Subject: Calibration impact of HIFI optical Standing Waves

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Abstract: After 18 months of HIFI operations, an assessment of the calibration impact of the optical standing waves is attempted. By using the existing measured system temperatures, a worst case estimate can be derived for line and continuum calibrations. The dominant standing waves are by now well understood for the different bands. Through simple modelling of the four dominant standing waves, the approach was validated , reproducing fairly well measured T_{SYS} and predicting results of modified calibration schemes.

The derived worst case numbers add up to about 4% error on the intensity calibration for all bands, both for continuum and lines. By removing the standing waves contribution from the Hot and Cold Blackbody loads, this error can be reduced to < ~1% for bands 1 and 2, can improve the central IF part for bands 3-4 to 2%. A modified HIFI calibration scheme is proposed here as an alternative pipeline that should be available to users.

Distribution:

Distribution lists:

HIFI SET	
HIFI AIV	
HIFI Calibration	

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1 Introduction

A lot of efforts were made in ILT, TBTV and CoP campaigns to understand and verify the optical standing waves. However a final assessment in terms of intensity calibration impact was not provided. By using the thousands measurements HIFI has performed so far, it becomes possible to make use of those statistics to provide an estimate for their calibration impact.

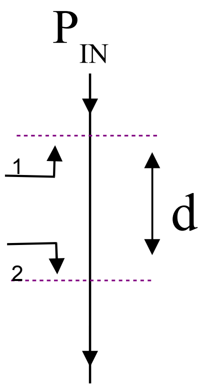
We begin reviewing the main optical standing waves HIFI suffers from, all of which are well understood. A very simple model incorporating those was then used able to reproduce fairly well the measured T_{SYS} for different bands. This also helps showing the intricate interactions they produce.

By using the existing spectral scans covering all of the HIF bands with the finest granularity, we derive a worst case error for continuum and lines. The naïve model also allows verifying that the current HIFI calibration scheme error in intensity calibration can be estimated through the deviations seen in the T_{SYS}.

A modified scheme is then proposed, where the loads standing waves are removed from their respective measurements. Application of this technique is illustrated with some examples, for strong continuum cases where the improvement is most noticeable, but this modified scheme would also improve the intensity calibration for spectral lines in bands 1 and 2.

2 Review of the dominant HIFI optical standing waves.

2.1 Introduction standing waves



As a brief introduction to standing waves, they are produced through the interference of a given input signal with a small part of itself, which is reflected back and forth by two reflecting surfaces. The distance d between the two surfaces gives rise to a phase delay, which defines the standing wave frequency. As a rule of thumb, the following formula can be used:

$$\Delta t = 2d/c \quad \rightarrow \quad f\_stdw\ (MHz) = 300 / 2d$$

$$P_{MEAS} = P_{IN} + {}_{1}\,{}_{2}\, P_{IN}\, (\Delta\varphi)$$

Fig. 1. Illustration of the standing wave principle.

This applies to any input signal. Figure 2 illustrates the measured signal when a 100 MHz standing wave is present and the input signals are:

a) a continuum signal, for example for a blackbody source. We approximate it here for our test frequency range to a constant power spectrum at all frequencies (from 980-1020 GHz)

b) a monochromatic input signal at a frequency F1 of intensity 1 K.

It is important to note that although the standing waves are easily noticeable for strong continuum objects, they are still modulating any spectral lines, though not as visually noticeable.

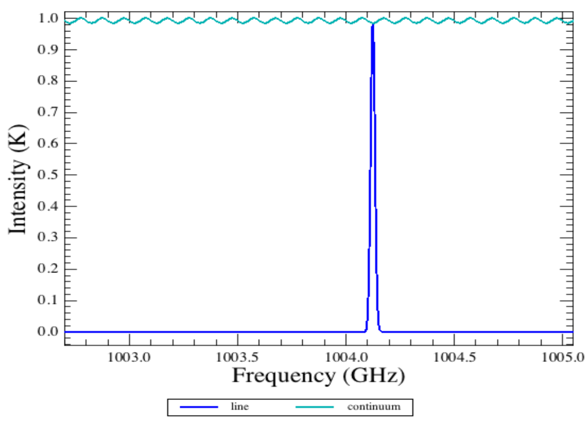


Fig. 2: Illustration of the standing wave effect on a continuum signal and on a spectral line.

2.2 Folding in a double sideband receiver

HIFI-Instrument uses DSB mixers, therefore with the mixing process, the upper sideband and lower sideband signals are folded together. This creates a difference in the treatment of continuum signal and signal present in only one sideband.

The following example illustrates the simple case of one standing wave of 100 MHz modulating different test signals. a) a flat continuum signal from ~990-1010 GHz, b) a spectral line at F1 = 1004.2 GHz in this example. c) a flat continuum signal, but only in the USB. (not physical but helps for visualization of folding aspects).

The signals are now folded and we plot them in the IF scale in Fig. 3.

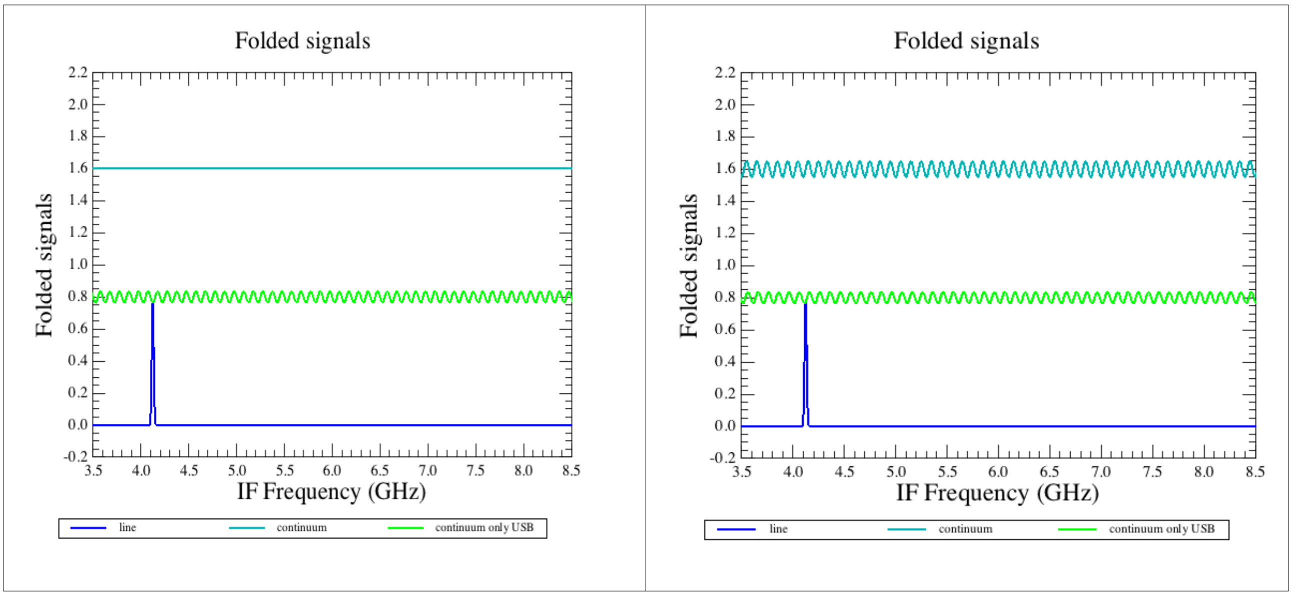


Fig. 3. Example of folded signals. For continuum signal. Depending on the phase. The standing wave can add up constructively or destructively. Those two extreme cases are illustrated here. *Left)* The standing wave is cancelled for the continuum measurement folded. *Right)* The standing wave is added up in phase for the continuum measurement folded.

2.3 Calibration of measured data

Figure 3 shows simplified example of measured signals. The last step is the calibration of these measured signals. For that, a pair of blackbody loads is used to derive the bandpass and the data is calibrated using it. These steps will be described in more detail in the following sections.

One point to note here is that we are using blackbody loads to calibrate. For a standing wave which is common for all measurements (like the LO-mixer one), in an ideal case using perfect loads, the calibrated data for continuum signals should always be free of standing waves, as the continuum measurements from the loads will match the pattern of standing waves. However for emission present in only one sideband, this will depend on the phase (see Fig. 4).

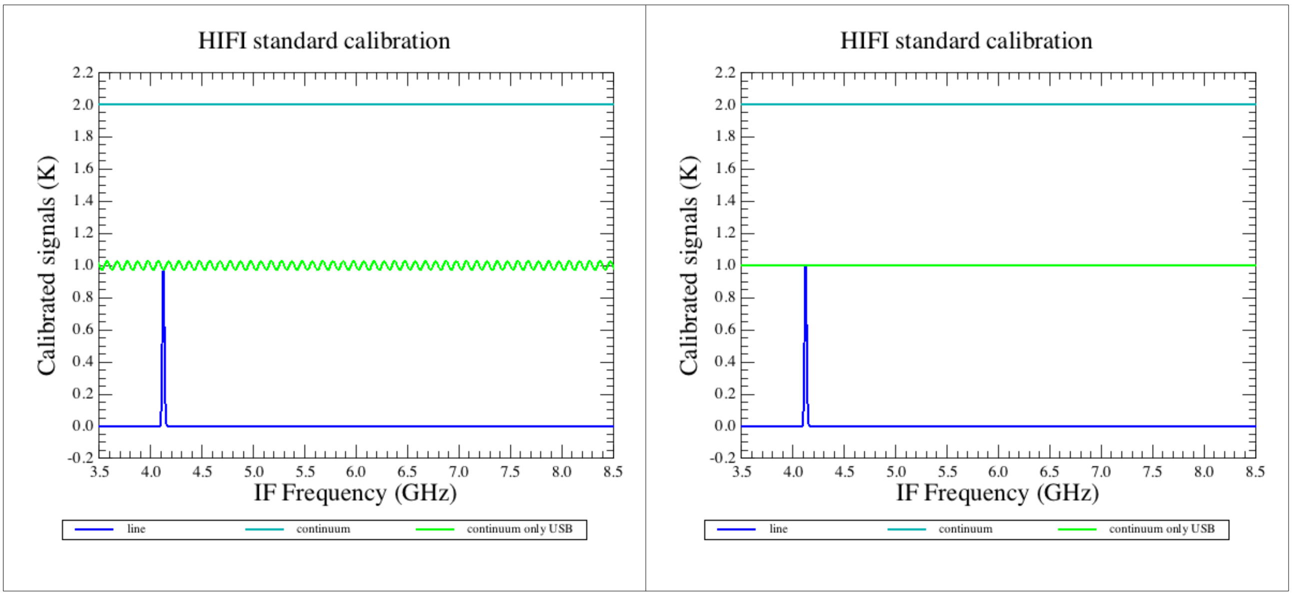


Fig. 4. Example of calibrated signals using perfect blackbody loads. The two extreme cases from Fig. 3 are used here.In both cases, the standing wave is calibrated out for the continuum measurement. However for emission in only one sideband: a) The standing wave is not calibrated out. b) The standing wave is calibrated out as the phase of the standing wave in USB matched the folded continuum one.

However, practical examples on Mars for example show that the continuum is not always calibrated out perfectly from the LO-mixer standing wave, due to the imperfect loads used in the calibration. (examples in 9.2).

For a more complete treatment of an example of standing wave (LO-mixer), the reader is referred to the Schieder note: https://kt.sron.nl/view.php?fDocumentId=1179.

2.4 HIFI optical standing waves

The following table 1 summarizes the main optical standing waves for HIFI.

Table 1. Summary of the main HIFI standing waves

Standing wave path	Distance (mm)	Frequency (MHz)
CBB - mixer	~ 1530	98
HBB - mixer	~ 1625	92
LO - mixer	~ 1490	100
RTM – mixer (only bands 3,4,6,7)	~ 240	620
Secondary - mixer	~4160	35

The secondary mirror-mixer is one of the most common in radio telescopes. However, until now, we have not seen any clear evidence of it in science data, proving that the design measures to prevent it were effective, or that the other ones are dominating over it, hence not allowing to measure it.

3 Modelling of HIFI optical standing waves.

3.1 Beamsplitter bands (1,2 and 5)

Figure 2 shows the simplified layout for a beamsplitter HIFI band. Those bands have sufficient LO power so that this LO coupling scheme was possible. Only a small fraction of the LO power is coupled through a beamsplitter (5 % for bands 1 and 2 and 20% for band 5).

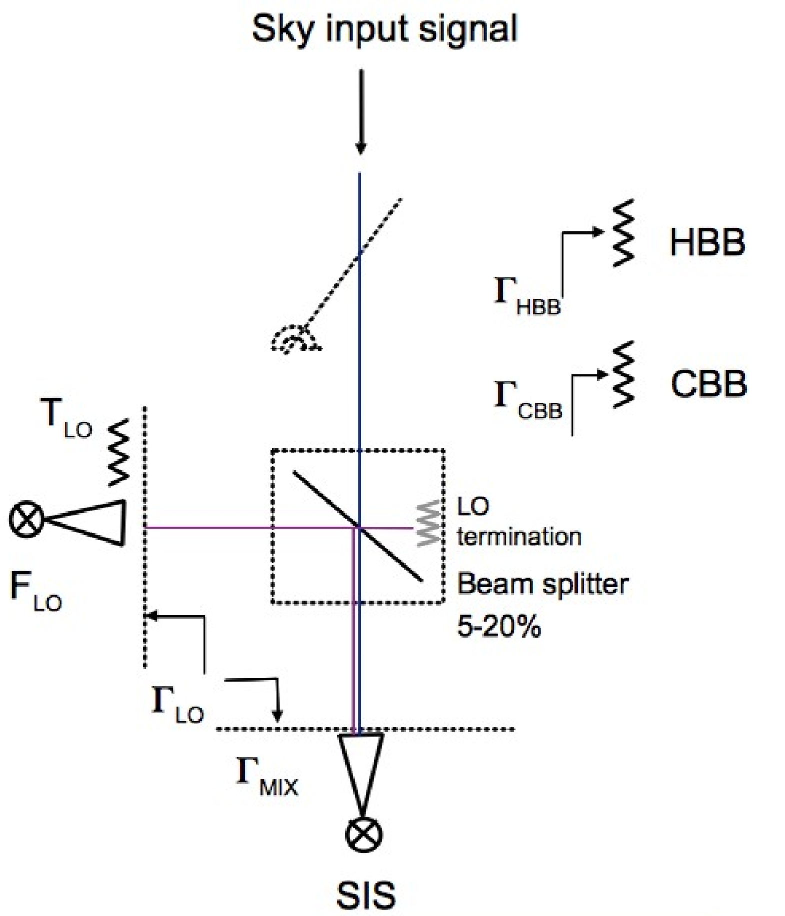


Fig. 5. Beam splitter LO injection simplified diagram. Bands 1, 2 and 5 use this type of scheme.

As can be seen, for those bands, the problematic standing waves are the HBB-mixer, CBB-mixer *during the loads measurements*, and the LO-mixer standing wave *for all measurements*.

3.2 Diplexer bands (3,4,6 and 7)

In those bands, the available LO power was more marginal, therefore a diplexer coupling mechanism was selected. It allows effectively to couple ~100% of the LO, although the major drawback is that if also means that 100% of the sky signal is only coupled at fixed frequencies (6 GHz apart of the LO frequency for bands 3 and 4 and 3.6 GHz apart of the LO frequency for bands 6 and 7). For the IF range we consider here (4 GHz for bands 3 and 4 and 2.4 GHz for bands 6 and 7), there will be about 15-25 % of the signal lost towards the edges. This also implies that that amount of the reflected signal is then coupled to the LO path. This has implication of higher noise temperatures, and higher standing waves from the LO-mixer at the edges.

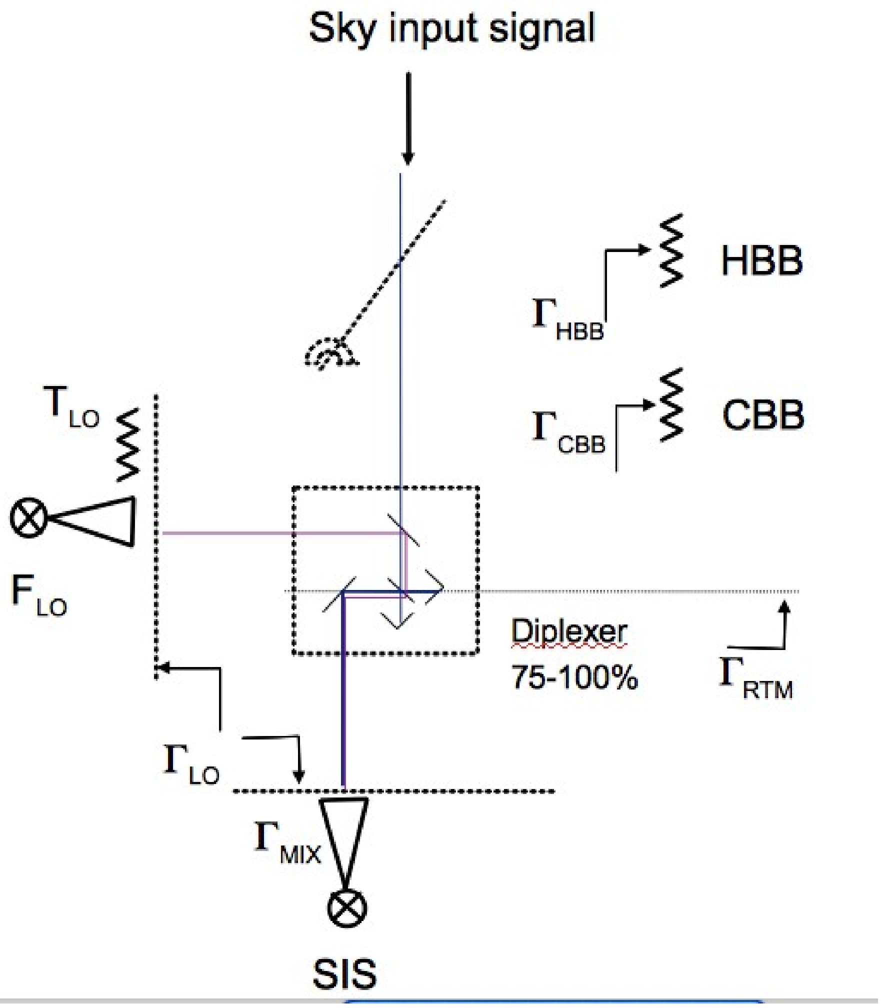


Fig. 6. Diplexer LO coupling simplified scheme. Bands 3, 4 ,6 and 7 use this type of scheme.

As can be seen, for those bands, the problematic standing waves are the HBB-mixer, CBB-mixer *during the loads measurements*, and the LO-mixer and RTM-mixer standing waves *for all measurements*.

3.3 A simple HIFI model

A very basic model was used. Standing waves are modelled as sinusoidal functions, of periods indicated in Table 1. Their free parameters are therefore their amplitude and phase. These standing waves are then included in the transmission of their path of interest. Different test signals are injected and the measured counts are simulated, taking into account the standing waves from different paths. the folding due to DSB mixers. The simulated "measured counts" are then calculated for the different input signals, and the standard calibration scheme is applied. Different alternative methods (see 7) can then be used and tested.

The appendix 9.2 gives more information about the model used and the parameters for the different bands. The following sections will show some of the simulated results.

4 Standing waves identification using planets as external blackbodies

Using the Saturn FPG measurements done in 2009. the planet itself was used as a hot blackbody and the sky OFF measurement was used as the cold measurement. Like this, T_{SYS} were derived and compared to the T_{SYS} derived from the internal blackbody loads. This method allows identifying which standing waves residuals are present only when looking at the internal loads, and which ones are common. Only few examples are shown here. For a more detailed report on this, a technical note is available here:

http://www.sron.rug.nl/~crisache/stdw/saturn.pdf

4.1 Bands 1,2 - comparison with simulated model

Figure 7 shows an example for band 1a. There are clearly additional components modulating the T_{SYS} when derived from the internal load measurements.

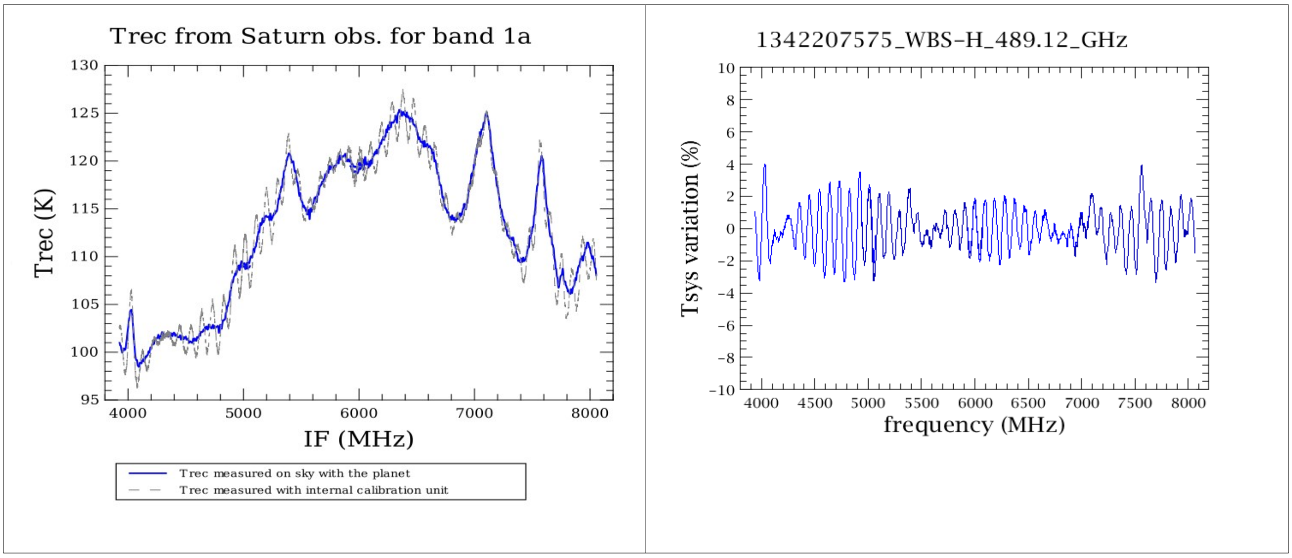


Fig. 7. Left) Measured T_{SYS} using Saturn as hot load and the cold sky as cold load. The dashed curve shows the T_{SYS} derived from the internal loads. Right) Residual between the two derived T_{SYS}.

By using the simple model, and only including the HBB-mixer and CBB-mixer standing waves, with amplitudes of 1-2%, the Fig. 8 shows simulated data matching quite well the measured cases.

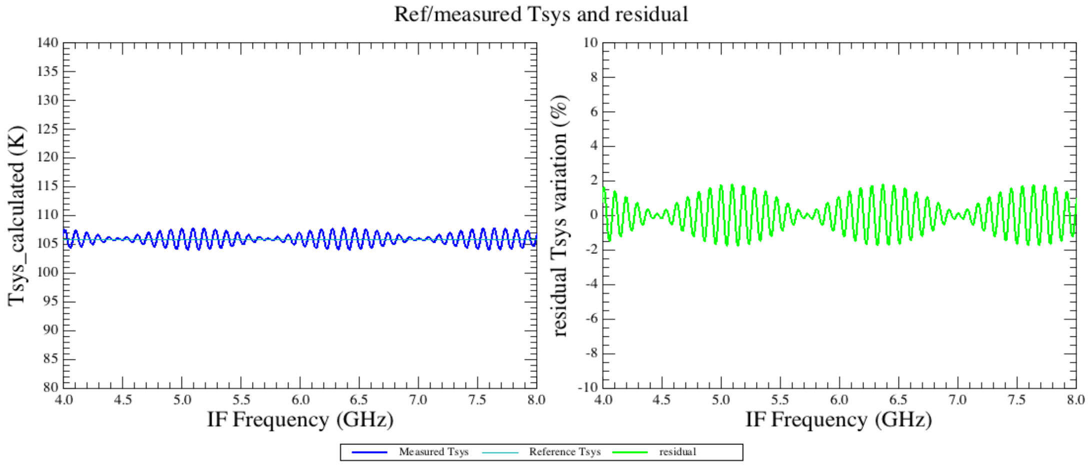


Fig. 8. Simulated T_{SYS} and residual including the HBB-mixer and CBB-mixer standing waves. The measured residual can be reproduced by changing the phase and amplitude of the standing waves.

For bands 1 and 2, the Saturn measurements show that the T_{SYS} measured with the internal loads includes these additional modulation from the loads themselves. The T_{SYS} derived from Saturn show no sign of other clear standing wave.

This allows to conclude that the dominant standing waves in bands 1 and 2 are the HBB-mixer and CBB-mixer. The LO-mixer one is not detected here.

4.2 Bands 3,4 - comparison with simulated model

Figure 9 shows an example for band 3a. There are components modulating the T_{SYS} common when using both the planet and sky or the internal loads. These are the LO-mixer and RTM-mixer standing waves. The LO-mixer standing wave is seen at the edges of the IF. The HBB-mixer and CBB-mixer are not common and are gone when using the planet (centre of the IF). The residual shown here is when comparing the measured T_{SYS} to a largely smoothed version of it.

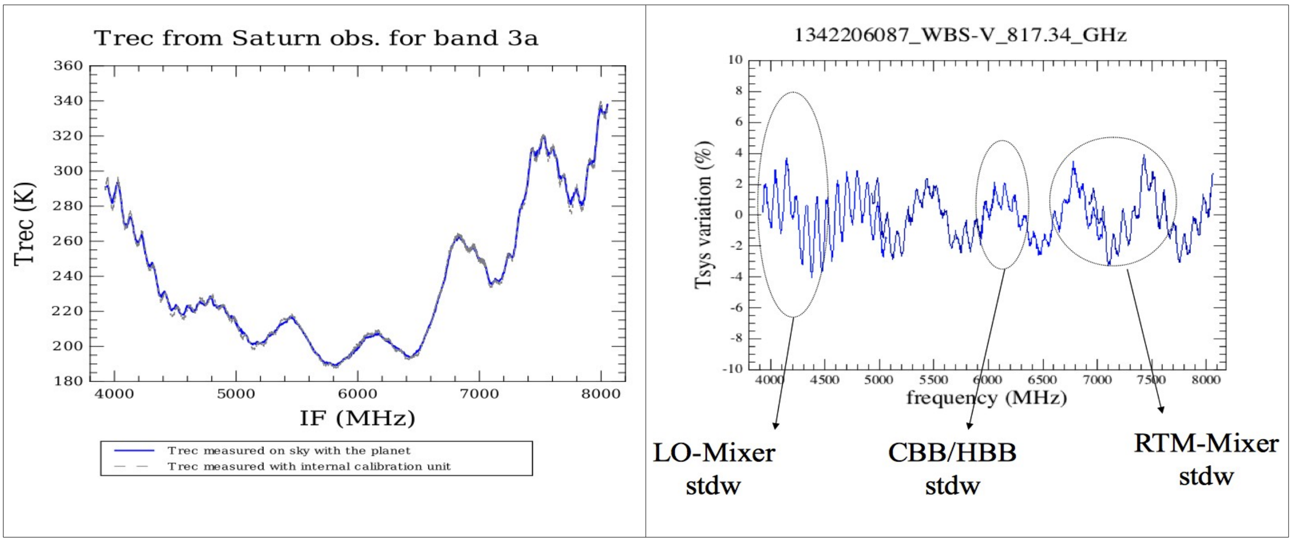


Fig. 9. Left) Measured T_{SYS} using Saturn as hot load and the cold sky as cold load. The dashed curve shows the T_{SYS} derived from the internal loads. Right) Residual between the measured T_{SYS} and a largely smoothed version of it. The four standing waves can then be identified on the residual plot.

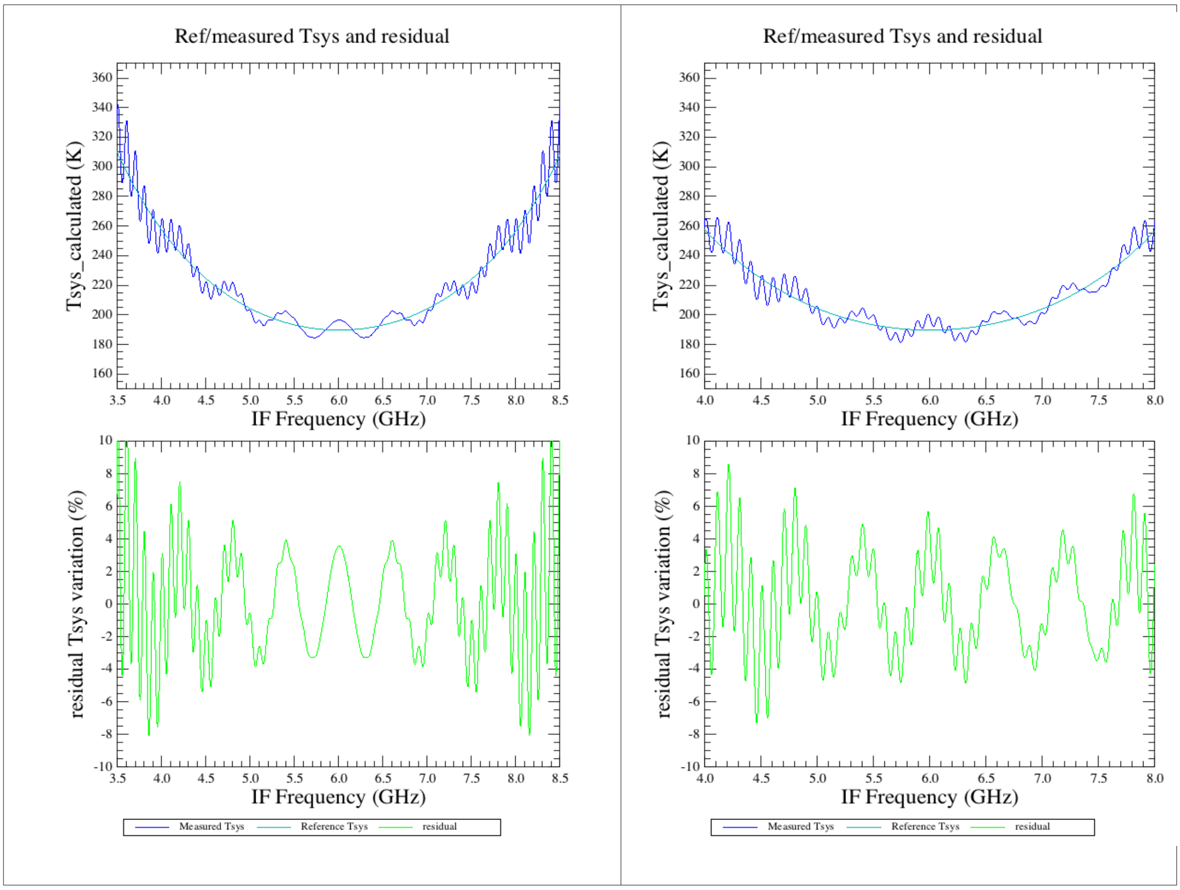


Fig. 10. Left) Simulated T_{SYS} including only LO-mixer and RTM-mixer standing waves. Right) Simulated T_{SYS} including LO-mixer, RTM-mixer and HBB-mixer, CBB-mixer standing waves.

For bands 3 and 4, the Saturn measurements show that the T_{SYS} measured with the internal loads includes the additional modulations from the loads themselves specially at the centre of the IF. The T_{SYS} derived from Saturn shows the RTM-mixer and LO-mixer standing waves at the edges of the IF.

This allows to conclude that the dominant standing waves in bands 3 and 4 are the LO-mixer at the IF edges, the RTM-mixer is present for the whole IF at a constant level and the HBB and CBB-mixer standing waves is mostly visible at the IF centre part.

4.3 Bands 5 - comparison with simulated model

Figure 11 shows an example for band 5a. There is a dominant component modulating the T_{SYS} common when using both the planet and sky or the internal loads. This is the LO-mixer standing wave. The HBB-mixer and CBB-mixer standing waves are not easily detectable here, and this means they contribute less than the LO-mixer one. The residual shown here is when comparing the measured T_{SYS} to a largely smoothed version of it.

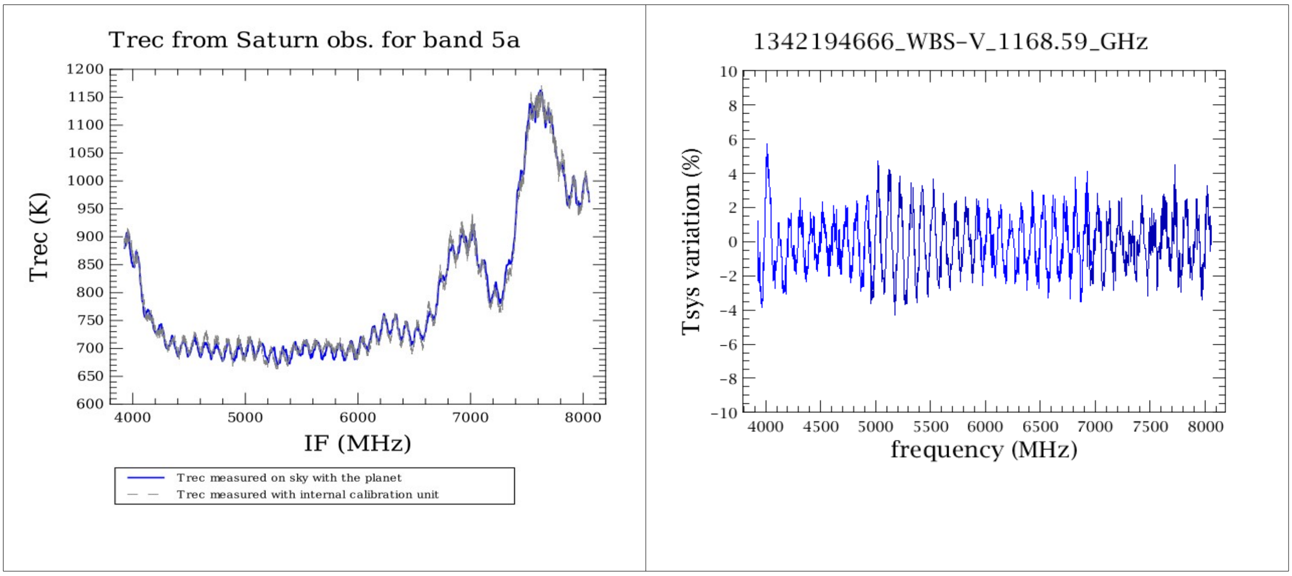


Fig. 11. Left) Measured T_{SYS} using Saturn as hot load and the cold sky as cold load. The dashed curve shows the T_{SYS} derived from the internal loads. Right) Residual between the two derived T_{SYS}.

This allows to conclude that the dominant standing waves in band 5 is the LO-mixer one. The HBB and CBB-mixer standing waves are present but at a lower level.

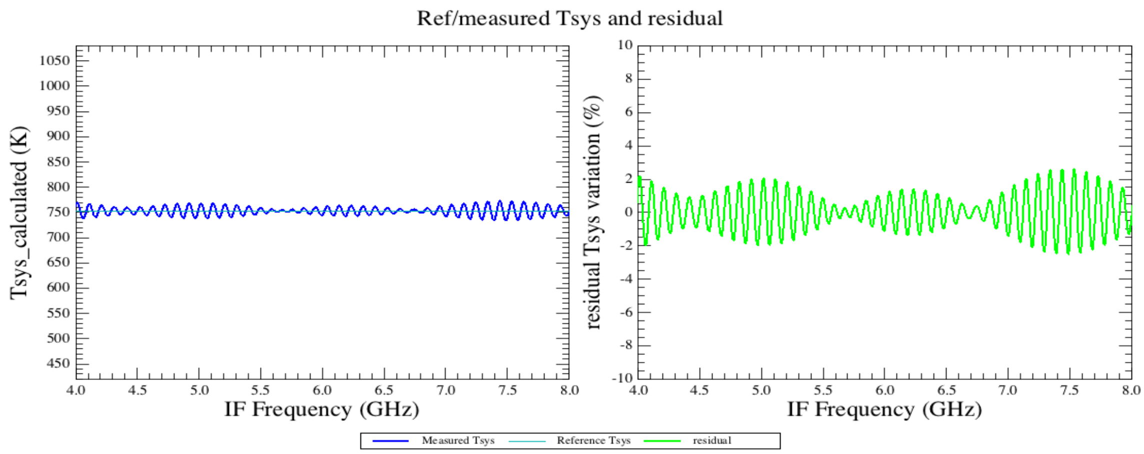


Fig. 12. Simulated T_{SYS} and residual including the HBB-mixer and CBB-mixer standing waves. The measured residual can be reproduced by changing the phase and amplitude of the standing waves.

4.4 Bands 6-7

Figure 13 shows an example for band 6b. There are components modulating the T_{SYS} common when using both the planet and sky or the internal loads. The residual shown here is when comparing the measured T_{SYS} to a largely smoothed version of it.

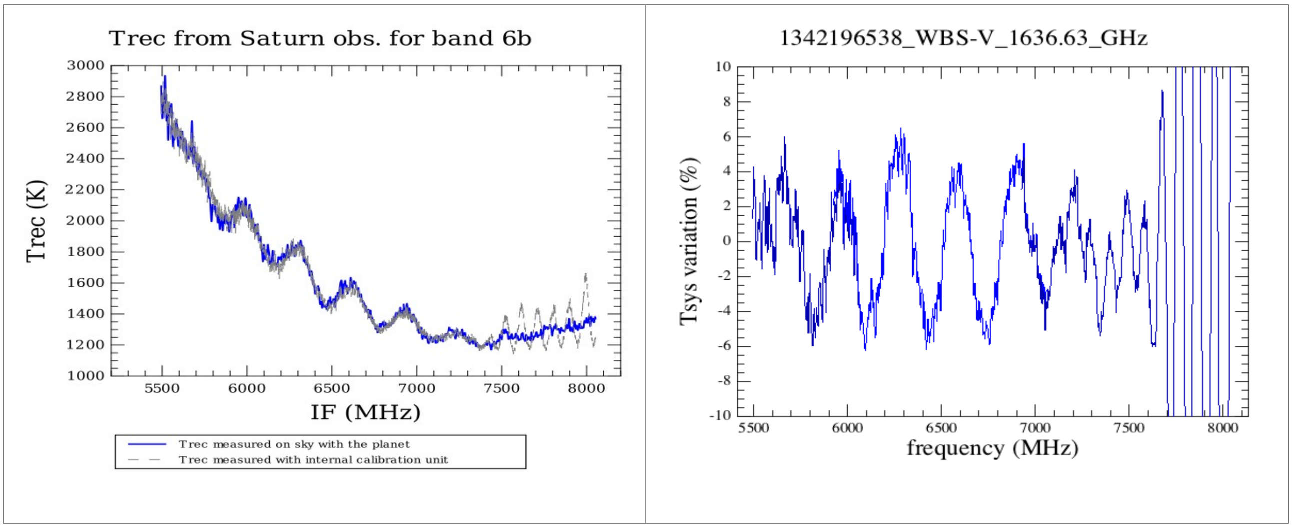


Fig. 13. Left) Simulated T_{SYS} including only LO-mixer and RTM-mixer standing waves. Right) Simulated T_{SYS} including LO-mixer, RTM-mixer and HBB-mixer, CBB-mixer standing waves.

The large standing waves at the edge of the IF in some frequency range are not well understood. The large period standing waves are not optical but are IF related, therefore out of the scope of this report. No attempts were done here to simulate HEB bands.

5 Analysis of full range spectral scans:

We used full range spectral scans with high redundancy which give fine granularity measurements. The following obsids were analysed.:

obsid_list = [1342207575, 1342196414, 1342206085, 1342196483, 1342206087, 1342204829, 1342206089,
1342206370, 1342194666, 1342204692, 1342196538, 1342194731, 1342194669]

For all of those, the T_{SYS} derived from the pipeline calibration were smoothed by different factors to disentangle the contribution from different standing waves. The residual plots were then plotted at all frequencies.

All of the data and full movies showing how the standing waves come and go for all bands, are available here:

http://www.sron.rug.nl/~crisache/stdw/

Example of such plots can be seen in the previous Fig. 9, 11, 13 and 15, the right hand plots show typical residuals.

Summary plots allowing to have an easier overview, are also available for all bands. They show the standard deviation per subband, giving an indication of the standing wave amplitudes and their contribution to the error in %. They are attached in appendix 9.1.

6 Calibration impact

From the previous exercise, we can now put concrete numbers, to the worse case calibration error that are due to the various standing waves. For a given measurement, we are not sure to catch a worse case as the folding of the continuum signal might add destructively the standing waves, but by doing so for all of the measurements, we are almost sure to catch some of the maxima and therefore we can estimate the error amplitudes.

Table 2. Summary of the main standing waves worst case errors on HIFI intensity calibration.

Bands	***1***	***2***	***3***	***4***	***5***	***6***	***7***
HBB/CBB-mixer	4 %	3 %	2 %	1 %	1 %	<1 %	<1%
LO-mixer	<1 %	<1 %	2-4 %	2-4 %	3 %	3 % - (25%)	3 %
RTM-mixer	-	-	1-2 %	1-2 %	-	<1 %	< 1%
Overall	4 %	3 %	4 %	4 %	3 %	3 %- (25%)	3 %

7 Proposal for a modified calibration scheme

7.1 Proposed alternative methods

The current HIFI calibration scheme uses the following formula (simplified case):

$$J_{ON}-J_{OFF}=\frac{C_{ON}-C_{OFF}}{C_{HBB}-C_{CBB}}\cdot J_{hot}-J_{cold} \qquad (1)$$

From the previous chapters, it is clear that for bands 1 and 2, the major error comes from the load measurements. The standing waves HBB-mixer and CBB-mixer are only present in the C_{HBB} and C_{CBB} measurements. The sky measurements do not suffer from those, but the bandpass division will then propagate them to the final calibrated signal.

A modified chopper wheel method was considered in the initial investigation:

$$J_{ON}-J_{OFF}=\frac{C_{ON}-C_{OFF}}{C_{OFF}}\cdot T_{SYS} \qquad (2)$$

The combinations of both standing waves CBB and HBB is seen in the T_{SYS} and therefore by removing it from the T_{SYS} in the chopper wheel scheme, this allows to effectively remove them from the calibrated signal.

The preliminary investigation demonstrated the usefulness of the method. Strong standing waves on the continuum of planets were easily removed, with some degradation though at the edges of the IF, due to the method used (DFT to remove the ripples). Drawback of this method is that it involves a large change to the current pipeline steps. Also, it loses the benefit of having always differences in both denominator and numerator. For the proper treatment of the chopper wheel technique, the contribution of the forward efficiency, telescope equivalent temperature, have to be included in the C_{OFF} term, which is not negligible. For the low frequency bands, improper inclusion of this term can amount up to 2% error, which is about the amount we want to improve here.

Based from the two previous schemes, the proposal here is to keep the current scheme, and remove the standing waves from their respective measurements.

$$J_{ON}-J_{OFF}=\frac{C_{ON}-C_{OFF}}{C_{HBB}^{Modified}-C_{CBB}^{Modified}}\cdot J_{hot}-J_{cold} \qquad (3)$$

The removal of the HBB and CBB standing waves can be done like this:

1. Compute $C_{\_HBB}/C_{OFF}$ and $C_{\_CBB}/C_{OFF.}$
2. Remove the standing waves with any of the following methods:
   a) Smoothing
   b) DFT removal of the 90-100 MHz region
   c) cubic spline
3. Compute the $C_{\_HBB\_modified}$ and $C_{\_CBB\_modified}$ by multiplying back with the C_OFF.

This means a simple modification of the mkFluxHotCold, allowing to keep the current calibration scheme logic, therefore all of the pipeline steps are the same. The only requirement is to have available an OFF measurement, which is the case for all observing modes, except for the NoRef modes. For those, this method will therefore not be possible.

To understand the principle, here are the simplified relations. The modulated transmissions with the LO-mixer. HBB-mixer and CBB-mixer standing waves are respectively called g_{LO}, g_{HBB}, g_{CBB}

$$C_{ON}=k\cdot B\cdot G_{REC}\cdot(T_{REC}+g_{LO}\cdot T_{ON}) \quad (4) \qquad C_{OFF}=k\cdot B\cdot G_{REC}\cdot(T_{REC}+g_{LO}\cdot T_{OFF}) \quad (5)$$

$$C_{HBB}=k\cdot B\cdot G_{REC}\cdot(T_{REC}+g_{LO}\cdot T_{HBB})\cdot g_{HBB} \quad (6) \qquad C_{CBB}=k\cdot B\cdot G_{REC}\cdot(T_{REC}+g_{LO}\cdot T_{CBB})\cdot g_{CBB} \quad (7)$$

$$\frac{C_{HBB}}{C_{OFF}}=\frac{(T_{REC}+g_{LO}\cdot T_{HBB})\cdot g_{HBB}}{T_{REC}+g_{LO}\cdot T_{OFF}} \quad (8)$$

$$\frac{C_{CBB}}{C_{OFF}}=\frac{(T_{REC}+g_{LO}\cdot T_{CBB})\cdot g_{CBB}}{T_{REC}+g_{LO}\cdot T_{OFF}} \quad (9)$$

As a rough approximation, $T_{CBB}\approx T_{OFF}\ll T_{REC}$

Therefore, $\frac{C_{CBB}}{C_{OFF}}\approx g_{CBB}$ (10)

For bands 1 and 2:

We saw that the LO-mixer standing wave is quite low, so it can be neglected, and we have :

$$\frac{C_{HBB}}{C_{OFF}} \approx \frac{T_{REC}+T_{HBB}}{T_{REC}+T_{OFF}} \cdot g_{HBB} \qquad (11)$$

This is the basis of the proposed method. The respective standing waves from the HBB and CBB can be, as a rough approximation, isolated by dividing the measured counts on the loads by the counts on the OFF (sky path). Once they are isolated, they can be removed by appropriate filtering.

For bands 3 and 4:

The situation is more complicated for bands 3-4. We saw from before that the LO-mixer standing wave is not negligible, specially at the edges of the IF. The rough approximation in (11) is not valid any longer. We suggest here two approaches:

a) Only modify the CBB measurement C_{CBB} and keep the original HBB $C_{HBB.}$

$$J_{ON}-J_{OFF}=\frac{C_{ON}-C_{OFF}}{C_{HBB}-C_{CBB}^{Modified}} \cdot J_{hot}-J_{cold} \qquad (12)$$

As the approximation (10) is still valid, we can remove the CBB-mixer standing wave. This can improve the situation in some cases.

b) For the HBB measurement, do the correction only for the two central subbands and keep the original for the two outer subbands.

$$J_{ON}-J_{OFF}=\frac{C_{ON}-C_{OFF}}{C_{HBB}^{Modified\ subbands\ 2-3}-C_{CBB}^{Modified}} \cdot J_{hot}-J_{cold} \quad (13)$$

This could then remove most of the HBB-mixer standing wave and keep the correction for the LO-mixer one at the edges.

For bands 5 :

The method here will most likely not work, as we are dominated by a strong LO-mixer standing wave. However in some cases, the previous method could help for better baseline for strong continuum sources.

For bands 6-7 :

The methods proposed previously can be tried but no real improvements are to be expected, but perhaps for the frequency range where there is the fast 100 MHz large ripple.

7.2 Examples – step by step

To illustrate these steps, we take an example obsid. This is an observation in band 1b done on Mars, and one of the worst cases. The default pipeline will produce the following level 1 data:

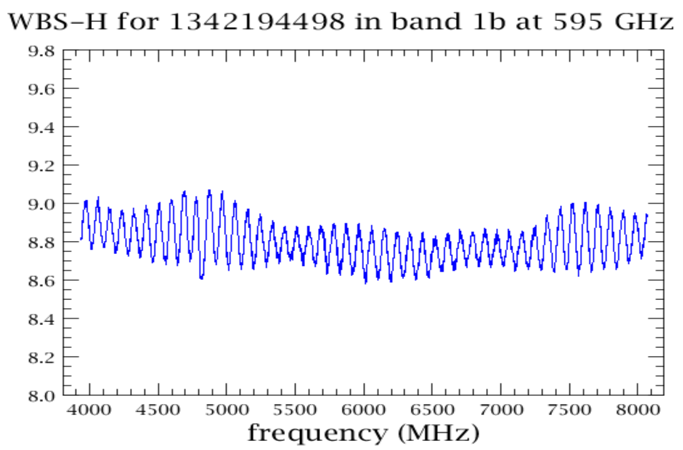


Fig. 14. Example of level 1 science data. The standing wave dominates the baseline and the absorption line is barely noticeable.

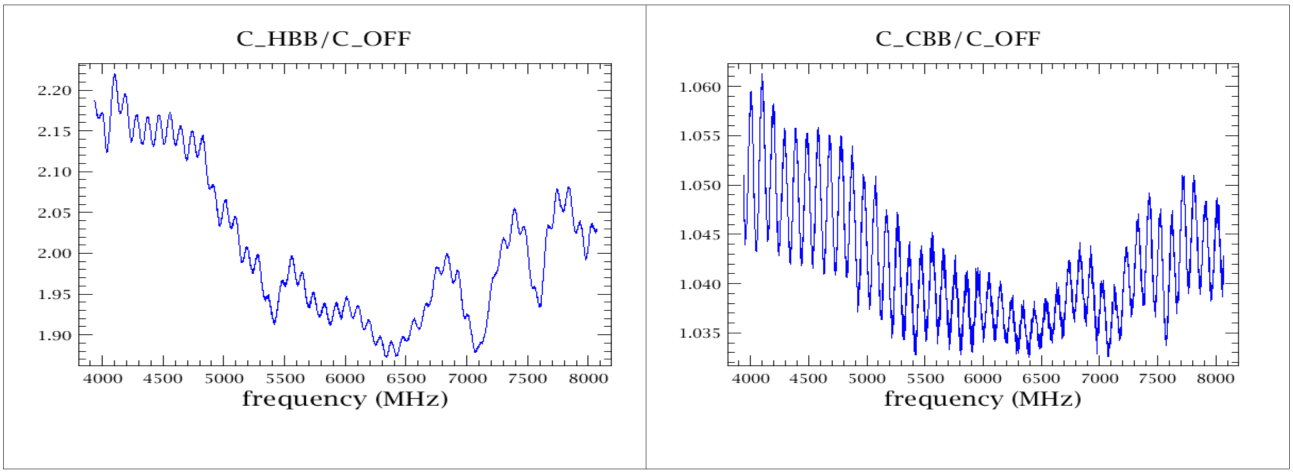


Fig. 15. First step: Divide the C_{HBB} and C_{CBB} by a C_{OFF}

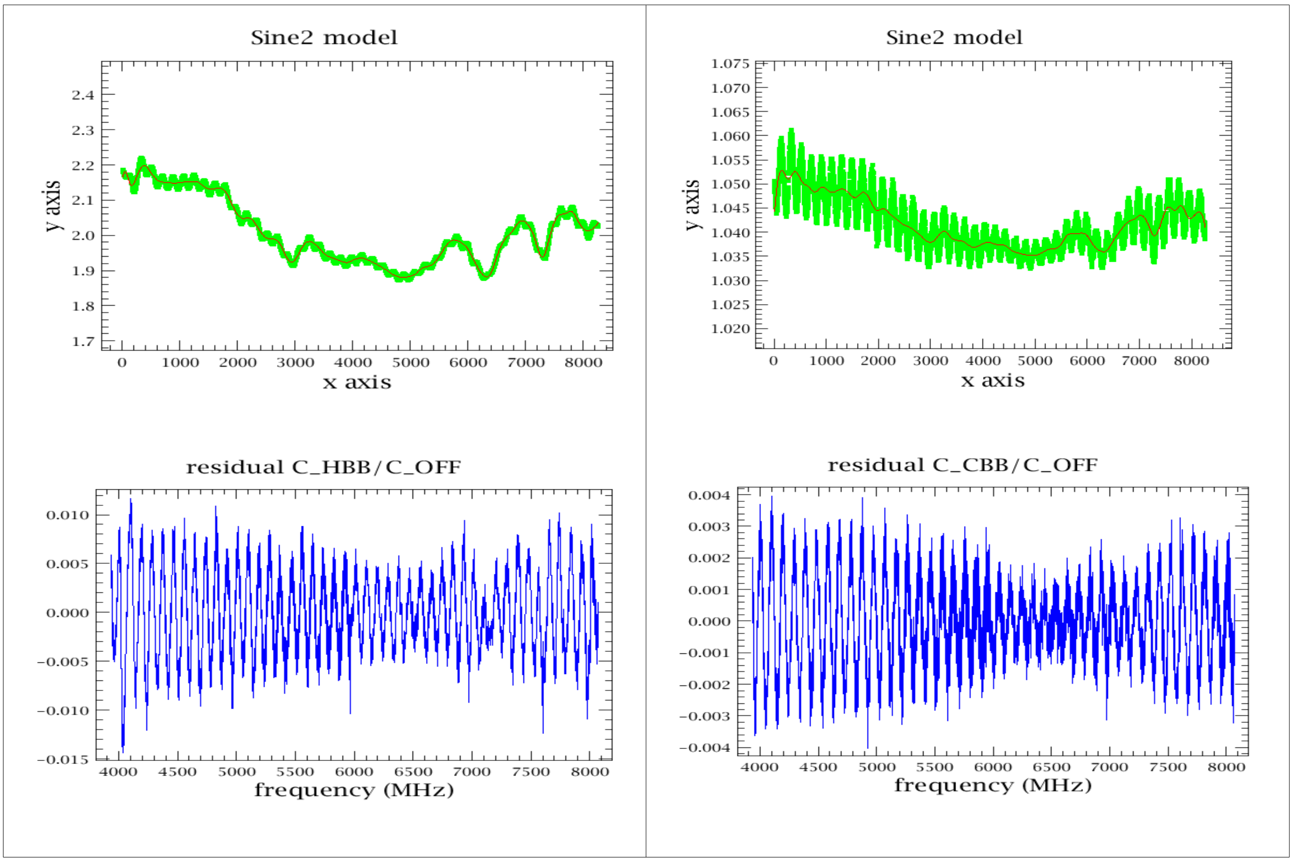


Fig. 16. Second step: remove the standing wave. In this example, this is done with the cubic spline method. The residuals are shown representing roughly the removed g_{HBB} and g_{CBB}

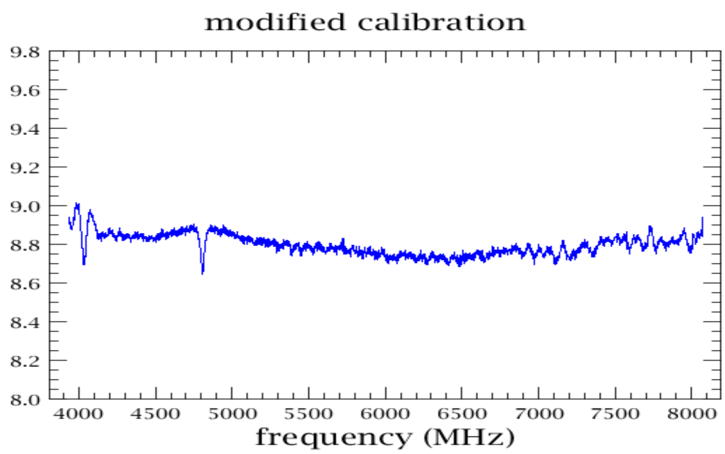
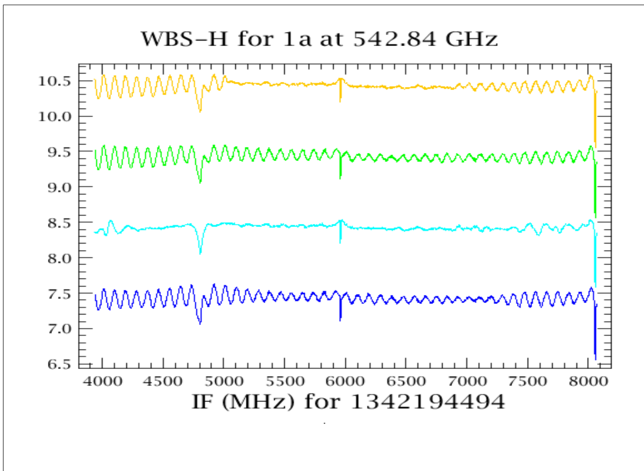
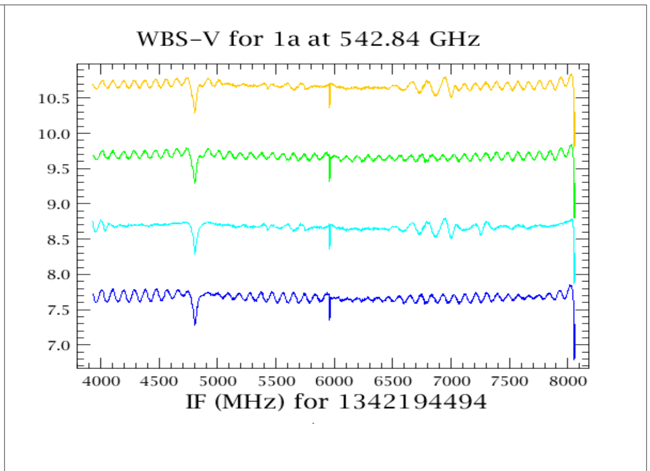


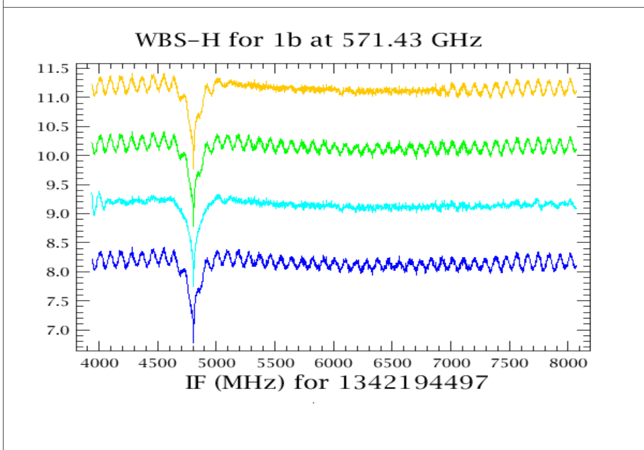
Fig. 17. Last step: Multiply back with the C_{OFF} and apply the calibration. The absorption line is well recovered. It suffers however at some places of imperfect calibration of IF features (at 4100MHz). The method can be possibly refined to overcome this (more nodes in the cubic spline in the problematic areas).

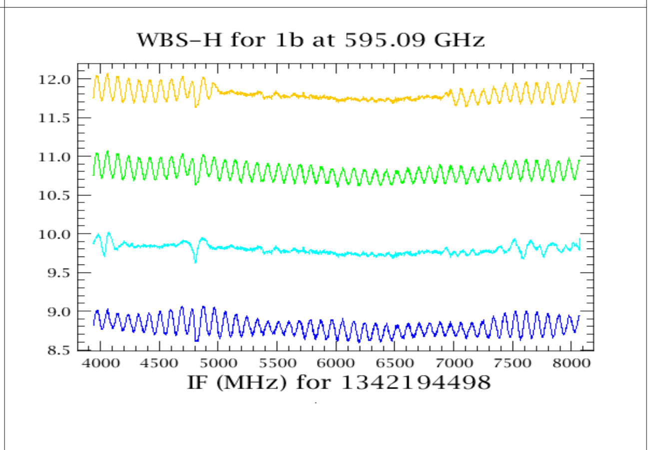
7.3 Examples

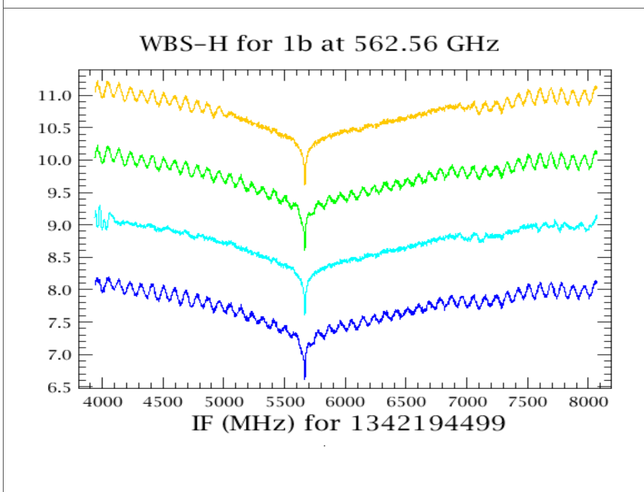
The following plots show the alternative calibrations (3), (12) and (13) applied to observations with strong continuum in several bands. For all plots. The bottom blue curve is the original data, the light blue curve uses the alternative calibration using (3), the green curve is using (12) and the orange curve is using (13).

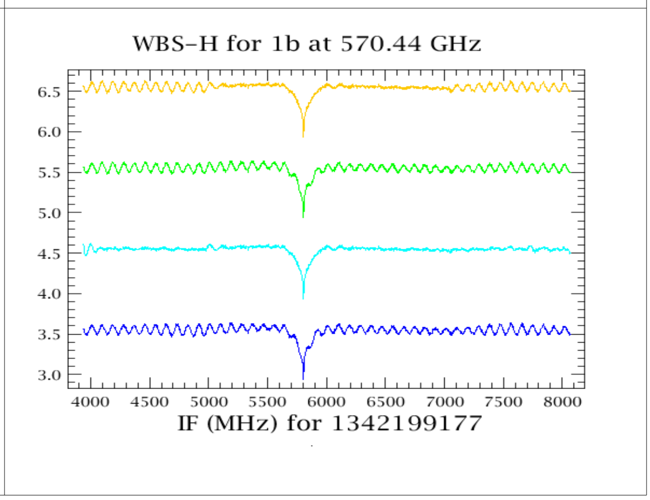


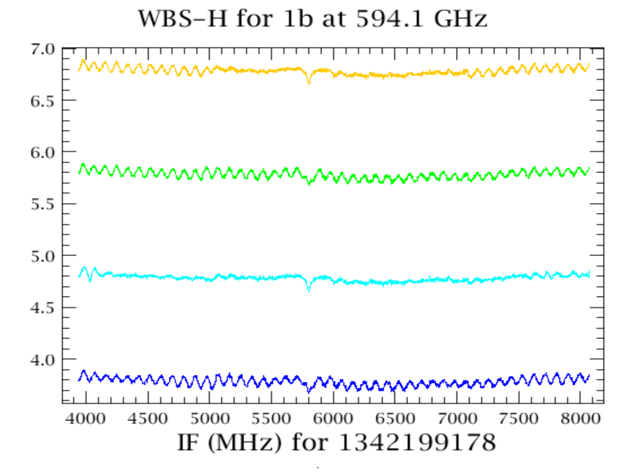


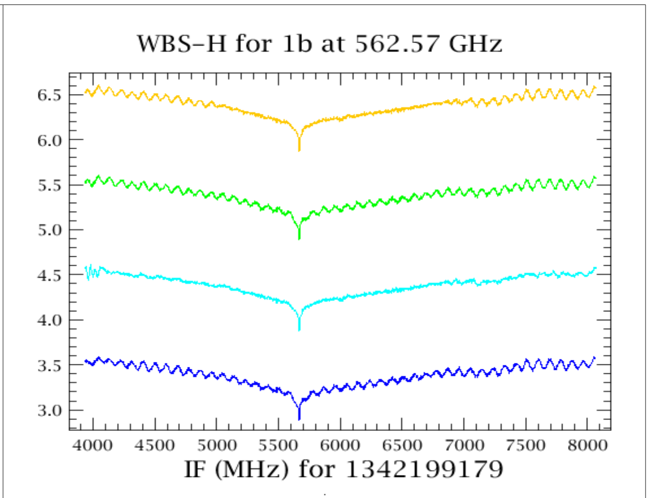


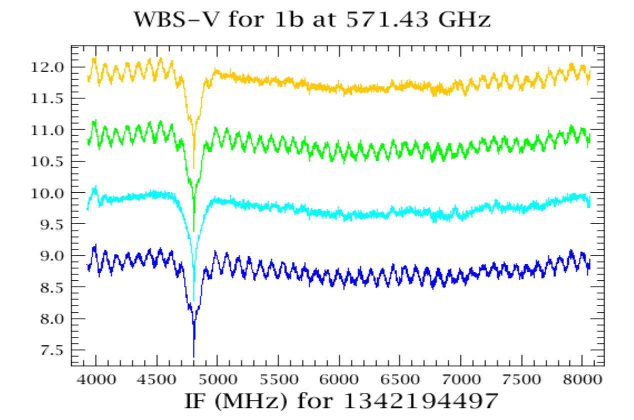


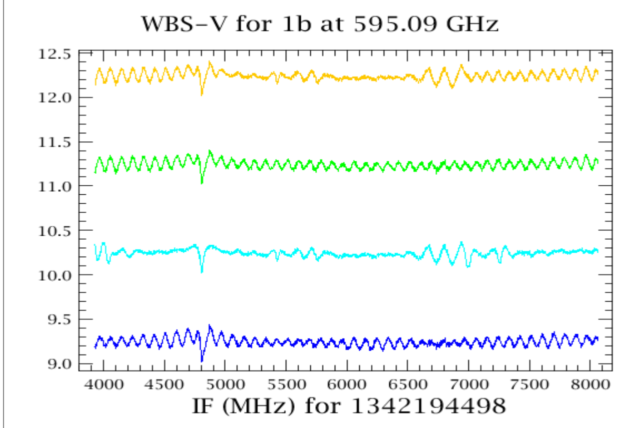


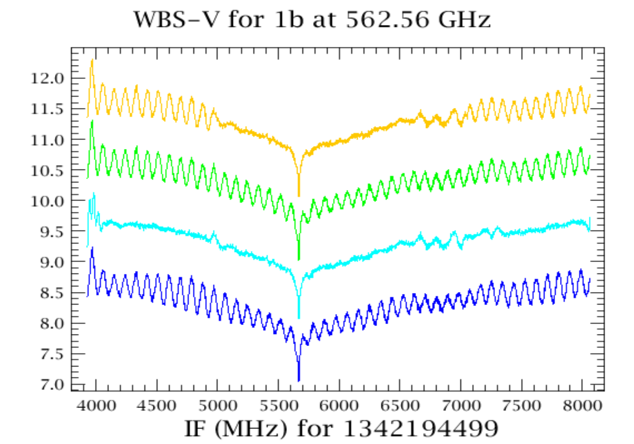


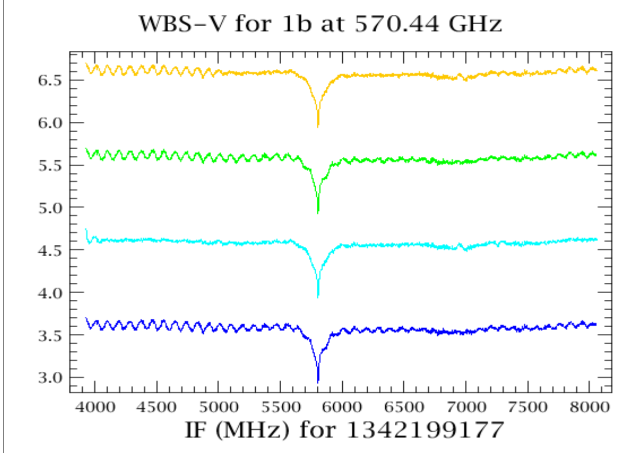

WBS–H for 1b at 594.1 GHz
IF (MHz) for 1342199178

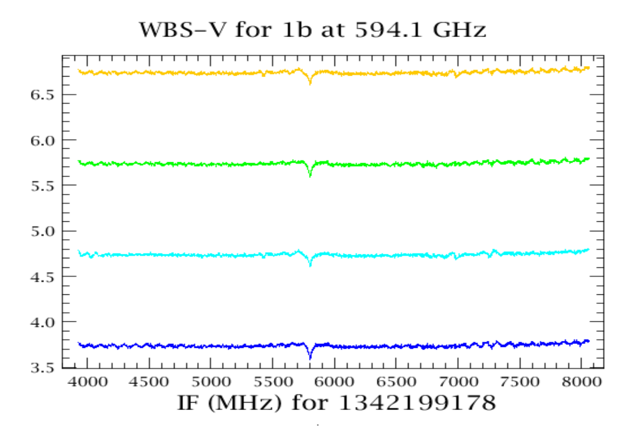

WBS–H for 1b at 562.57 GHz
IF (MHz) for 1342199179


WBS–V for 1b at 571.43 GHz
IF (MHz) for 1342194497

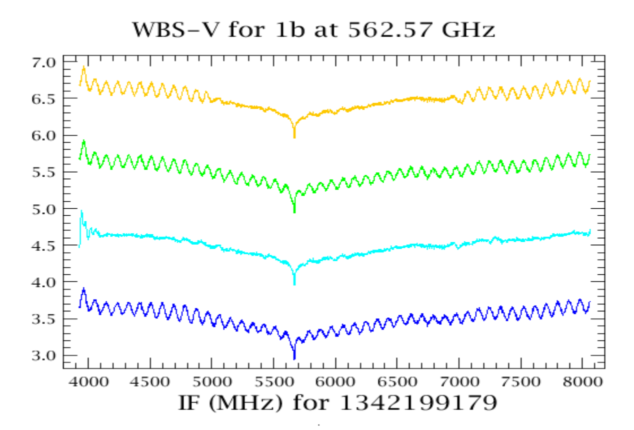

WBS–V for 1b at 595.09 GHz
IF (MHz) for 1342194498


WBS–V for 1b at 562.56 GHz
IF (MHz) for 1342194499

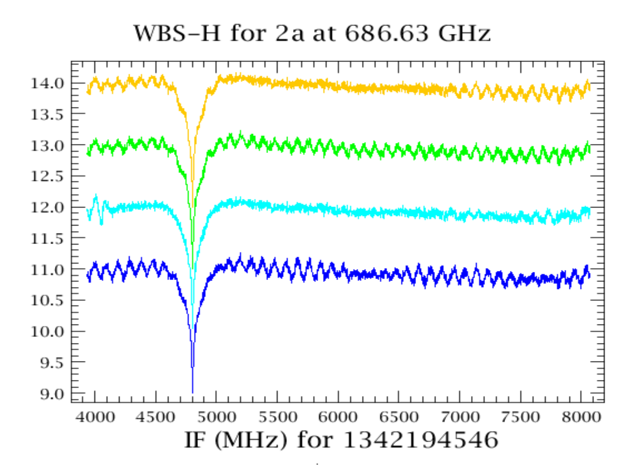

WBS–V for 1b at 570.44 GHz
IF (MHz) for 1342199177



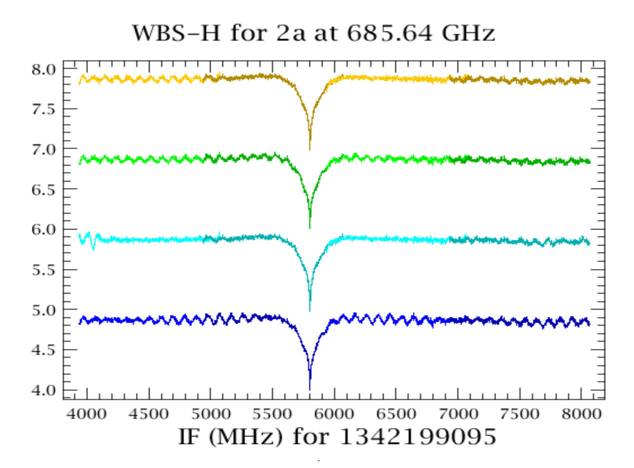
WBS–V for 1b at 594.1 GHz
6.5
6.0
5.5
5.0
4.5
4.0
3.5
4000 4500 5000 5500 6000 6500 7000 7500 8000
IF (MHz) for 1342199178



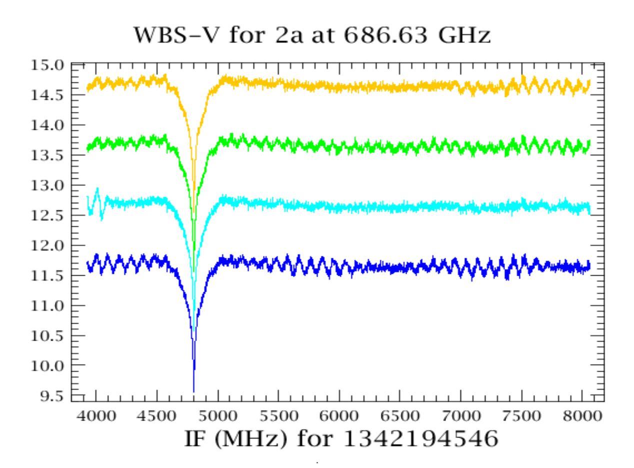
WBS–V for 1b at 562.57 GHz
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
4000 4500 5000 5500 6000 6500 7000 7500 8000
IF (MHz) for 1342199179



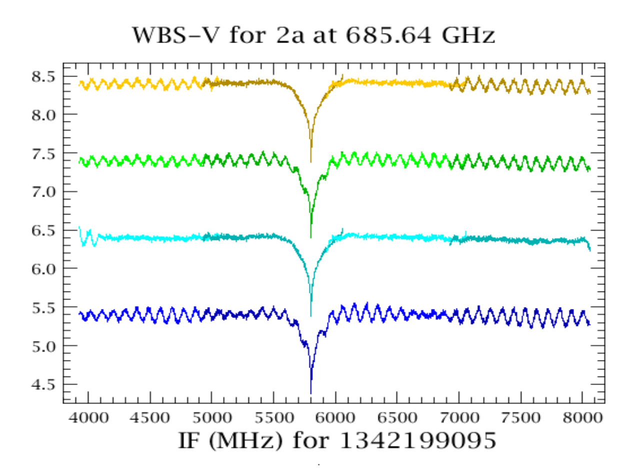
WBS–H for 2a at 686.63 GHz
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
9.0
4000 4500 5000 5500 6000 6500 7000 7500 8000
IF (MHz) for 1342194546



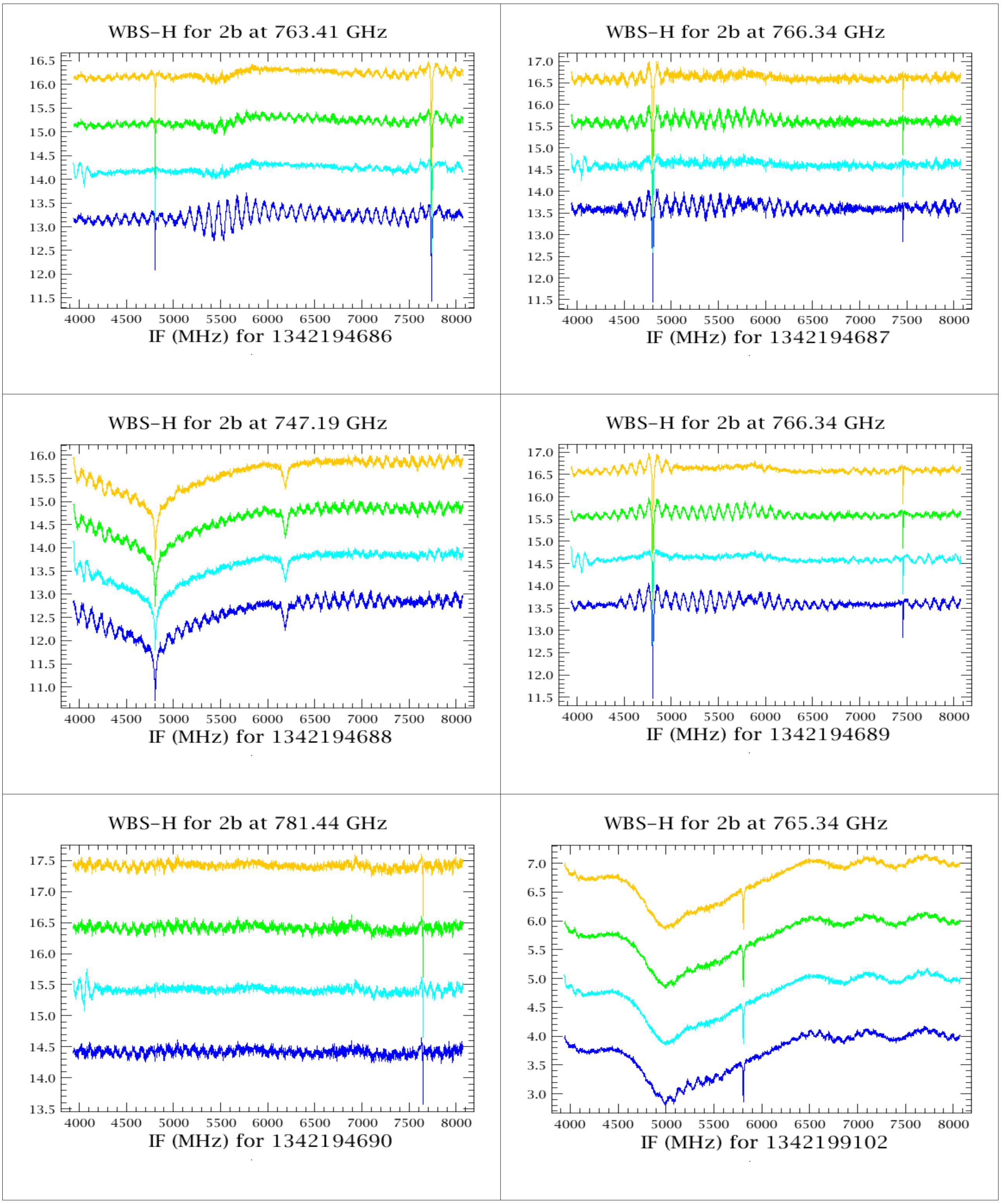
WBS–H for 2a at 685.64 GHz
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
4000 4500 5000 5500 6000 6500 7000 7500 8000
IF (MHz) for 1342199095



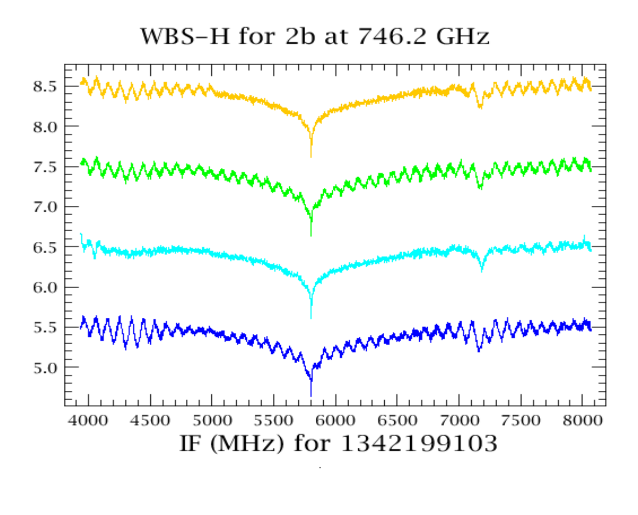
WBS–V for 2a at 686.63 GHz
15.0
14.5
14.0
13.5
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
4000 4500 5000 5500 6000 6500 7000 7500 8000
IF (MHz) for 1342194546



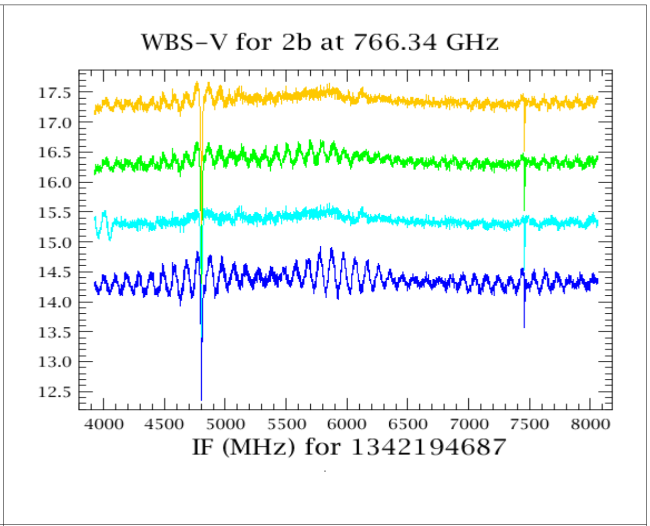
WBS–V for 2a at 685.64 GHz
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4000 4500 5000 5500 6000 6500 7000 7500 8000
IF (MHz) for 1342199095



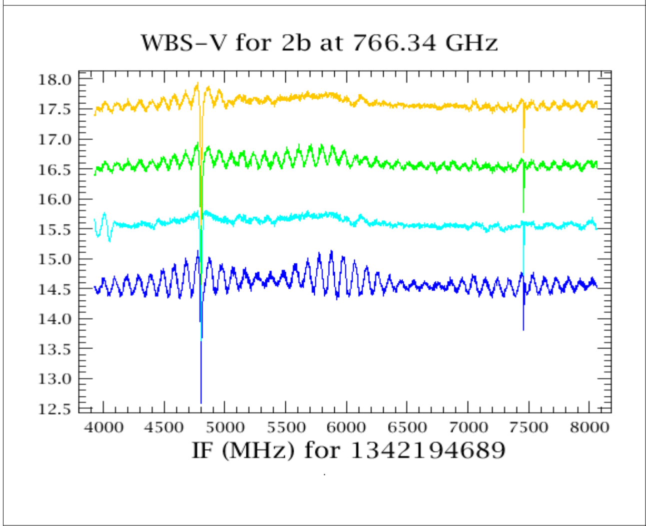
WBS–H for 2b at 763.41 GHz
IF (MHz) for 1342194686
WBS–H for 2b at 766.34 GHz
IF (MHz) for 1342194687
WBS–H for 2b at 747.19 GHz
IF (MHz) for 1342194688
WBS–H for 2b at 766.34 GHz
IF (MHz) for 1342194689
WBS–H for 2b at 781.44 GHz
IF (MHz) for 1342194690
WBS–H for 2b at 765.34 GHz
IF (MHz) for 1342199102



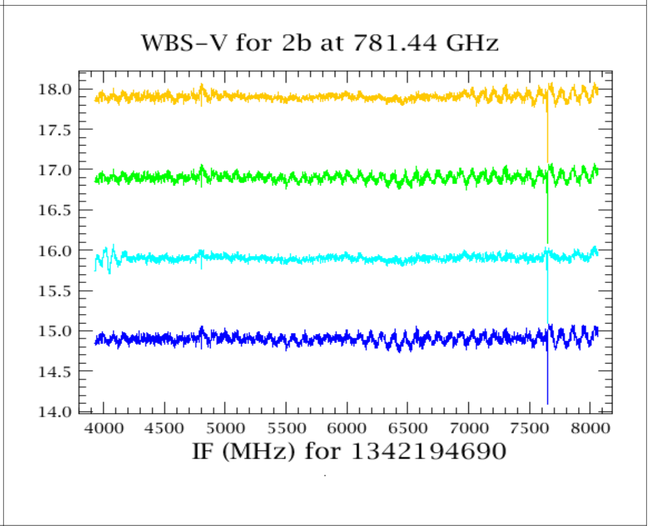
WBS−H for 2b at 746.2 GHz
IF (MHz) for 1342199103



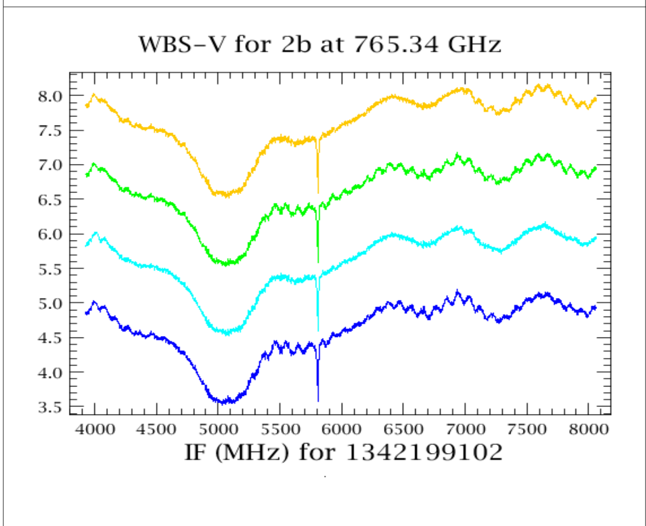
WBS−V for 2b at 766.34 GHz
IF (MHz) for 1342194687



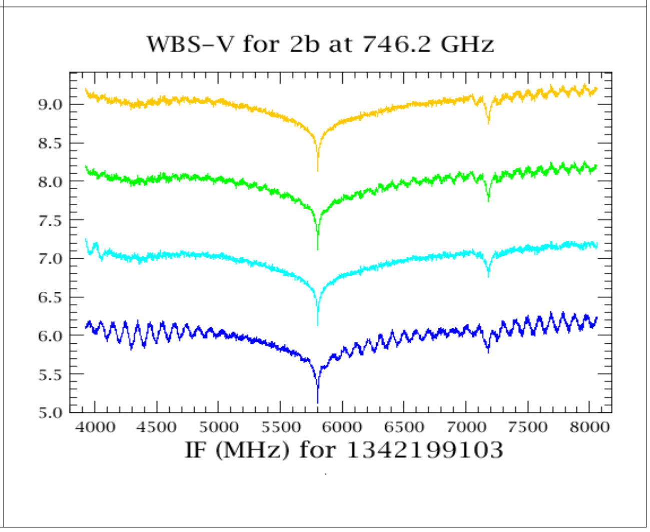
WBS−V for 2b at 766.34 GHz
IF (MHz) for 1342194689



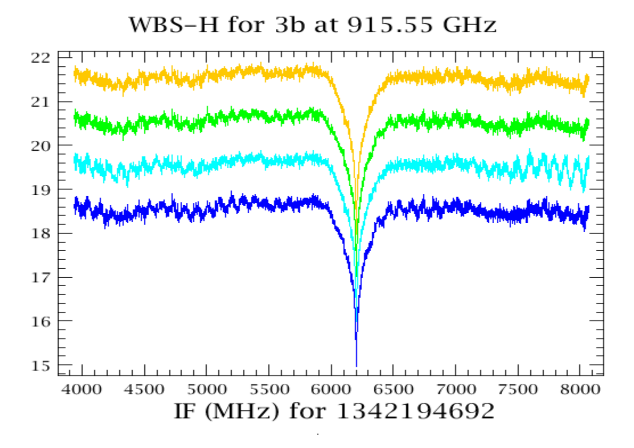
WBS−V for 2b at 781.44 GHz
IF (MHz) for 1342194690



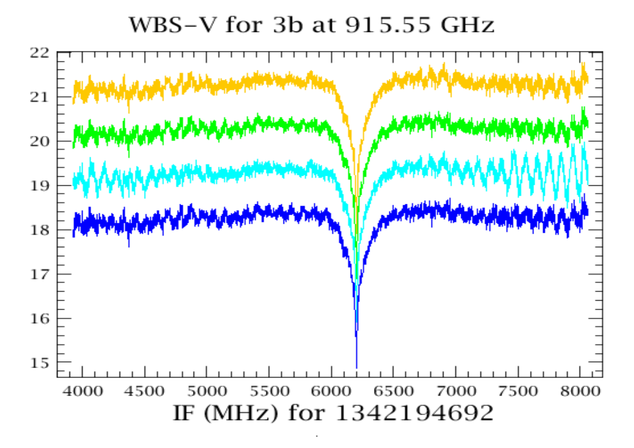
WBS−V for 2b at 765.34 GHz
IF (MHz) for 1342199102



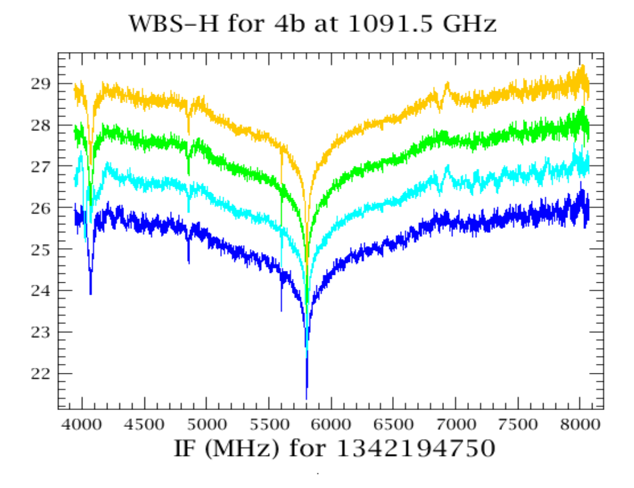
WBS−V for 2b at 746.2 GHz
IF (MHz) for 1342199103



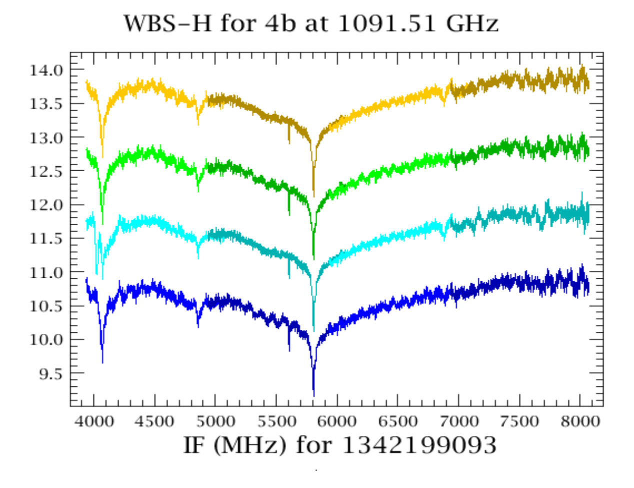
WBS−H for 3b at 915.55 GHz
IF (MHz) for 1342194692



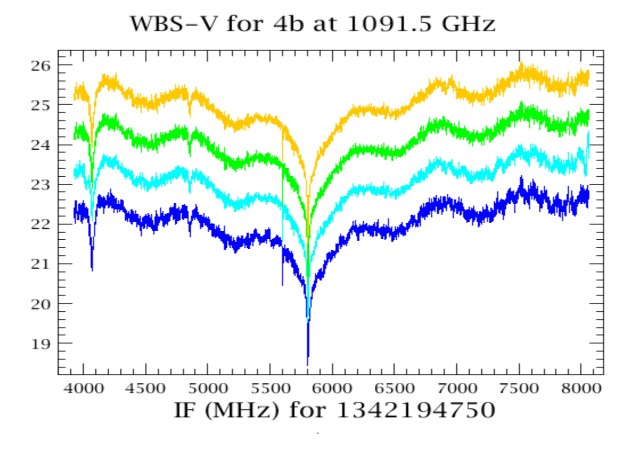
WBS−V for 3b at 915.55 GHz
IF (MHz) for 1342194692



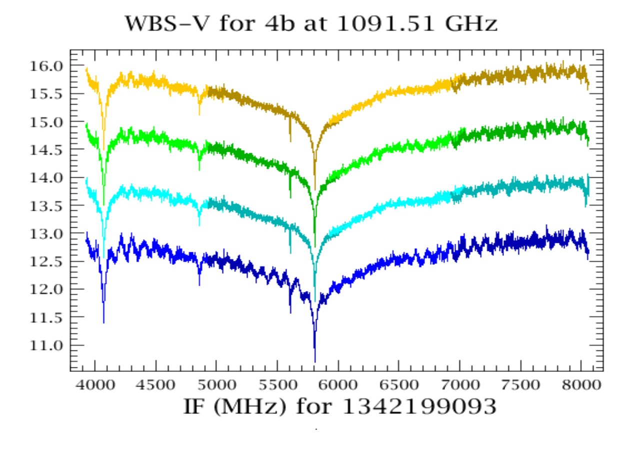
WBS−H for 4b at 1091.5 GHz
IF (MHz) for 1342194750



WBS−H for 4b at 1091.51 GHz
IF (MHz) for 1342199093



WBS−V for 4b at 1091.5 GHz
IF (MHz) for 1342194750



WBS−V for 4b at 1091.51 GHz
IF (MHz) for 1342199093

8 Conclusion

1. Intensity calibration impact from standing waves are estimated for all bands. A worst case value of 3-4 % if obtained for all bands:

   a) HBB/CBB-mixer standing waves are the dominant ones for bands 1 and 2.

   b) LO-mixer standing wave is the dominant one for bands 3-5.

2. These errors are worst case and will affect both continuum and spectral line calibration.

3. A modified calibration scheme is suggested, which effectively removes the standing waves from the respective load measurements. For that, it needs an OFF measurements at the same frequency. All the HIFI observing modes have it, except for the NoRef modes.

4. By using this modified calibration scheme, the error for bands 1 and 2 would decrease to only 1%. **both for continuum and spectral line observations**. This technique can also improve the calibration in the central IF part of the bands 3 and 4.

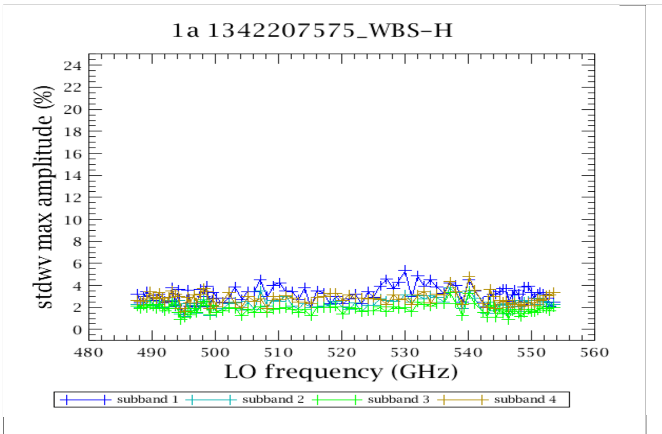
5. Plans are to include this in the pipeline as an alternative mkFluxHotCold.

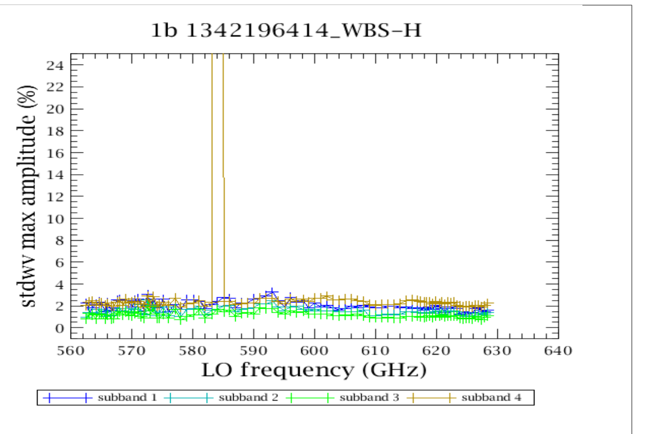
6. SCR HIFI-4085 tracks this.

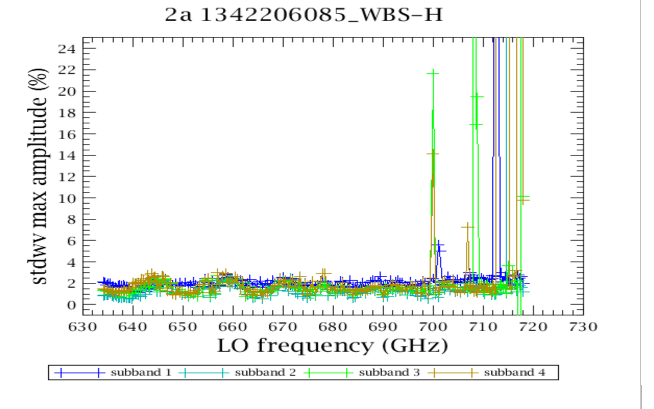
9 Appendices:

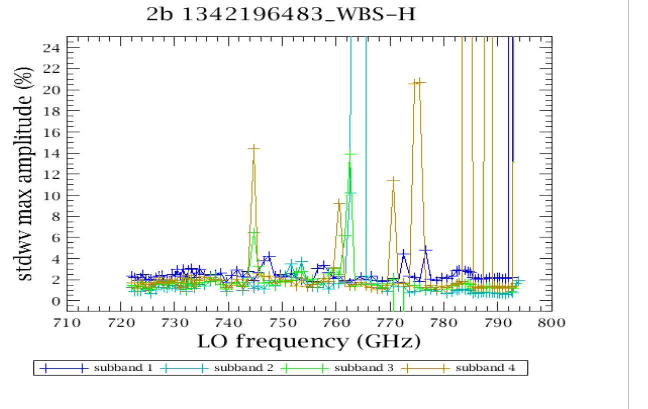
9.1 Standing wave residual plots

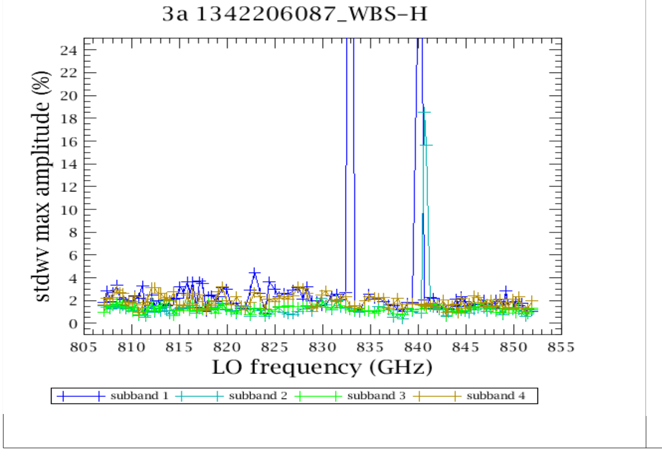
These plots show the residual standing waves amplitude for full range spectral scans. Large spikes are often due to spurs and IF features will also degrade the subband measurement.

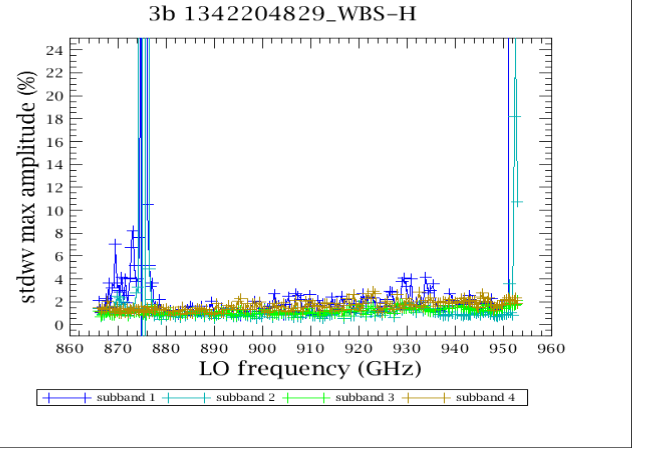


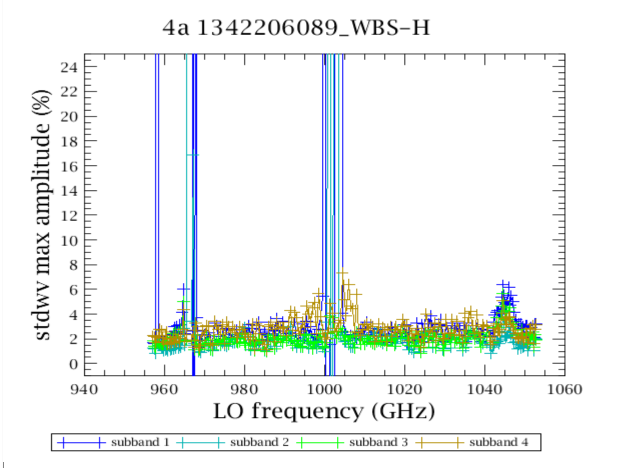




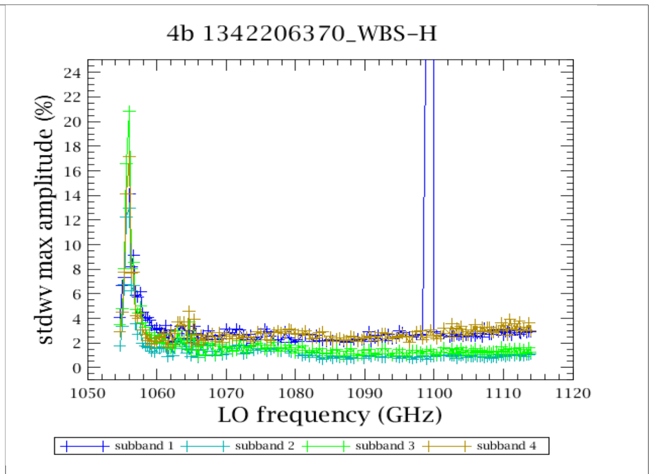




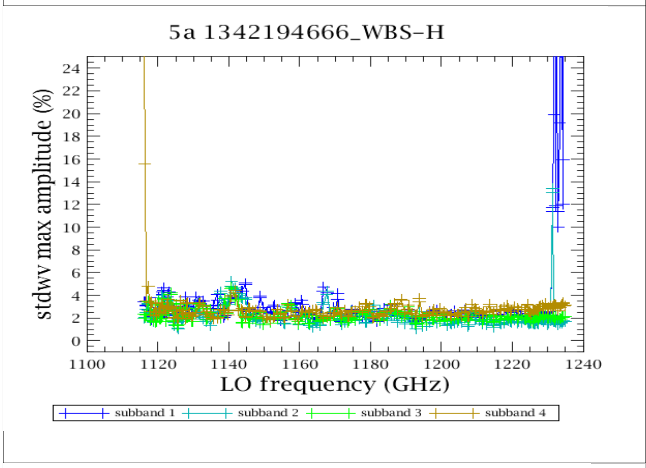




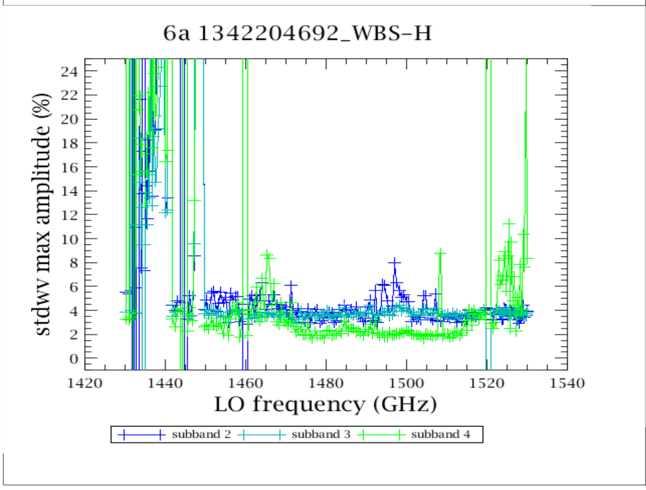
4a 1342206089_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4



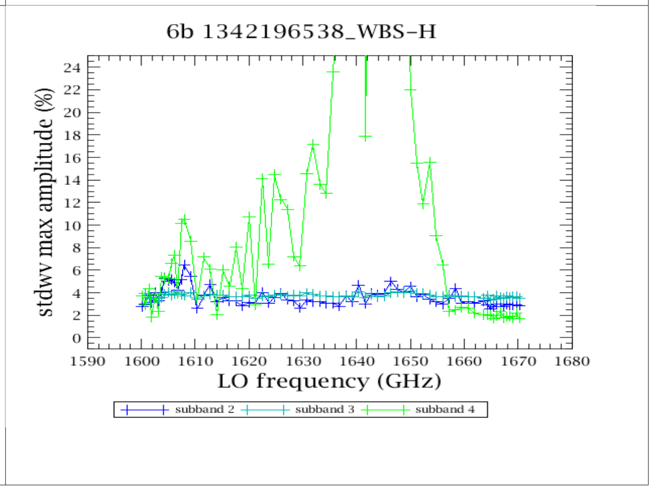
4b 1342206370_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4



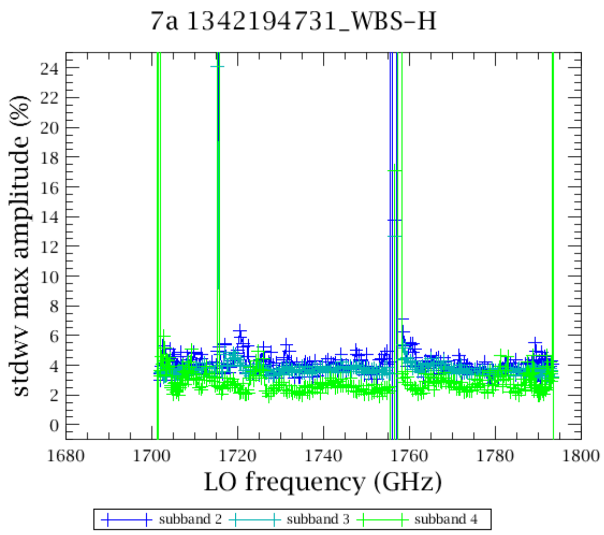
5a 1342194666_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4



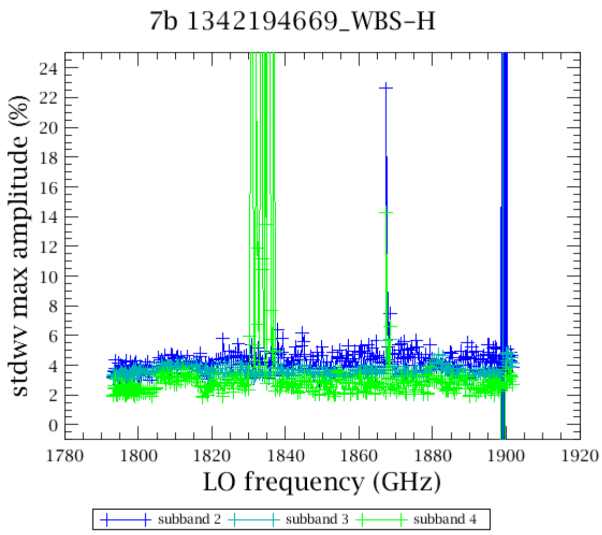
6a 1342204692_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4



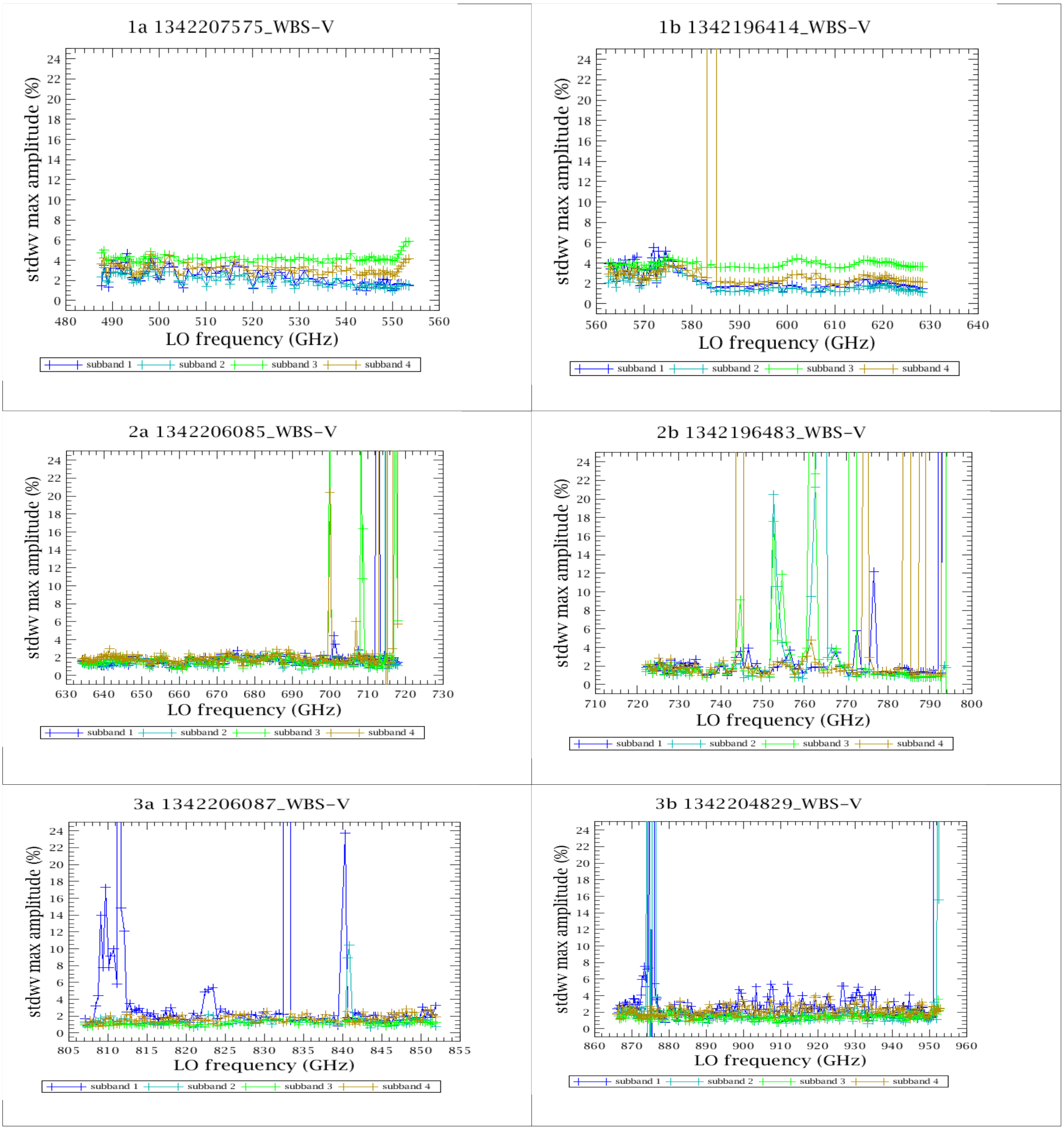
6b 1342196538_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4



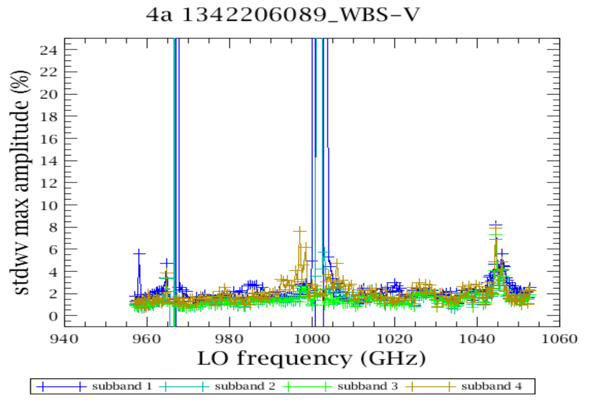
7a 1342194731_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4

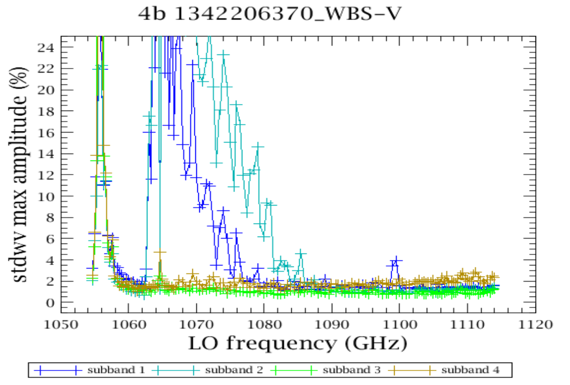


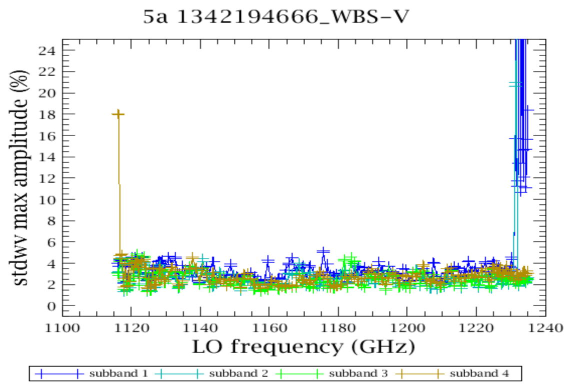
7b 1342194669_WBS-H
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4

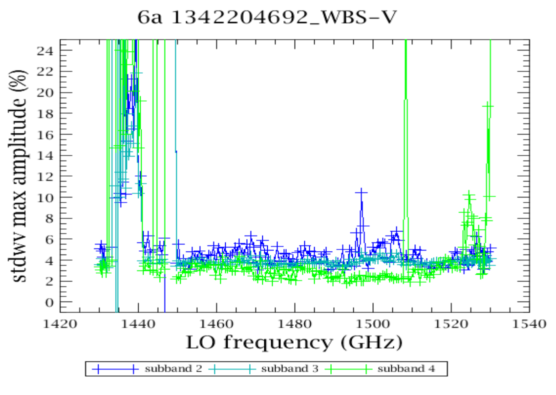


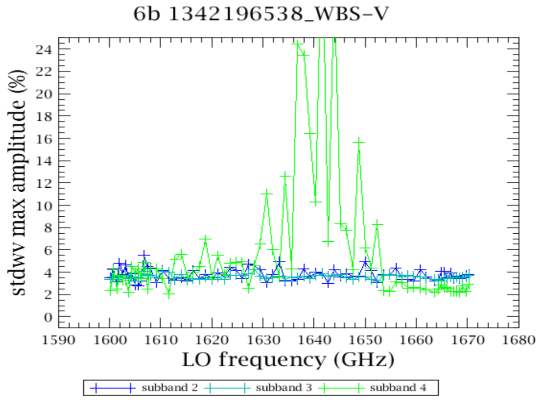
1a 1342207575_WBS-V
1b 1342196414_WBS-V
2a 1342206085_WBS-V
2b 1342196483_WBS-V
3a 1342206087_WBS-V
3b 1342204829_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4

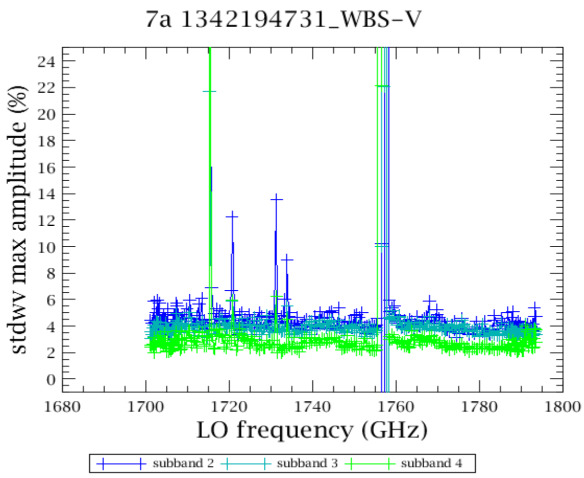

4a 1342206089_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4


4b 1342206370_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4

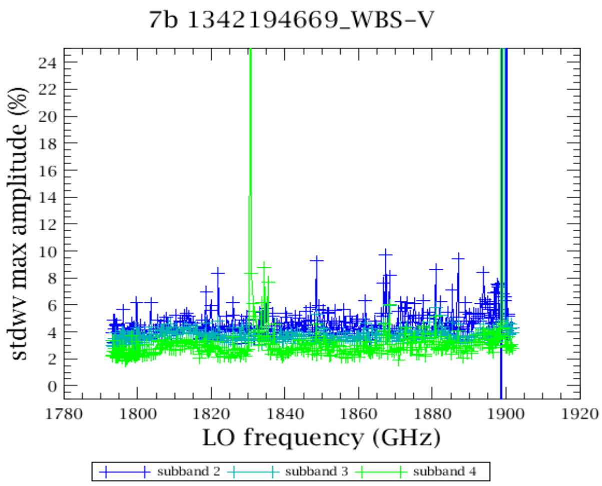

5a 1342194666_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 1
subband 2
subband 3
subband 4


6a 1342204692_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4


6b 1342196538_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4



7a 1342194731_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4



7b 1342194669_WBS-V
stdwv max amplitude (%)
LO frequency (GHz)
subband 2
subband 3
subband 4

9.2 Model parameters

Several test signals are used as input signals. We compute then the measured C_{ON}, C_{OFF}, C_{HBB} and C_{CBB}, taking into account the different standing waves. The calibrated data using the standard calibration and modified scheme can also be simulated.

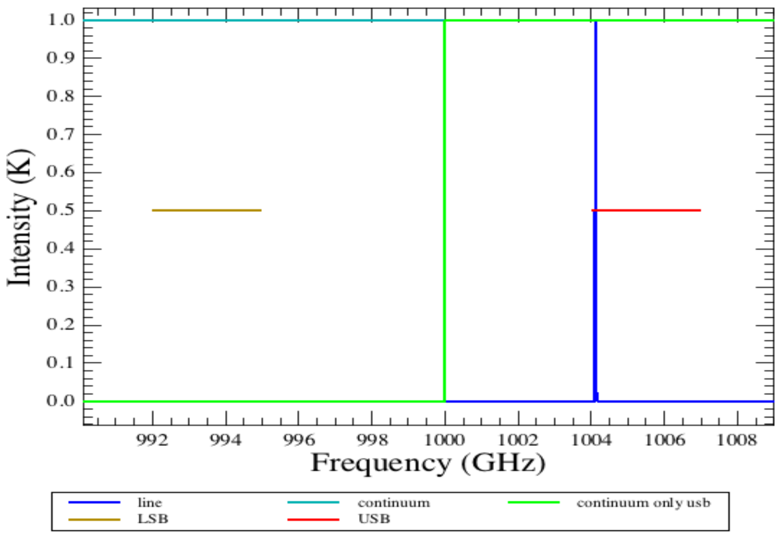


Fig. 18: Test signals. The LO is at 1000 GHz. The short brown and red lines show respectively the LSB and USB range of interest. We consider: a) a flat continuum signal of 1 K from ~990-1010 GHz, b) a spectral line of 1K at F1 = 1004.2 GHz in this example. c) a flat continuum signal, but only in the USB. (not physical but helps for visualization of folding aspects).

9.2.1 Model parameters for bands 1-2

This band uses a perfect beam-splitter of transmission 95% for the sky signal, so it couples 5% of the LO signal.

The considered standing waves are : LO-mixer (100 MHz), CBB-mixer (98 MHz) and HBB-mixer (92 MHz):

Trec = 100

Beamsplitter LO coupling : 5%

To match the measured data, a very small amplitude LO-mixer standing wave was used (<1%), and a larger 2-3% CBB-mixer and HBB-mixer standing waves was needed.

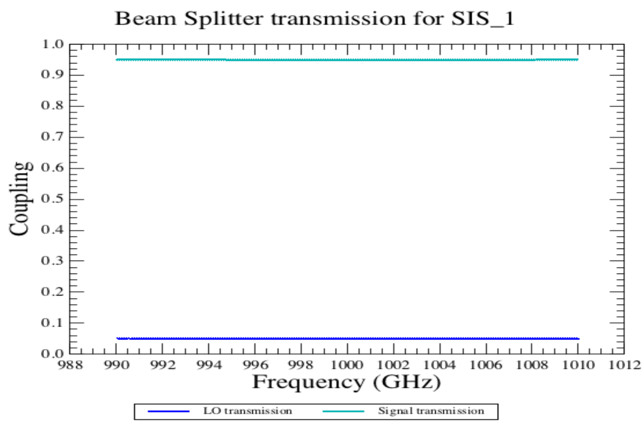


Fig. 19: Shows the beam splitter signal transmission and LO coupling.

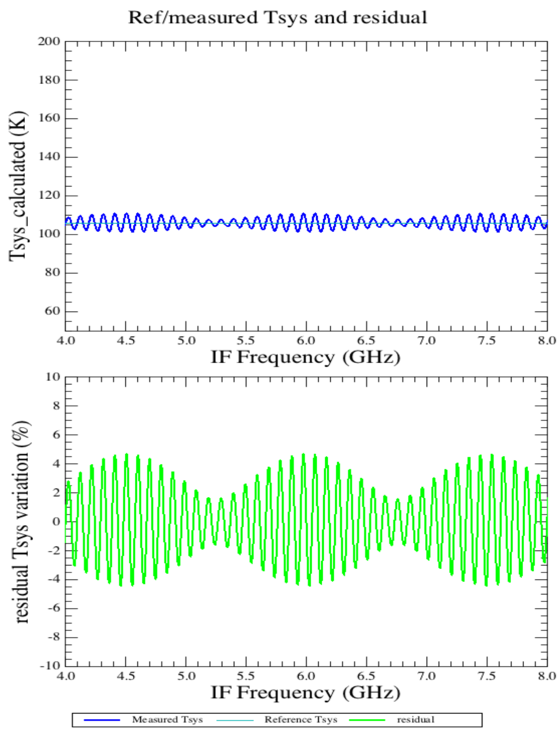


Fig. 20: Simulated measured T_{SYS} compared to the case with no standing waves and residual.

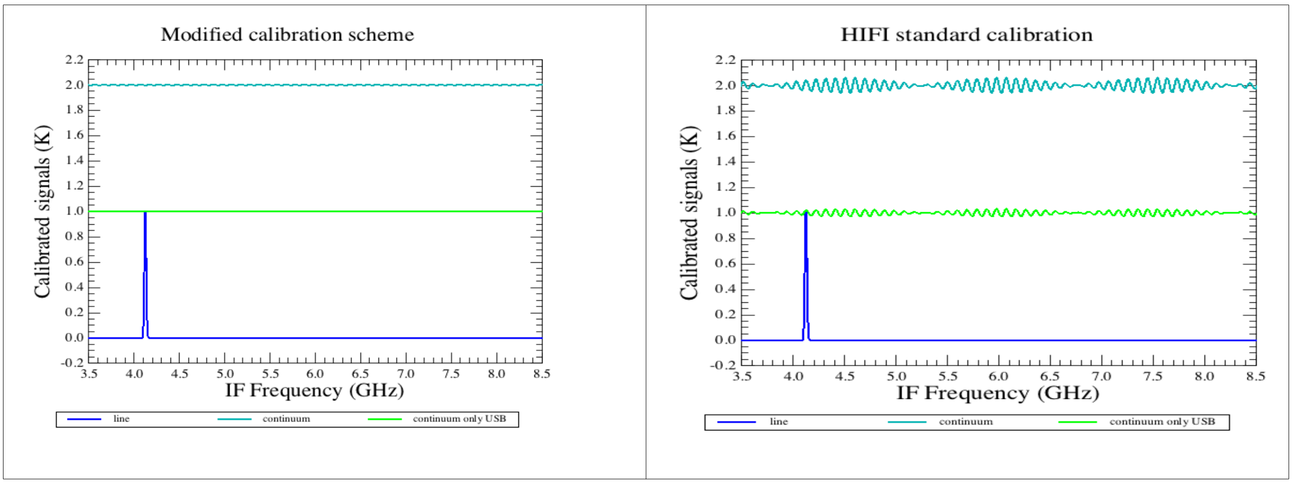


Fig. 21: Simulated calibrated signals using the current default scheme (left) and using the modified scheme proposed in 7 (right).

9.2.2 Model parameters for bands 3-4

These bands use a perfect diplexer whose signal and LO transmissions are approximated by perfect sinusoidal functions. Figure 22 shows example of diplexer coupling for our test cases.

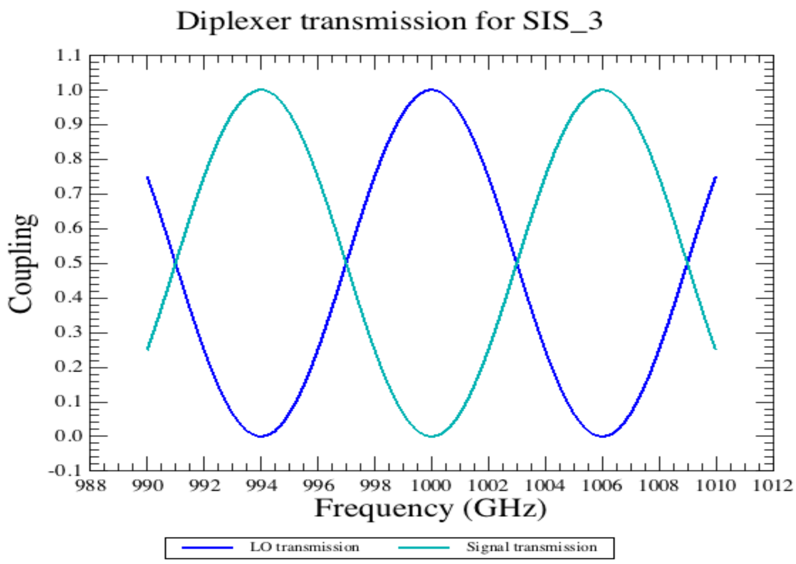


Fig. 22: Simulated diplexer coupling. The LO is set at 1000 GHz and the signal LSB and USB range are from 992-996 GHz and 1004-1008 GHz.

The considered standing waves are : LO-mixer (100 MHz), CBB-mixer (98 MHz), HBB-mixer (92 MHz) and RTM-mixer (620 MHz)

Trec = 200

To match the measured data, a large amplitude LO-mixer standing wave was used (20%), a 1-2% CBB-mixer and HBB-mixer standing waves were included, and a ~8% RTM-mixer was included.

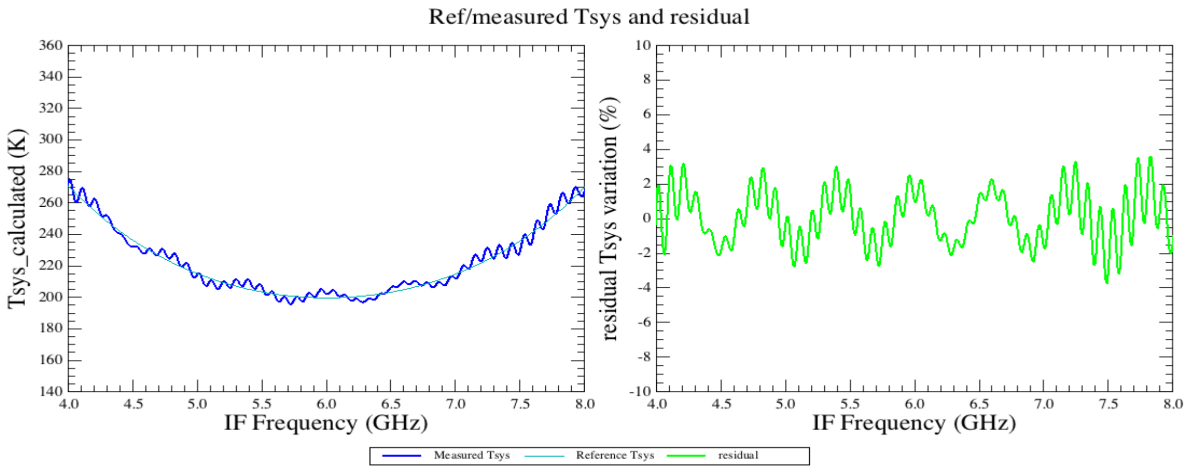


Fig. 23: Simulated calibrated signals using the current default scheme (left) and using the modified scheme proposed in 8 (right).

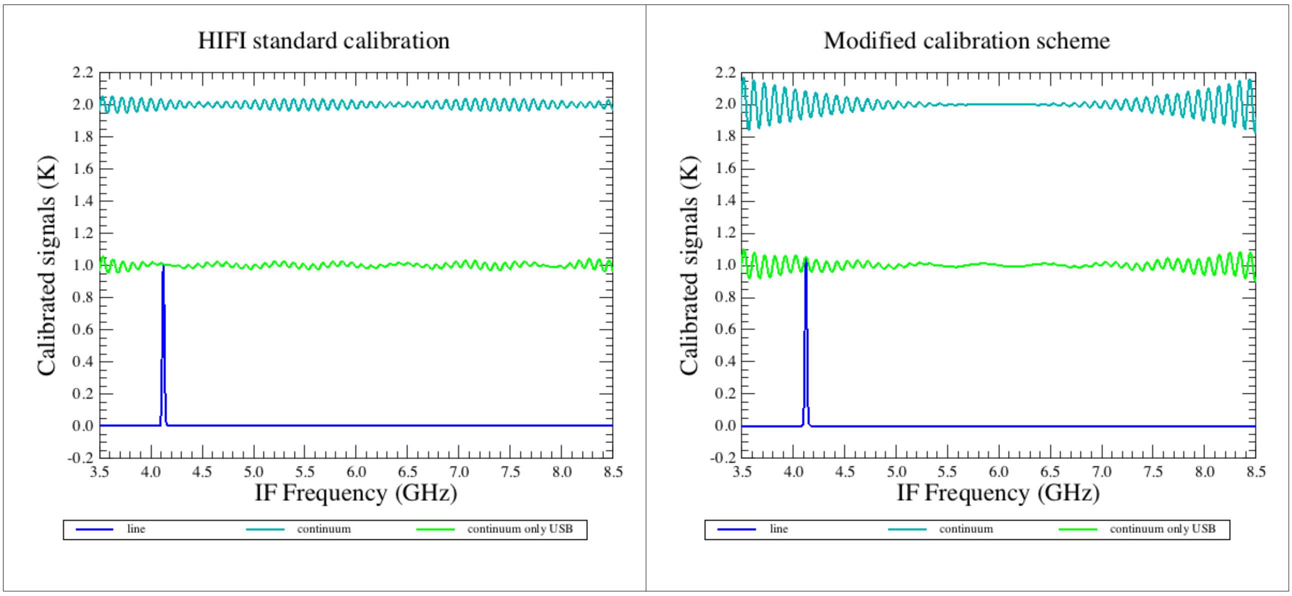


Fig. 24: Simulated calibrated signals using the current default scheme (left) and using the modified scheme using eq. (3) proposed in 7 (right). The HBB/CBB are removed from the centre part of the IF, however the edge effect are worse.

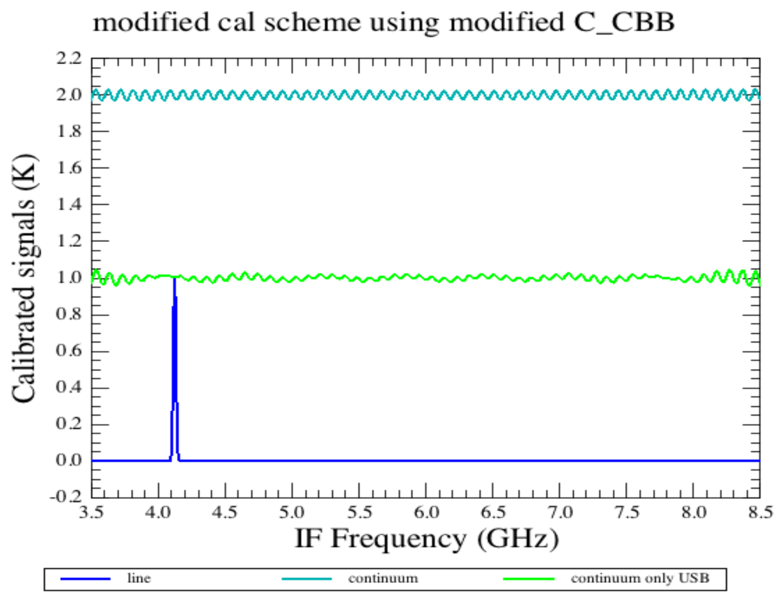


Fig. 25: Simulated calibrated signals using the modified scheme proposed in 7 using eq (12).

9.2.3 Model parameters for bands 5

This is very similar to 9.2.1. This band uses a perfect beam-splitter of transmission 80% for the sky signal, so it couples 20% of the LO signal. The considered standing waves are : LO-mixer (100 MHz), CBB-mixer (98 MHz) and HBB-mixer (92 MHz).

Because of the larger LO coupling and to the fact that there is no LO attenuator, the LO-mixer standing wave is much stronger and dominates over the other two.

Trec = 500

Beamsplitter LO coupling : 20%

T_LO = 10K

To match the measured data, a LO-mixer standing wave of ~ 20% amplitude was used, and a 1% CBB-mixer and HBB-mixer standing waves were needed.

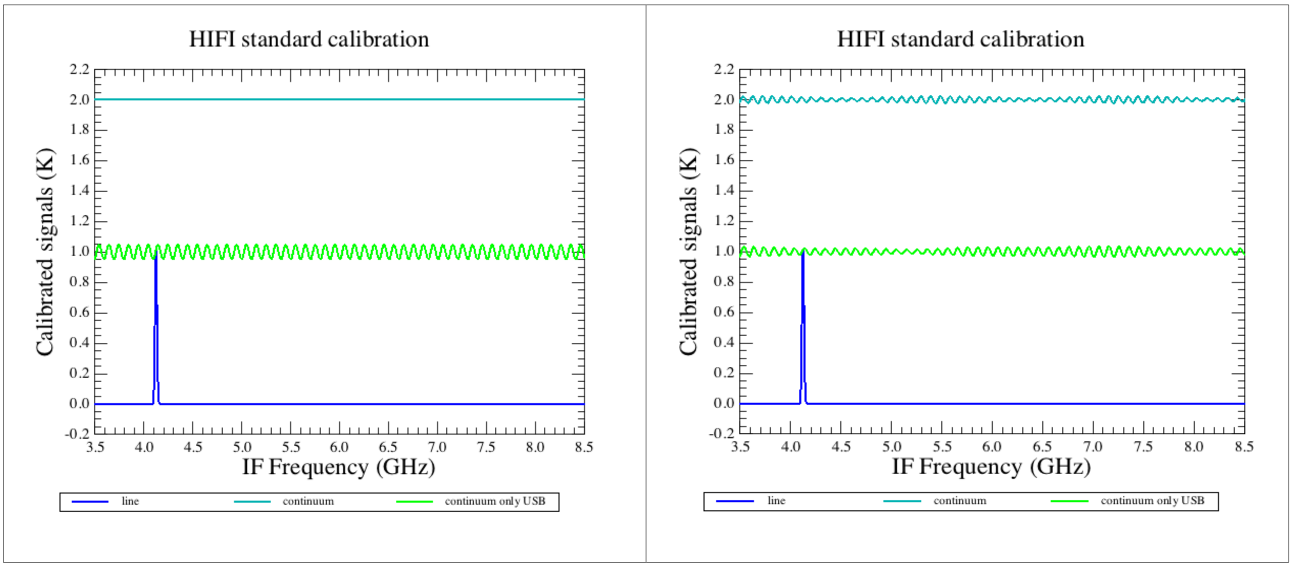


Fig. 26: Simulated calibrated signals using the current default scheme. Left plot shows the case with no HBB and CBB standing waves. For those cases, the continuum calibration should be perfect. The right plot shows the results when the HBB and CBB are included, even at a very moderate level (~0.2%), the continuum calibration is no longer perfect.

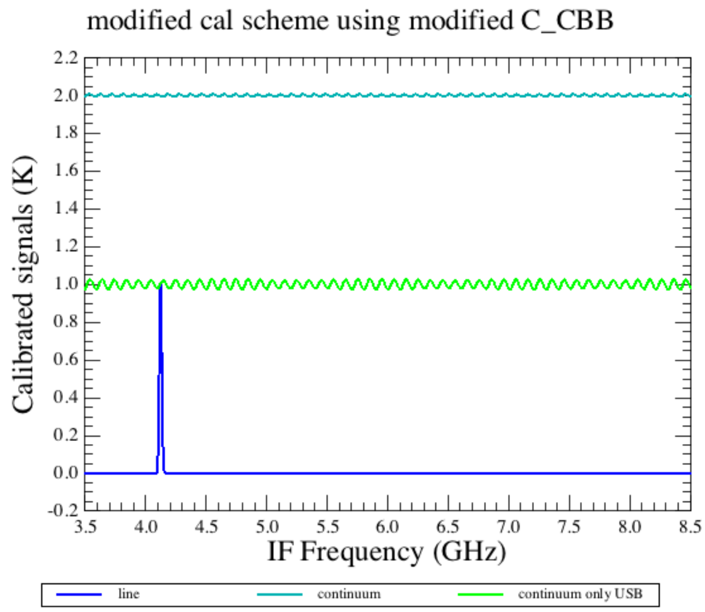


Fig. 27: For the previous case (right plot in Fig. 26), demonstration of results when using the modified calibration scheme only using a modified C_{CBB}. It shows moderate improvement for the continuum calibration, whereas no improvement for spectral line calibration.