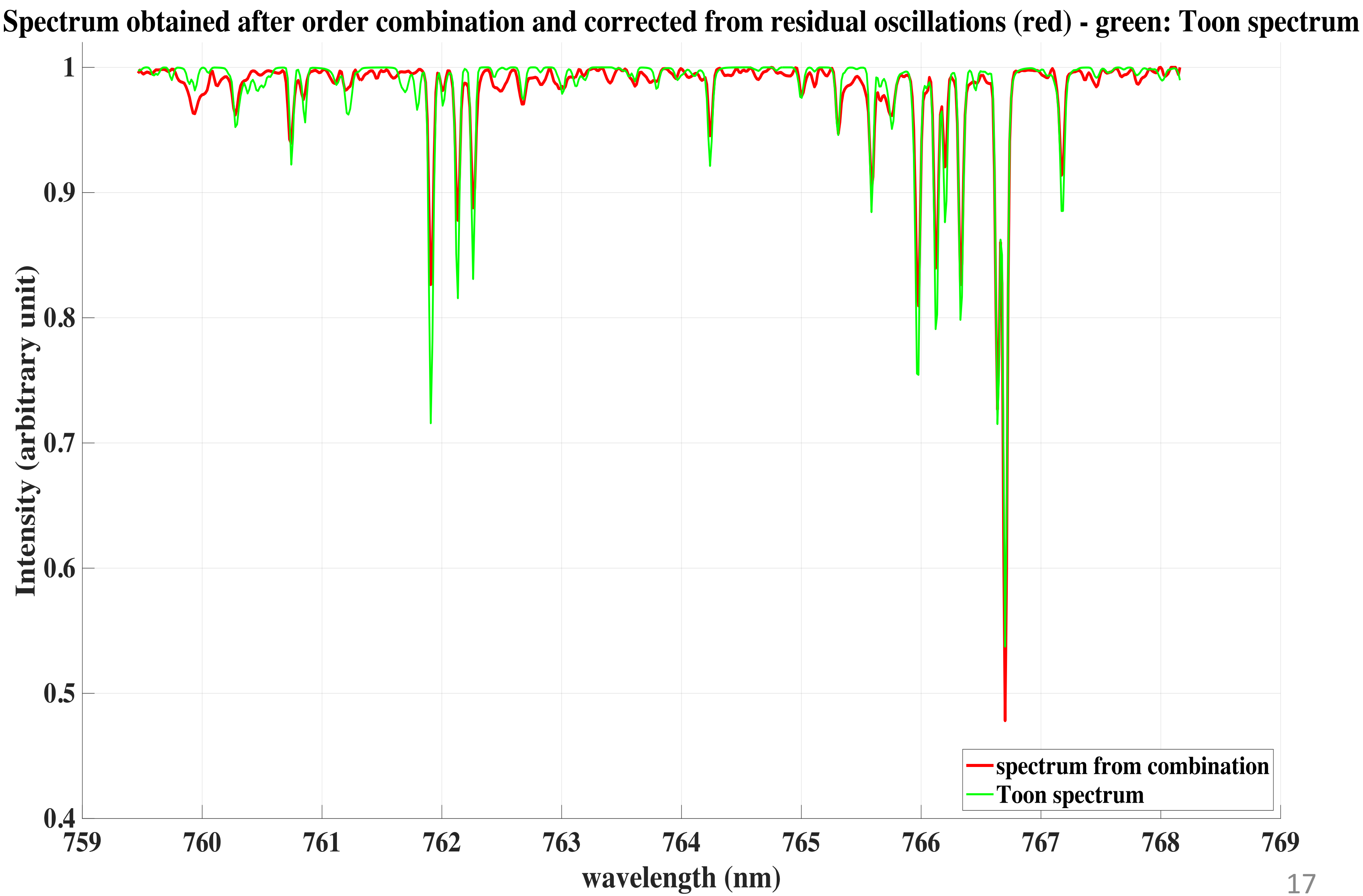


# Spectral bands obtained from combination of image regions

***Red***: Spectral band of **order 101** after order combination and correction from residual oscillations

***Green***: Toon's reference spectrum

A good agreement is observed



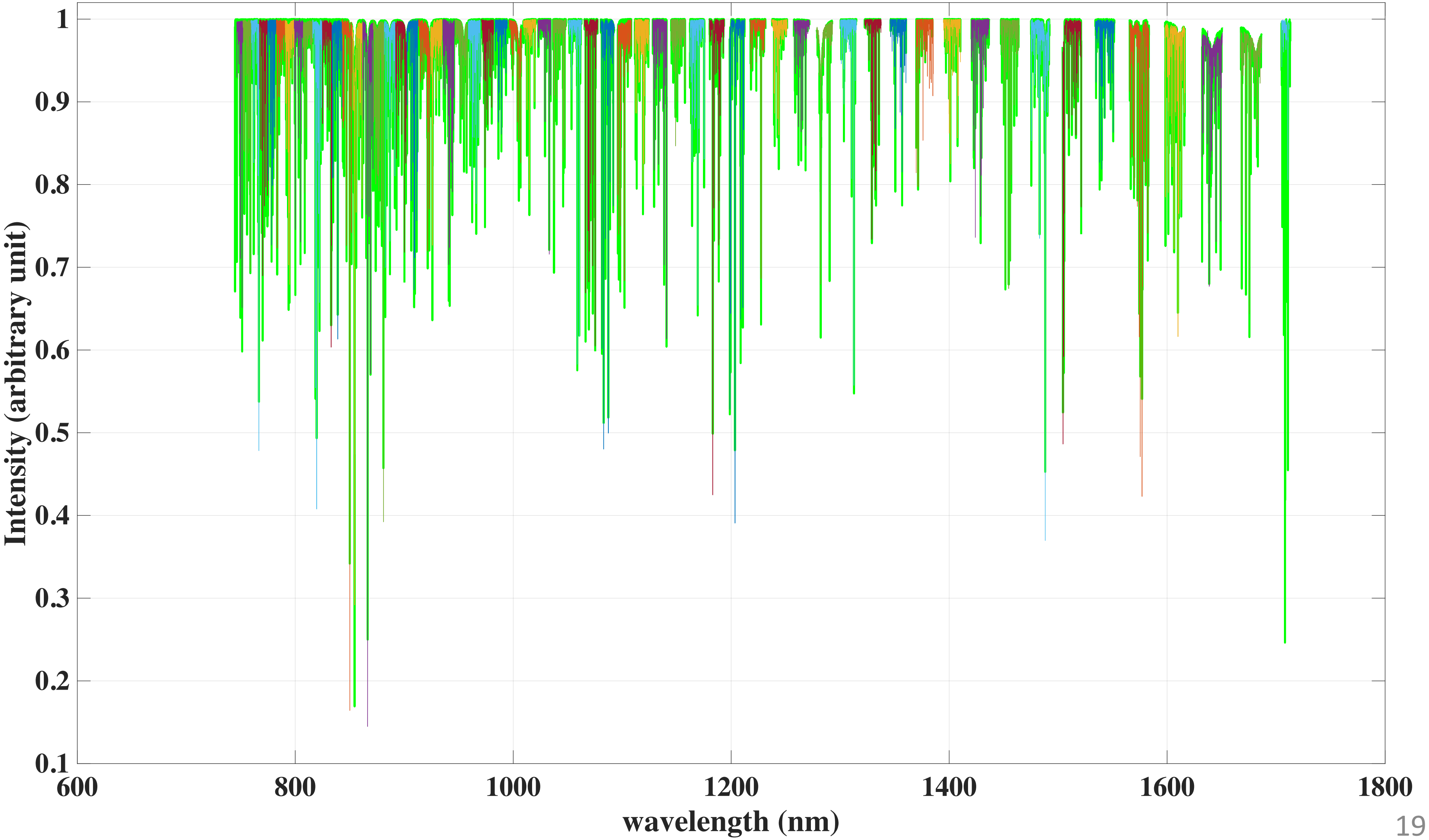
# IV – New ACS-NIR solar spectrum and comparison with Toon's reference spectrum

# The solar spectrum as obtained from the NIR spectrometer

The **solar spectrum on the 0.7-1.7 µm range** is calculated using the combined method with all NIR orders.

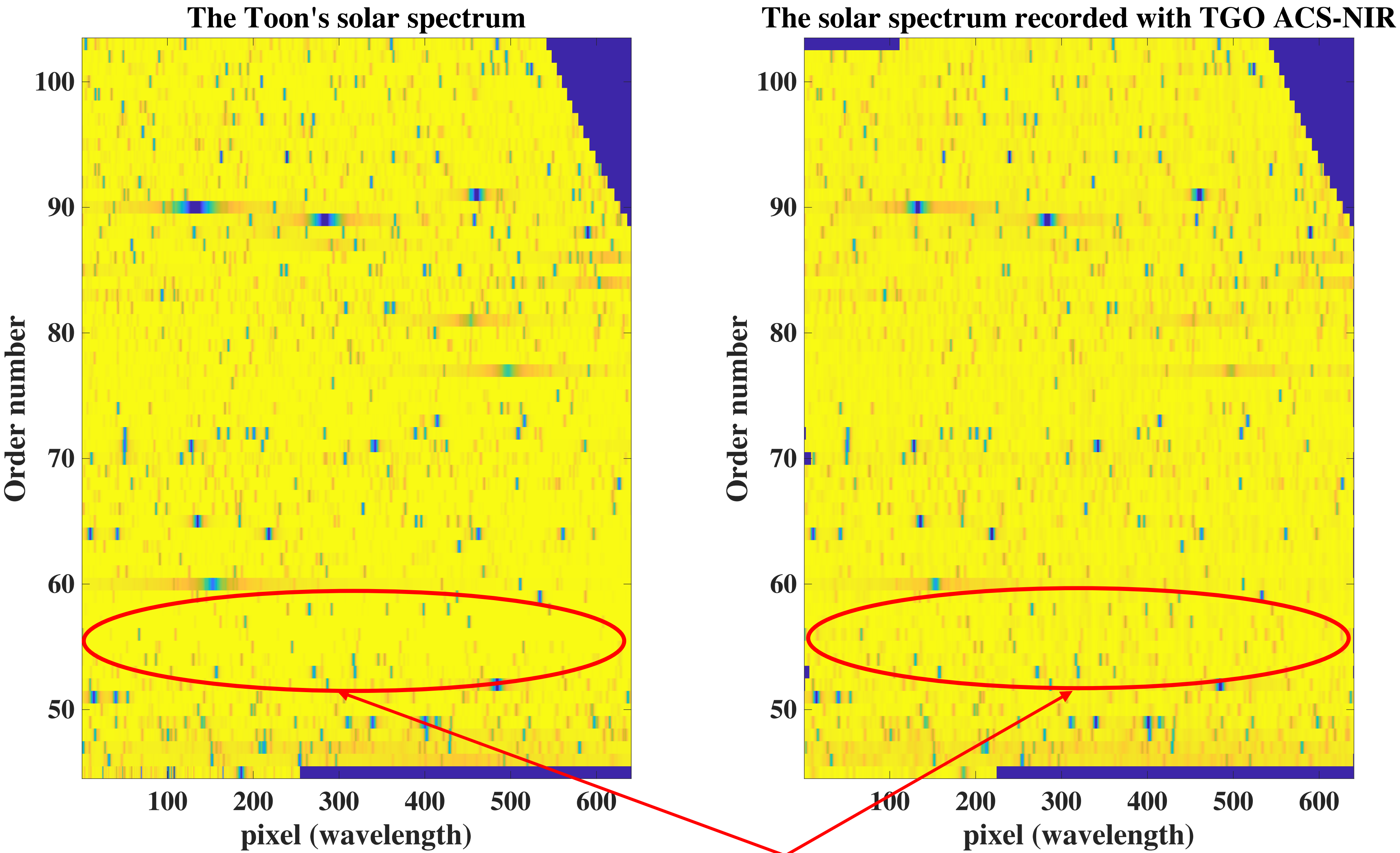
A **good agreement** is observed with the **Toon's reference spectrum**.

ACS-NIR spectrum by order combined method (color) – Toon's spectrum (**green**)



# NIR solar spectrum and Toon’s one

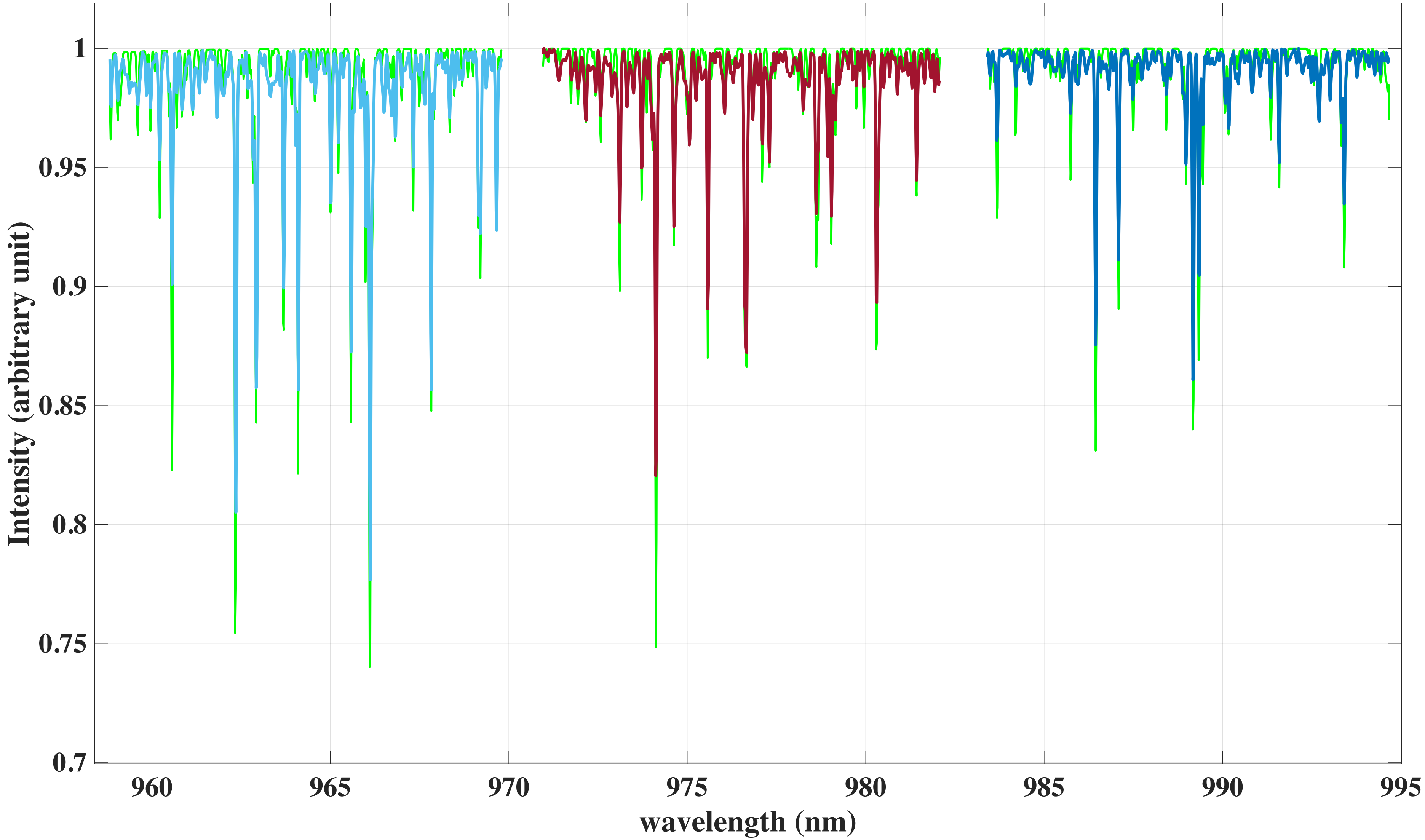
**Agreement** with Toon’s reference spectrum is well evidenced when plotting both spectra as **images** where **each line** represents the **spectral band of an order**




Some **image differences** are however observed

# The spectral bands 80, 79 and 78 showing the good agreement with the reference

ACS-NIR spectrum by order combined method (color) – Toon’s spectrum (**green**)

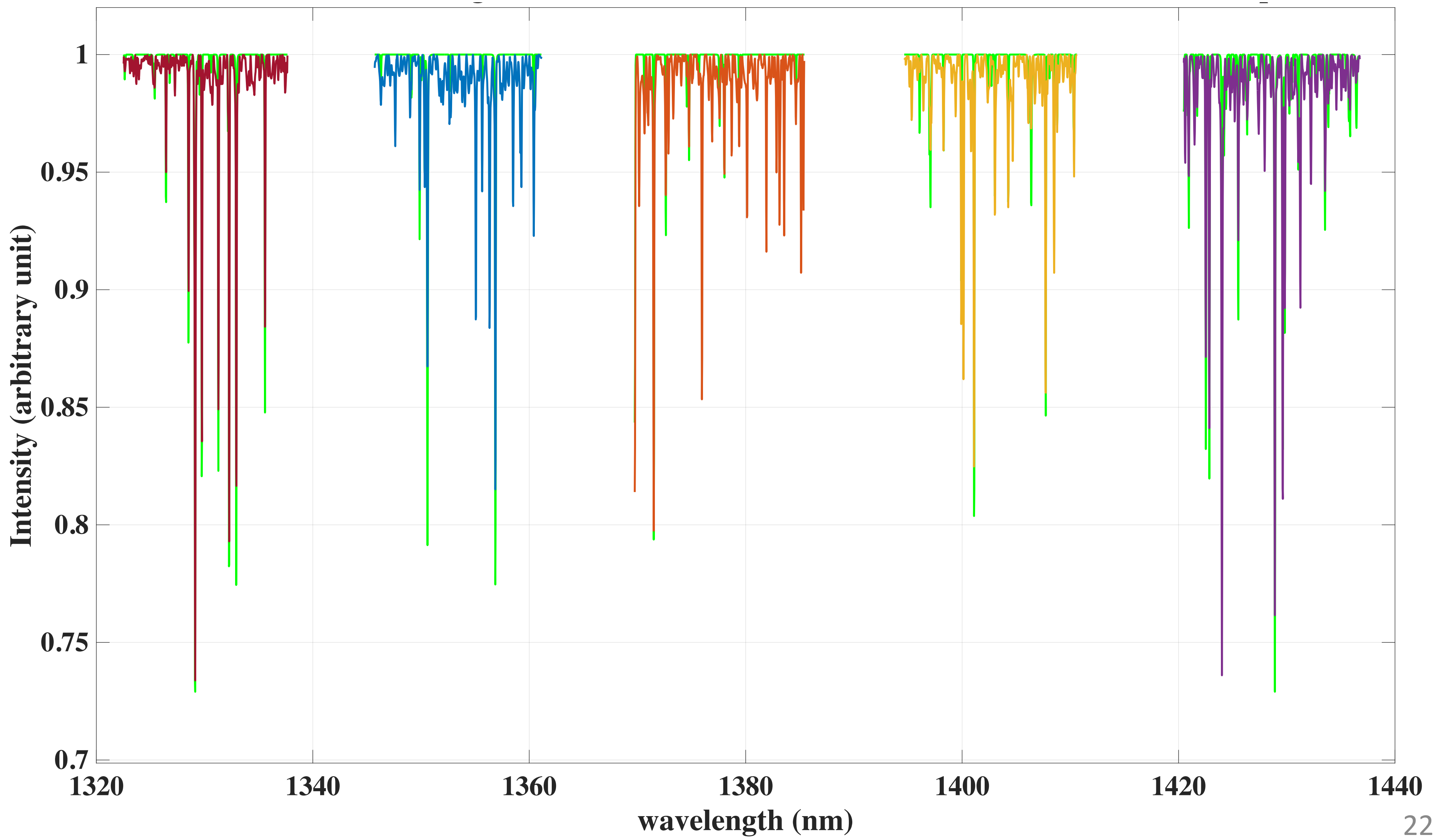



Excellent agreement of these spectral bands with the **Toon’s reference spectrum**

Some NIR spectral bands compared to Toon’s reference (**green**)

# The NIR solar spectrum compared with the Toon's one

ACS-NIR spectrum by order combined method (color) – Toon's spectrum (**green**)

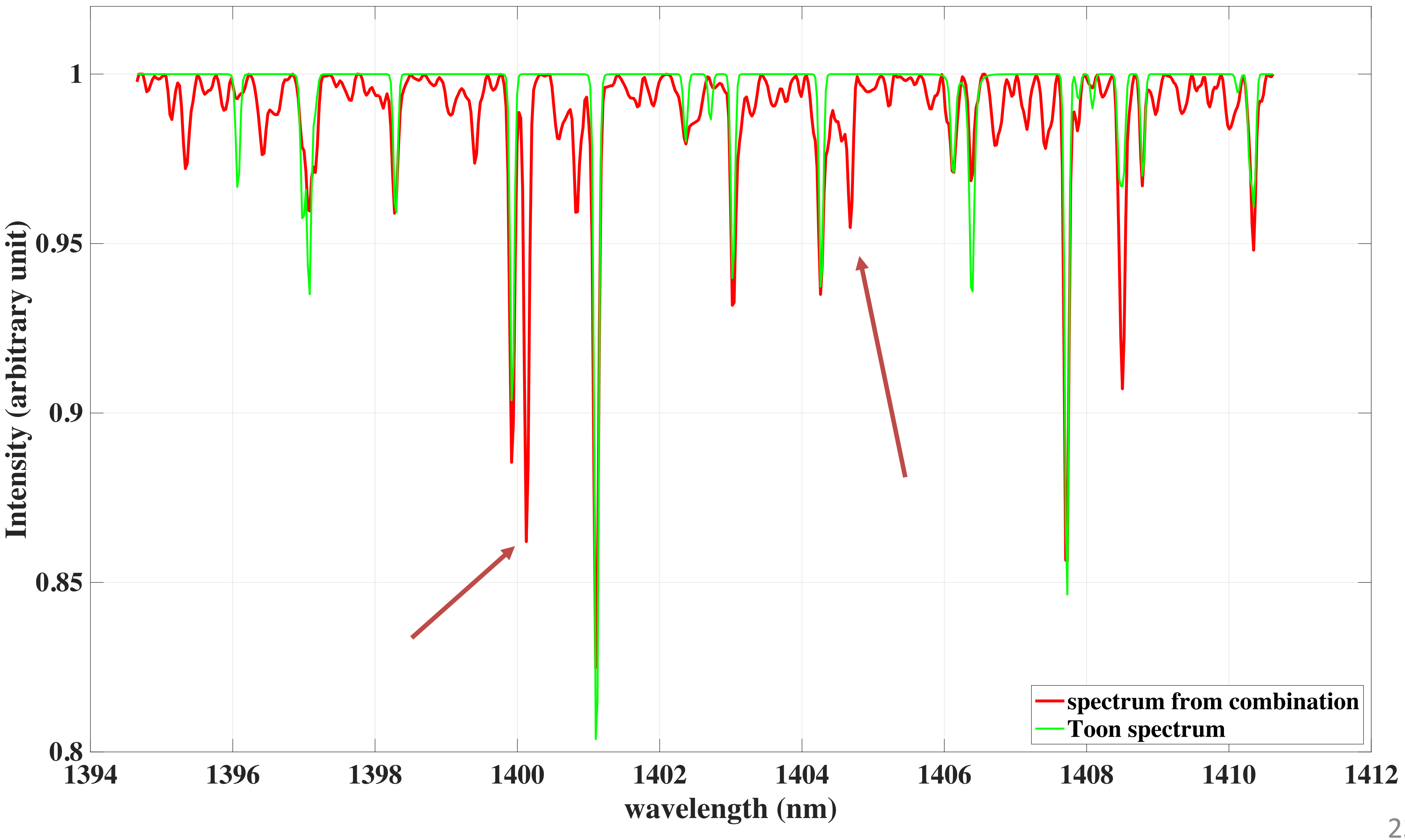



Some solar lines are present in the NIR spectrum but not in the **Toon's reference spectrum**

# Zoom on order 55

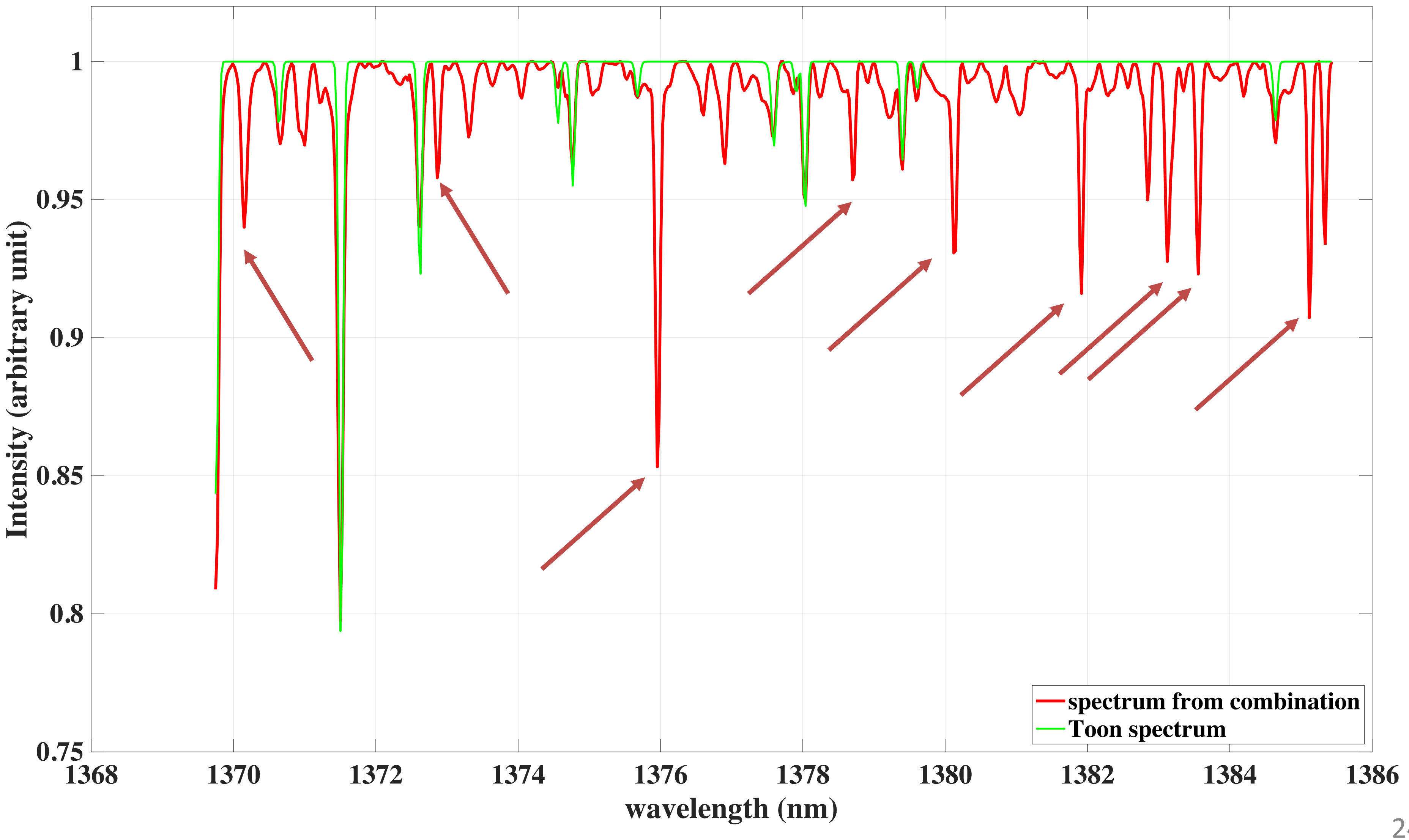
ACS-NIR spectrum by order combined method (**red**) – Toon's spectrum (**green**)

New solar lines are clearly visible in the **spectral band of order 55** compared to the **Toon's reference spectrum**



# Zoom on order 56

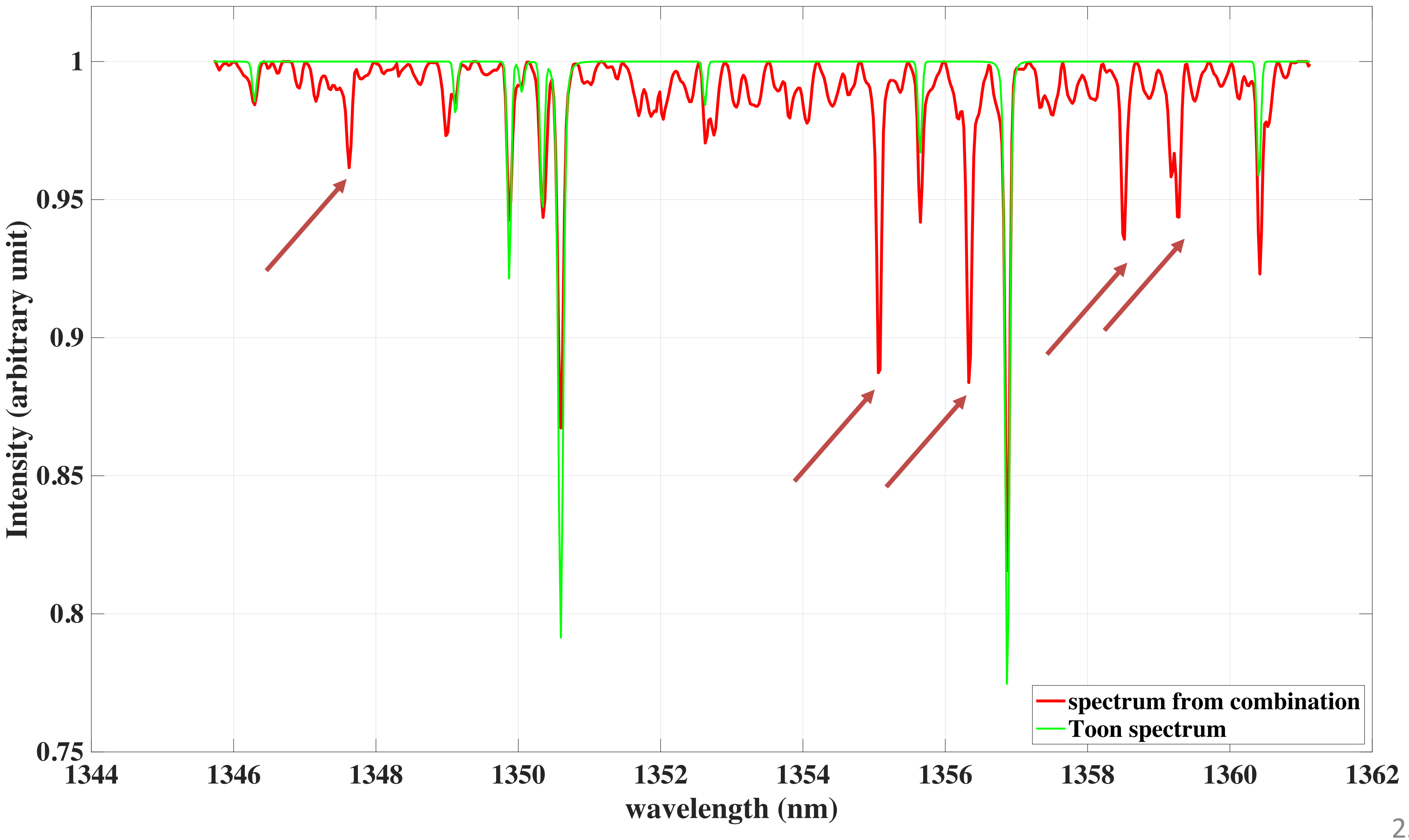
ACS-NIR spectrum by order combined method (**red**) – Toon's spectrum (**green**)




New solar lines are clearly visible in the **spectral band of order 56** compared to the **Toon's reference spectrum**

# Zoom on order 57

ACS-NIR spectrum by order combined method (**red**) – Toon's spectrum (**green**)




New solar lines are clearly visible in the **spectral band of order 57** compared to the **Toon's reference spectrum**

# Summary

- **HR (0.02 nm) solar spectrum on 0.75 – 1.69 µm domain** was obtained using **calibration data** from the **ACS-NIR spectrometer on TGO**

- **New method** to **avoid order contamination uses** and **combines image pieces** of **3 off-center images** of the **same order obtained** with **3 AOTF frequencies**

- **Excellent agreement** with the **Toon's solar spectrum** used as **reference spectrum**

- The **solar spectrum obtained** with the **ACS-NIR spectrometer** reveals **numerous** **solar lines** **never observed** from **the ground (absorbed by atmospheric water vapor bands)** and **visible only from space**