REPORT ON THE NOMAD INSTRUMENT CALIBRATION

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1. Preface

The following document describes updated results and efforts to produce a new calibration recipe for the Acousto Optical Tunable Filter (AOTF) NOMAD SO and a corresponding updated model. This model builds and updates our original findings initially reported in August 28th 2017 (email at 2:45pm by GLV, and then published in Liuzzi et al. 2019), with updates and the "recipe" sent on October 2nd 2018 (email at 8:09am by GLV).

This AOTF and ILS "recipe" is at the core of the analysis performed since 2017 by the GSFC group. The new improvements as described in this report lead to better residuals and a more accurate representation of the spectra, yet with modest changes to the derived columns/abundances. As we will present in this document, this original calibration recipe is generally validated, yet improved, by the latest calibration investigation.

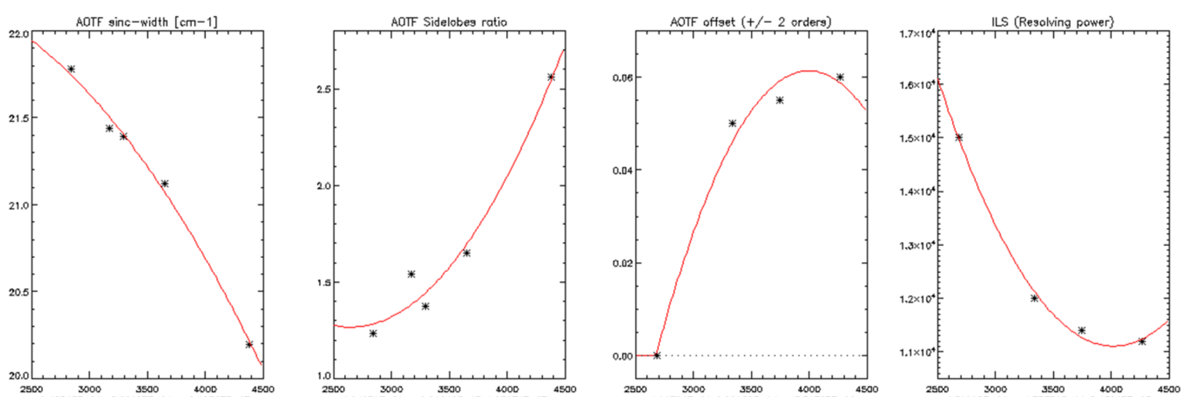

Figure 1: Original calibration method for the AOTF and ILS of the SO channel (October 2nd 2018, email at 8:09am by GLV). As we present in the next sections, the width and symmetrized sidelobe ratio has not changed much, yet we have now added an asymmetry for greater accuracy. The AOTF "offset" was quantified to be ~0.05 for the high orders, when employing +/- 2 orders, equivalent

to an absolute offset of 0.25, and consistent with our new findings (see Liuzzi, May/2021 report). Our original quantification of the ILS defined it to be a single gaussian with a greater width, capturing the issues of the double ILS. In May/2020, we reported on our findings of the findings of the double ILS and a calibration method for such (email sent on May/4/2020 at 1:21 AM by GLV).

2. Characterizing the AOTF filter

We have used miniscans taken in 2018, 2019 and 2020 across a broad range of orders to investigate the properties of the AOTF. We particularly focused in solar mini-scans in which the Sun observed, and the AOTF is tunned at fine intervals. By probing the intensity of Fraunhofer one can recover the transmissive properties of the filter. The actual spectrum measured by the instrument is actually a combination of the effects of the grating (blaze, frequency solution, etc.) and the AOTF. We build on our previous investigation of the grating (Liuzzi et al. 2019) to establish those quantities and their thermal evolution (Figure 3). We then agnostically investigate the intensity of a series of solar lines across the mini-scans and determine the AOTF properties.

An important first test was on the accuracy of the impact of temperature on the AOTF center frequency. As we demonstrate in Figure 2, our original thermal calibration model nicely compensates for the movement of the AOTF in frequency. Importantly, we also see that the AOTF properties appear to remain stable across the years.

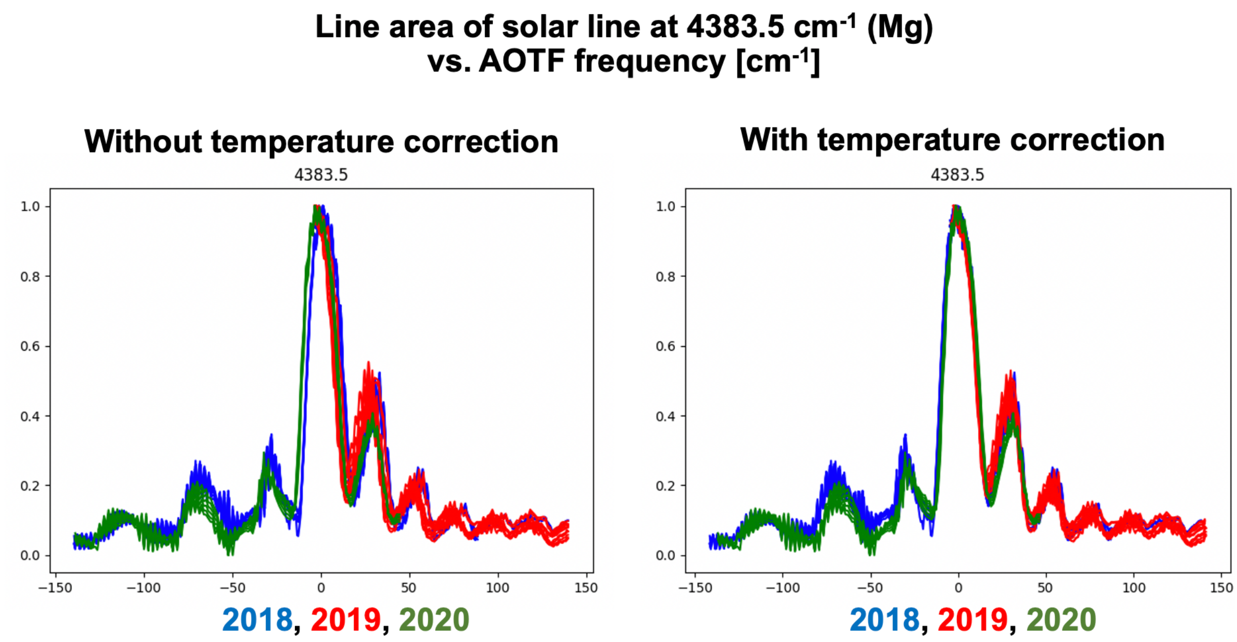

Figure 2: Characterization of the AOTF near 4385 cm-1 (2.28 um) by investigating the intensity of the Mg solar line as the AOTF is finely tuned across these frequencies. We processed data from miniscans in 2018, 2019 and 2020 and when correcting for the AOTF temperature, we observe relatively good agreement.

```python
# Calibration coefficients (Liuzzi+2019 with updates in Aug/2019)
cfaotf  = np.array([1.34082e-7, 0.1497089, 305.0604])        # Frequency of AOTF [cm-1 from kHz]
cfpixel = np.array([1.75128E-08, 5.55953E-04, 2.24734E+01])  # Blaze free-spectral-range (FSR) [cm-1 from pixel]
tcoeff  = np.array([-0.736363, -6.363908])                   # Blaze frequency shift due to temperature [pixel from Celsius]
aotfts  = -6.5278e-5                                         # AOTF frequency shift due to temperature [relative cm-1 from Celsius]
blazep  = [0.22,150.8]                                       # Blaze pixel location with order [pixel from order]
```

```python
freq  = np.polyval(cfaotf,aotf[i])
if freq<line-140 or freq>line+140: continue
freq += aotfts*mtempa*freq
order = round(freq/(np.polyval(cfpixel,160.0)))
ipix  = range(320)
xdat  = np.polyval(cfpixel,ipix)*order
dpix = np.polyval(tcoeff,mtemp)
xdat += dpix*(xdat[-1]-xdat[0])/320.0

blazep0 = round(np.polyval(blazep,order)) # Center location of the blaze  in pixels
blaze0 = xdat[blazep0]                    # Blaze center frequency [cm-1]
blazew = np.polyval(cfpixel,blazep0)      # Blaze width [cm-1]
dx = xdat - blaze0; dx[blazep0] = 1e-6
blaze = (blazew*np.sin(np.pi*dx/blazew)/(np.pi*dx))**2
```

Figure 3: Parameters and numerical methods employed to describe the blaze and frequency solutions.

3. Modeling, contaminants and multiple sincs

As we were exploring different solar lines across the whole SO wavelength range, we noticed some peculiar non-sinc shapes, which could be associated to strong non-asymmetries or abnormal behavior of the filter. As we explored the issue more closely, we realized that these "excess" transmittances were actually related to overlapping solar lines from other orders, that coincidentally had a matching a pixel location. Specifically:

- The AOTF profile may be contaminated with solar lines from other orders.
- How this affect the profile would appear intractable, but due to the AOTF and grating system, the contaminations only occur for lines exactly at distances of blaze times order.
- These contaminations would appear as a shifted sinc at that position, and can be easily identified and removed.
- These are not part of the AOTF transfer function - They are simply representations from another line!
- These contaminant sincs are actually very useful for further refining the asymmetry and shape of the AOTF.

Using this information and a solar atlas, we identified these "contaminants" and incorporated them in the characterization of the fit. For the modeling of the AOTF, we considered a non-symmetric sinc function, with enhanced sidelobes. The AOTF is then modeled at each frequency with 3 parameters (width, sidelobes factor, asymmetry factor).

4. Recipe

The AOTF is then modeled at each frequency with 3 parameters (width, sidelobes factor, asymmetry factor), which are defined at each center frequency by a 2nd order polynomial fit. The factors and corresponding fits are shown in Figure 4. Importantly, and as shown in the Figure 4, our new solution is relatively comparable to our findings on 2018 (see Figure 1).

```
# AOTF shape parameters
aotfwc  = [1.11085173e-06, -8.88538288e-03,  3.83437870e+01] # Sinc width [cm-1 from AOTF frequency cm-1]
aotfsc  = [2.87490586e-06, -1.65141511e-02,  2.49266314e+01] # sidelobes factor [scaler from AOTF frequency cm-1]
aotfaf  = [-5.47912085e-07, 3.60576934e-03, -4.99837334e+00] # Asymmetry factor [scaler from AOTF frequency cm-1]
```

```
wd0 = np.polyval(aotfwc,line);
sl0 = np.polyval(aotfsc,line);
af0 = np.polyval(aotfaf,line);
```

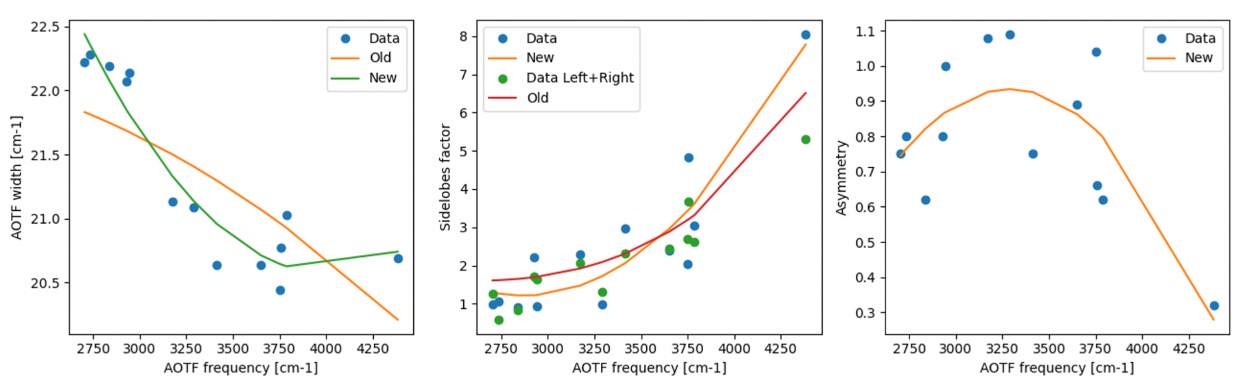

Figure 4: Recipe and modeling method of the AOTF across the SO tunable frequency range. The new values are compared to a symmetrized solution as presented in Figure 1.