

# Accurate line center frequencies

## Report - IRAM 30m telescope

Version 1.4

Christof Buchbender, Carsten Kramer, Albrecht Sievers, Gabriel Paubert

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### Abstract

At the 30m, the local oscillator and its synthesizers are constantly adjusted during observations to track the changing Doppler factor for one spectral line with its rest frequency. This causes a slight shift of lines observed simultaneously at a different frequency. This shift is proportional to the frequency difference and the Doppler factor. **CLASS** corrects for this shift by adapting the spectral resolution.

During commissioning of the new wideband high resolution fourier transform spectrometers (FTS) at the 30m, we conducted a series of tests which are describe here, to test the accuracy of the frequency of spectral lines which are upto 20 GHz apart from the tuned rest frequency. We encountered frequency shifts of upto 800 kHz. After correcting for two bugs in **MIRA** and **CLASS**, no shifts are visible anymore within an accuracy of about 10 kHz.

**MIRA** contains the bug fix since version 2.5, which is the default version for on-line data processing at the telescope since August 16, 2011. From version apr11 of **GILDAS Class** comprises a new average scheme that can be accessed with the command "average /new /resample" and that solves the shifts.

The test observations were done on the very bright late type star RLeo with very small source velocity. Further tests with large source velocities of several  $100 \text{ kms}^{-1}$  and hence large Doppler factors, are pending. For this dark clouds with narrow lines are preferable.

The correction of the spectral resolution in **CLASS** leads to resolutions which vary with the Doppler factor and thus with the movement of the earth. Averaging such spectra requires resampling to a coarser frequency grid, as long as there is no hardware to correct these variations.

## 1 General Information

All setups to investigate the frequency shift observe SiO(V1) (86.243350 GHz) in the source RLEO with wobbler switching. The date of the observations was August 3, 2011; the project account used t17-11. Every setup is observed twice for 4 min (setups 0-1 – 0-2) or 6 min (setups 1-4) divided in scans of 2 minutes: once with the FTS connected in the wide (200kHz) and once connected in the fine (50kHz) mode. In both cases VESPA is connected in its highest resolution mode, i.e. 3.3 kHz, to the sub-band containing the SiO(VI) line. Whenever possible the FTS cover all four sub-bands of E090 in both polarizations. The outer bands are observed with the FTS in all setups. For setups where we connect VESPA to an outer sub-band, we can only cover one of the inner bands with the FTS. This is due to the fact that we have to connect one of the "old" IF cables using the PAKO receiver command to one outer band such that VESPA can be connected to this band. The tested setups are listed in Table 1 and Table 2 gives the corresponding **CLASS** Header variables of the VESPA spectra. Please find the corresponding PAKO Setup and Scripts in the Appendix D. This contains also a line catalog with the rest frequencies used for the different setups and receiver commands.

We compared FTS spectra with VESPA spectra by smoothing the latter to the particular resolution of the FTS  $\sim 50$  kHz or 200 kHz. The comparison shows that the spectra taken with both backends are consistent with each other in frequency and flux for all scans that have been made in this test. See Figures 8 through 11 in the Appendix B.

A comparison between the FTS in narrow (50 kHz) and wide (200 kHz) mode also yields that the two modes give consistent results. See Figure 12 in Appendix C.

Below an analysis of the tests is performed. The analysis uses mainly the VESPA spectra but as said before they are consistent with the FTS spectra in position and flux, so that both are inter-changeable.

The analysis uses the standard "AVERAGE" command in CLASS (cf. Section 6) and spectra calibrated by a MIRA version prior to 15/08/2011.

Below in Sections 5 and 6 we explain why the shift arises and describe the changes that have now been made in MIRA and CLASS to correct for it. Using these new versions of CLASS and MIRA it is possible to correct all shifts seen in this test. However, we plan to use narrow lines in dark clouds in an upcoming test to confirm that no shifts smaller than 10 kHz are present and that the corrections hold also for high source velocities.

Table 1: Description of the observed E090 setups.

Setup Name	Line Name	Frequency	Sub-Band	Freq. relative to SIO(V1)	VESPA Setup
0-1	SIO(V1)01	86.243350	LI	SIO(V1)	LI
0-2	SIO(V1)02	86.46835	LI	SIO(V1) + 0.225 GHz	LI; fshift -225 MHz
0-3	SIO(V1)03	86.01835	LI	SIO(V1) - 0.225 GHz	LI; fshift +225MHz
1	SIO(V1)1	98.743350	UI	SIO(V1) + 12.5 GHz	LI
2	SIO(V1)2	89.42335	LI	SIO(V1) + 3.18 GHz	LO
3	SIO(V1)3	105.10335	UO	SIO(V1) + 18.86 GHz	LO
4	SIO(V1)4	86.243350	LO	SIO(V1)	UO

Table 2: CLASS Header Variables of the VESPA Spectra for the different setups. Note that setup 4 covers the SiO(V1) line only with the FTS. The entry "f(SiO)-f(tune)" is the distance between the "true" SiO(VI) line frequency (f(SiO)) and the tuning frequency (f(tune)). The entry "freq. error" is the derived shift between "true" and observed frequency of the SiO(V1) line, **before** the correction with new versions of MIRA and CLASS.

Setup Name	F0 [MHz]	Fi [MHz]	Df [MHz]	Dv [km/s]	f(SiO)-f(tune) [GHz]	freq. error [kHz]
0-1	86234.3500	98742.8002	$3.255 \times 10^{-3}$	$-1.1136 \times 10^{-2}$	0	?
0-2	86468.3450	98967.7988	$3.255 \times 10^{-3}$	$-1.1286 \times 10^{-2}$	-0.225	10
0-3	86018.3450	98517.7976	$3.255 \times 10^{-3}$	$-1.1345 \times 10^{-2}$	0.225	10
1	86243.3500	98742.7951	$3.255 \times 10^{-3}$	$-1.1131 \times 10^{-2}$	12.5	506
2	89423.3500	101922.7932	$3.255 \times 10^{-3}$	$-1.0913 \times 10^{-2}$	3.18	143
3	86243.3500	105102.5084	$3.255 \times 10^{-3}$	$-1.1315 \times 10^{-2}$	18.86	841
4 (FTS)	86243.3500	105102.5079	$4.88 \times 10^{-2}$	-0.1697326	0	$\sim 0$

## 2 Setups 0-1 through 0-3

### 2.1 Idea

With the setups 0-1 through 0-3 we test, if the frequency shift is visible on small scales inside one sub-band; here LI. To do so we first tune E090 LI to the SiO(V1) line and observe the spectrum of SiO(V1) with the high resolution, 3.3 kHz, mode of VESPA (Setup 0-1).

In Setup 0-2 we shift the tuning-frequency by -225 MHz and VESPA by a corresponding positive frequency offset, +225 MHz. Such that we observe the same part of the spectrum as before.

Setup 0-3 is similar; only tuning 225 MHz higher than setup 0-1 and shifting VESPA by -225 MHz. Again, VESPA sees the same range of frequencies as setups 0-1 and 0-2. The scan numbers for these observations are given in table 3.

### 2.2 Results

**Averaged Spectra** Figures 1a and 2a show the observed VESPA spectra in the three setups plotted on top of each other with different zoom levels. The black spectra corresponds to the un-shifted setup 0-1, the blue one to the positively shifted (+225 MHz) and red to the one with the negative shift (-225 MHz). All plots show averaged lines with a total 13 min integration time. As can be seen, the line of SiO(V1) is shifted slightly in frequency between the different setups. When tuning a lower frequency the shift is negative; tuning a higher frequency the shift is positive. We also checked single scans without averaging and could confirm that this behavior is the same in all scans, although the shifts vary slightly.

We estimate an average shift by measuring the shifts using the "DRAW" command in CLASS in four sets of observations (single scans). To estimate the shift, the distances between the setups tuned +/- 225 MHz and the un-shifted one are measured. Further, we measure also the distance between the +225 MHz and -225 MHz setup and divide the result by two. From this set of 12 measurements we calculate a mean shift of  $10.2 \pm 2.2$  kHz. For comparison, the shift in the averaged spectra is found to be 9.35 kHz. Note that the line is very broad with respect to this shift thus it is difficult to say which of the setups is closest to the real frequency of SiO(VI). The accuracy may be improved using an dedicated line fit to the profile of the SiO(VI) line.

This confirms that a shift is present also inside one sub-band and for small distances from the tuned frequency. So far a line fit to the SiO line is missing to derive accurate values of the frequency shift.

**Single spectra** Without Illustration. For these setups looking at single spectra the shifts are not present or smaller than 10kHz (The SiO lines are very broad to be more precise). Therefore the shifts are an outcome of the usage of the "AVERAGE" commando in CLASS. Please see Section 5 and 6.

**Corrected Spectra** In Figures 1b through 2b we show the spectra after the corrections made in the new versions of MIRA and CLASS (see the explanations in Sections 5 and 6). These Figures show the same data, re-calibrated by a new MIRA version and using the "AVERAGE /NEW /RES" command of CLASS. The shifts are not present anymore as far as can be told from the broad SiO line. There may still be shifts present, however, smaller than 10kHz.

Table 3: Scan Numbers for setups 0-1 to 0-3. "cal" means calibration; "track" means the actual observation

Setup	FTS Mode	Scan Numbers
0-1	fine	cal:150 track:151-152
0-1	wide	cal:154 track:155-156
0-2	fine	cal:161 track:162-163
0-2	wide	cal:165 track:166-167
0-3	fine	cal:170 track:171-172
0-3	wide	cal:174 track:175-176

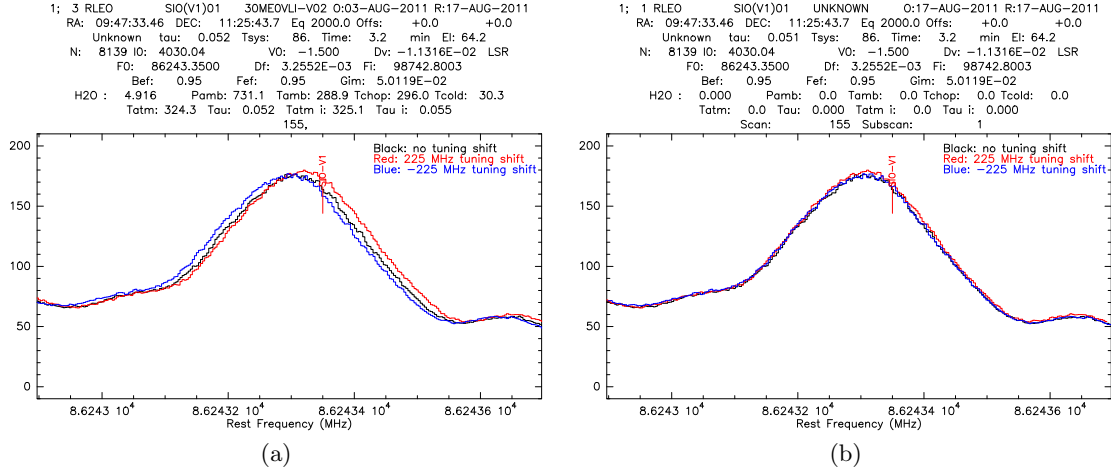


Figure 1: This plot shows the spectra observed in the setups 0-1 through 0-3 on top of each other. Only a small frequency range is shown here, the entire line shapes are seen in Fig. 1. In the black spectra the SIO(VI) line is tuned exactly to the LI. For the blue spectra the tuning frequency was shifted by +225 MHz and VESPA by -225 MHz. For the red one the tuning frequency was shifted -225 MHz and VESPA by +225 MHz. Thus in all setups, VESPA saw the same range of frequencies. **Left** Here, we show the spectra calibrated by a MIRA version prior to the date 15/08/2011 and use the old standard "AVERAGE" commando of CLASS. Using these, shifts are present. **Right** Here we show the same data, re-calibrated by a new MIRA version (from 15/08/2011 or younger) and make use of the new "AVERAGE /NEW /RES" commando in CLASS (version apr11 and higher). Here no shifts larger than 10 kHz are present.

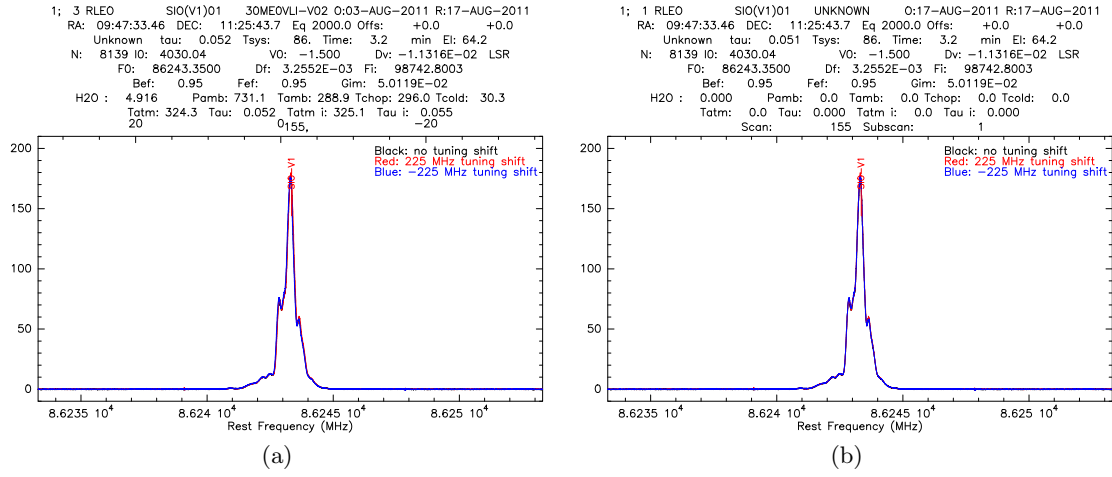


Figure 2

### 3 Setup 1

#### 3.1 Idea

In this setup we tune the Local Oscillator (LO) to the same frequency as in setup 0-1. The difference is that, we specify the corresponding frequency in the UI, i.e.  $f(\text{SiO}(\text{V1})) + 12.5 \text{ GHz} = 98.743350 \text{ GHz}$ . We observe the SiO(V1) line in LI with VESPA and all sub-bands with the FTS once in narrow and once in wide. The spectra of this setup can be compared with the one of setup 0-1, since VESPA observed both times the same frequency range. The corresponding scan numbers are listed in Table 4.

#### 3.2 Results

Figures 3 and 4 show the spectra taken in setup 0-1 (in black) and 1 (in red) with VESPA. Figures a) show again the "old" reduction (c.f. Sect. 1 and 2) here the shift is more prominent than in Setup 0 and its value is **560 kHz**. The latter has been determined by using the draw command of class. The SiO(VI) frequency in setup 0-1 where we tune and observe the LI is consistent with the real one. Again Figure b) shows the "new" reduced spectra that show the correct frequency for both setups.

**Corrected Spectra** Again, like in Section 2, Figures labeled b) anticipate the results using the new versions of CLASS and MIRA (cf. Sections 5 and 6)

Table 4: Scan numbers of Setup 1. Same semantic as in Table 3

Setup	FTS Mode	Scan Numbers
1	fine	cal:182 track:183-185
1	wide	cal:190 track:191-193

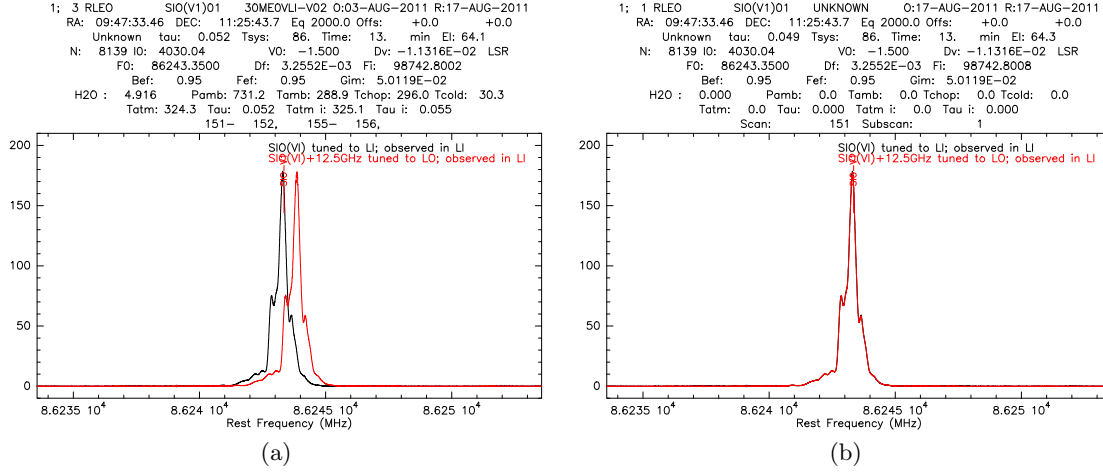


Figure 3: Here we compare the results of Setup 0-1 (black) tuning SiO(VI) to LI and Setup 1 (red) tuning SiO(VI)+12.5 GHz to UI. a) Both setups should show the same frequency range in the LI. As can be seen the lines are shifted in frequency in both setups. b) As in Figure 1 this shows the same data re-calibrated and averaged with the new versions of MIRA and CLASS respectively.

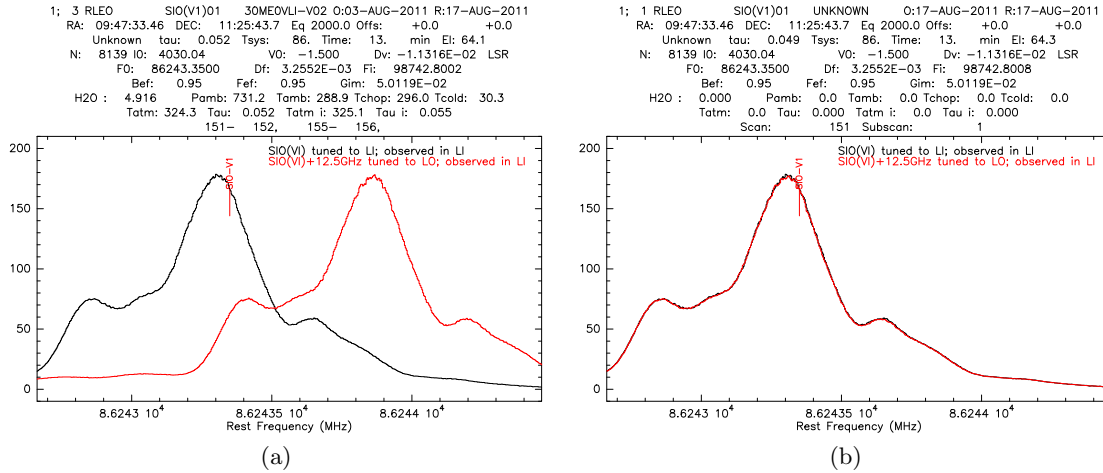


Figure 4: Same as Fig 3 but zoomed in.

## 4 Setup: 2–4

### 4.1 Idea

Tuning E090 three times such that SiO(V1) always falls in the LO sub-band. First: (Setup 2) by specifying the frequency in LI, i.e.  $f(\text{SiO(V1)}) + 3.18 \text{ GHz} = 89.42335 \text{ GHz}$ . Second: (Setup 3) by specifying the frequency in UO, i.e.  $f(\text{SiO(V1)}) + 18.86 \text{ GHz} = 89.42335 \text{ GHz}$ . The first two times VESPA is connected to the LO observing the same frequency range. Third: (Setup 4) by specifying the frequency in LO, i.e.  $f(\text{SiO(V1)}) = 86.24335 \text{ GHz}$ . Here we connected VESPA to the UO. But the FTS covered the spectrum of SiO(VI) in LO. For these setups the FTS only cover the sub-bands LO LI and UO, due to the reasons explained above. The corresponding scan numbers are listed in Table 5.

### 4.2 Results

For the "old" reduction we determine the shifts, as before, using the "draw" command in class. In accordance with the above results, the shift is visible for the other sub-bands and depends on the distance to the center of the sub-band specified in the tuning. There is no shift with respect to the "real" frequency of SiO(VI) for setup 4 tuning SiO(VI) in LO and observing LO. VESPA spectra have been smoothed to match the  $\sim 50 \text{ kHz}$  resolution of the narrow mode FTS. See plots 5 and 6. The value of the shifts are:

- between tuning in LO and LI:  $\sim 143 \text{ kHz}$
- between tuning in LI and UO:  $\sim 698 \text{ kHz}$
- between tuning in LO and UO:  $\sim 841 \text{ kHz}$

Also here, the shifts have been determined using the "draw" command in class.

Note that for all setups the Local Oscillator frequency was very similar and we did not have to retune. However the Receiver temperatures were higher as usual  $\sim 80\text{-}100 \text{ K}$  and higher in the horizontal polarization.

**Corrected Spectra** Figures labeled b) show again the same spectra, reduced with the new MIRA and CLASS version described below. Also here the shift is solved in first order.

Table 5: Scan numbers of Setups 2 through 4. Same semantic as in Table 3

Setup	FTS Mode	Scan Numbers
2	fine	cal:202 track:203-205
2	wide	cal:208 track:209-211
3	fine	cal:214 track:215-217
3	wide	cal:220 track:221-223
4	fine	cal:227 track:228-230
4	wide	cal:234 track:235-237



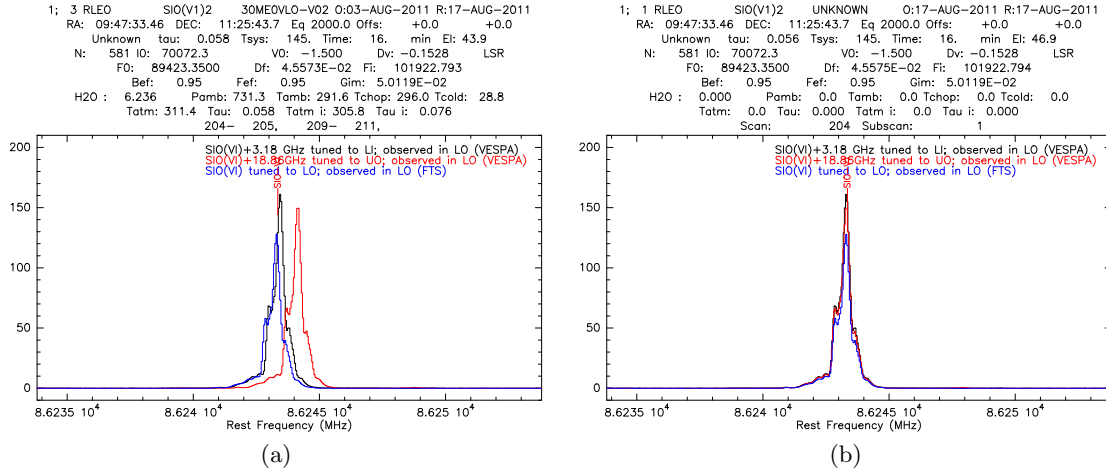


Figure 5: Plots of setups 2 trough 4. All are observed in the LO. Black shows setup 2 tuning SiO(VI)+3.18 to LI; Red SiO(VI)+18.86 tuned to UO and Blue SiO(VI) tuned to LO. Note in all setups the Local Oscillator frequency is the same and it was not retuned. a) The shift gets larger if the distance to the specified sub-band is larger. b) Re-Reduced spectra as in Figures 1 and 3.

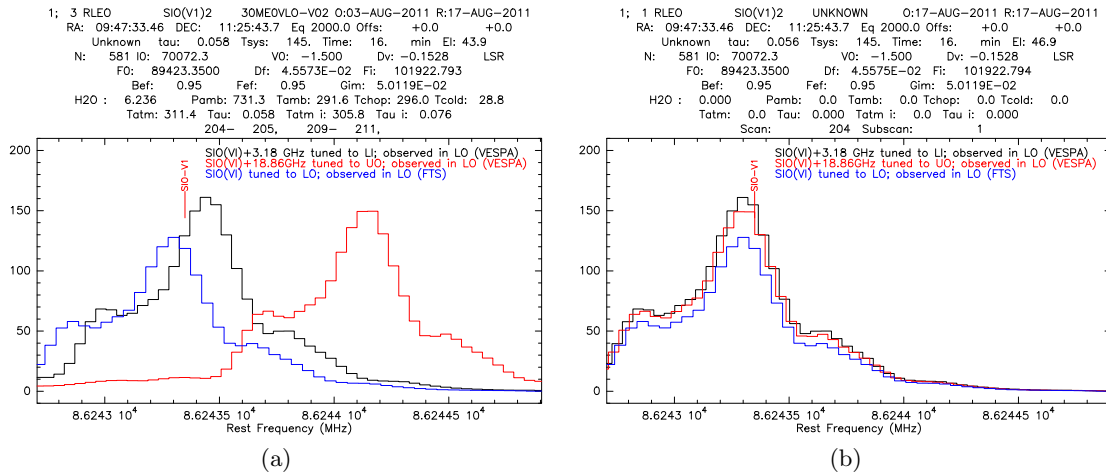


Figure 6: Same as Fig. 5 but zoomed in.

## 5 Explanation of the Shift

### 5.1 General explanation

The receivers are tuned to the rest frequency  $F_{1,\text{rest}}$  which is specified in the `pako` receiver command. To observe this frequency, the tuning has to take into account the Doppler movement of the source relative to LSR and of the telescope relative to LSR. At the 30m telescope, the optical convention is used for the Doppler correction:  $D_{\text{opt}} = 1/(1+v/c)$  ( $v$  is the full time variable Doppler velocity) to derive the observed frequency  $F_{1,\text{obs}}$ :

$$F_{1,\text{obs}} = F_{1,\text{rest}} \cdot D_{\text{opt}} \quad (1)$$

and

$$\Delta F_1 = F_{1,\text{rest}} - F_{1,\text{obs}} \quad (2)$$

$$= F_{1,\text{rest}}(v/c \times D_{\text{opt}}) \quad (3)$$

This tuning is however not exactly correct for a different rest frequency, as we will show next:

If the observer would decide (at the same time) to observe a different rest frequency  $F_{2,\text{rest}} = F_{1,\text{rest}} + F_{\text{diff}}$ , the same formulas would apply, of course:  $\Delta F_2 = F_{2,\text{rest}}(v/c \times D_{\text{opt}})$ . However, the exact tuning would be different, i.e. the exact synthesizer settings would be slightly different, i.e. the frequency offset between observed and rest frequency would be different. This is because:

$$\Delta F_2 = (F_{1,\text{rest}} + F_{\text{diff}})(v/c \times D_{\text{opt}}) \quad (4)$$

$$= \Delta F_1 + F_{\text{diff}}(v/c \times D_{\text{opt}}) \quad (5)$$

the term  $F_{\text{diff}}(v/c \times D_{\text{opt}})$  is the error made at the rest frequency  $F_{2,\text{rest}}$ , when tuning correctly the rest frequency  $F_{1,\text{rest}}$ :

$$\boxed{F_{\text{error}} = F_{\text{diff}}(v/c \times D_{\text{opt}})} \quad (6)$$

For small Doppler velocities,  $D_{\text{opt}} \sim 1$ , the ratio of the frequency error divided by the frequency difference between both rest frequencies times the speed of light equals the Doppler velocity:

$$F_{\text{error}}/F_{\text{diff}} \times c = v \quad (7)$$

Without correcting for  $F_{\text{error}}$ , the observed 2nd line  $F_{2,\text{rest}}$  will lie  $F_{\text{error}}$  too high being (wrongly) calculated by  $F_{1,\text{rest}}$  plus the number of channels  $N$  times the spectrometer resolution  $\Delta\nu_{\text{spec}}$ . This means that the spectrometer resolution should be reduced to correct for this frequency error:

$$N\Delta\nu_{\text{spec}} = N\Delta\nu_{\text{correct}} + F_{\text{error}} \quad (8)$$

It follows:

$$\Delta\nu_{\text{correct}} = (N\Delta\nu_{\text{spec}} - F_{\text{error}})/N = \Delta\nu_{\text{spec}} - F_{\text{diff}}(v/c)D_{\text{opt}}(1/N) \quad (9)$$

$$= \Delta\nu_{\text{spec}} - \Delta\nu_{\text{correct}}(v/c)D_{\text{opt}} \quad \text{with} \quad F_{\text{diff}} = \Delta\nu_{\text{correct}}N \quad (10)$$

$$\Delta\nu_{\text{spec}} = \Delta\nu_{\text{correct}}(1 + v/c \times D_{\text{opt}}) \quad (11)$$

The corrected frequency resolution is then:

$$\boxed{\Delta\nu_{\text{correct}} = \Delta\nu_{\text{spec}} / (1 + v/c \times D_{\text{opt}})} \quad (12)$$

CLASS attempts to do this correction but uses a different formula (e.g. in `sumlib-new.f90`):

$$\Delta\nu_{\text{correct}} = \Delta\nu_{\text{spec}} / (1 + D_{\text{radio}}) \quad \text{with} \quad D_{\text{radio}} = -v/c \quad (13)$$

**At present, it is unclear where the discrepancy comes from.**

## 5.2 Comparison with test observations

For all test observations on 03-Aug-2011, the full Doppler velocity was about  $13.1 \text{ km s}^{-1}$  (using `astro`). Table 6 compares the observed error or shift with the shift predicted from the above equation.

The two numbers agree within 3%. The shifts are entirely explained by the incomplete treatment of the Doppler correction for frequencies that differ from the specified rest frequency in the receiver command by a significant amount. This suspicion was confirmed, bugs were identified, and the new versions of `MIRA` and `CLASS` do not show shifts anymore.

Table 6: Comparison between the observed shifts (cf. Sections 2–4) and the calculated correction after Formula 6.

Setup	$v$ [km/s]	$F_{\text{diff}}$ [GHz]	$F_{\text{error,obs}}$ [kHz]	$F_{\text{corr}}$ [kHz]
0-2	13.1	0.225	-10.2	-9.82
0-3	13.1	-0.225	10.2	9.82
1	13.1	12.5	560	545.81
2	13.1	3.18	143	138.85
3	13.1	18.86	841	823.51

## 6 New Versions of CLASS and MIRA

As shown in the previous sections the shifts are consistent with the fact that the Doppler correction is not applied correctly for frequencies other than the tuned rest frequency  $F_{1,\text{rest}}$ . Discussing the shifts we identified the erroneous part in the data reduction chain. One part of the shifts is due to the fact that the default "AVERAGE" command of CLASS does not apply the Doppler correction, here the shifts are preset regardless of the setup. As second part of the shift was due to a bug in MIRA and appeared only when observing in the side-band that was not tuned. The changes to correct the shifts in the two programs are described subsequently.

### 6.1 New "AVERAGE" scheme in CLASS version apr11

As shown in the above analysis, no shift is present for a single (i.e. no "AVERAGE" commando has been used) spectra if the observation and tuning was done in the same side-band (LSB or USB). However, when averaging several single spectra the shifts arose. This problem has been known to the CLASS developers already for some time. In the new CLASS version apr11 they provide a new averaging scheme that successfully corrects for this by employing the Doppler correction to all rest frequencies. At the moment the command to use the new average is:

```
AVERAGE /NEW
```

As mentioned above the Doppler correction is time variable and its implementation leads to time-variable frequency resolutions. To co-add spectra with different x-axes, i.e. different frequency resolutions, the new "AVERAGE" commando also provides an option to re-sample the x-axis to it's coarsest common resolution via:

```
AVERAGE /NEW /RESAMPLE
```

Using the new average scheme alone corrects shifts that arise when observing in the same side-band that has been tuned. Therefore, in our test observations this corrects setups O-1 trough 0-2 as well as setup 2.

### 6.2 MIRA version 2.5 and higher

With the new "AVERAGE /NEW" routine alone still large shifts are present, when observing in a side-band that has not been tuned. This was due to a bug in MIRA. MIRA re-centers spectra observed in the not-tuned side-band to a corresponding  $F_0$ , rather than using the tuned  $F_0$  for the header variables. During this process the previous MIRA versions did not take the additional Doppler correction, explained in Section 5, into account and this was the cause for the shifts.

From Mira version 2.5 on (also available in the GILDAS apr11 release) the Doppler correction, for the recenter operation, is implemented in MIRA. To be consistent with CLASS these corrections are not done to  $F_0$ , but to the reference channel  $I_0$ .

After correcting the spectra in MIRA it is still necessary to use the new "AVERAGE /NEW" command in CLASS. Please note that the Mira version 2.5 which is the default for on-line data processing since August 16, 2011. Therefore, all observations obtained before this date have to be recalibrated with a version younger or equal to 2.5 in order to solve the shift described above.

**6.3 Summary: How to correct shifted spectra**

When observing in the same side-band that also has been tuned, it is sufficient to use the new "AVERAGE /NEW" command in the most recent version of CLASS apr11. However, when the observations are done in the other side-band, the spectra have to be re-calibrated by a MIRA version 2.5 and higher. At the moment this is the default version on mrt-lx3 and for OdP. In case you need help, please contact the Granada SOG.

## A ODP Problem with Setups 2–4

In Setups 2–4 the LO sub-band is recorded two times with the FTS. This is because the new IF cables are fixed on the outer band and we have to specify the LO in the receiver command to be able to connect VESPA. The latter connects one "old" cable also to the LO. Using the spectra created by ODP we found that one (hor. and ver.) of the two simultaneous FTS spectra (F06 and F08) have  $\sim 2.5$  times higher fluxes than the other one (F01 and F03).

After re-calibrating the spectra by hand, all spectra of the LO in one scan are consistent. Please see Figure 7 for an example.

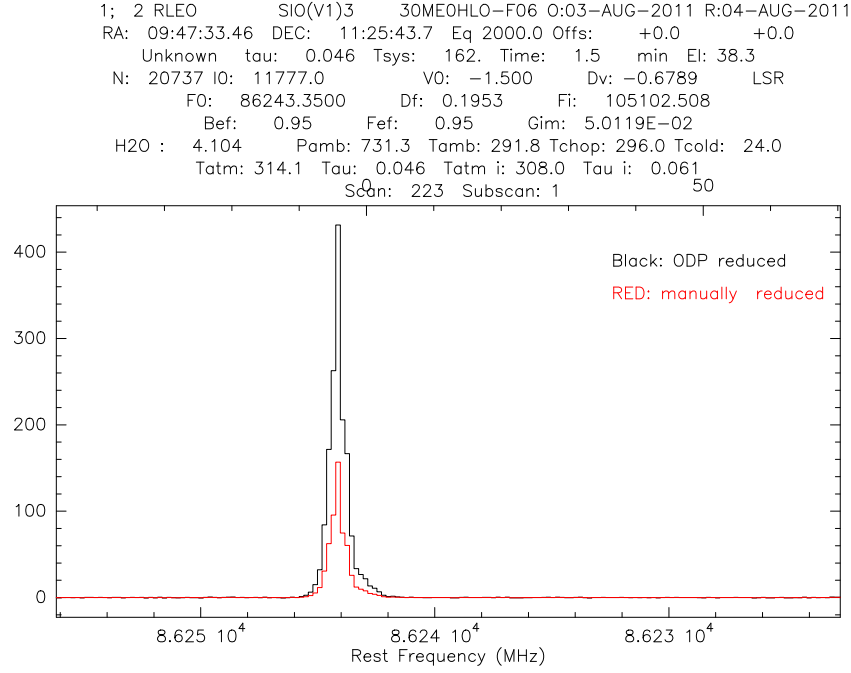


Figure 7: Comparison the automatically and manually calibrated spectra of FTS unit 06 in scan 223.

## B Comparison VESPA and FTS

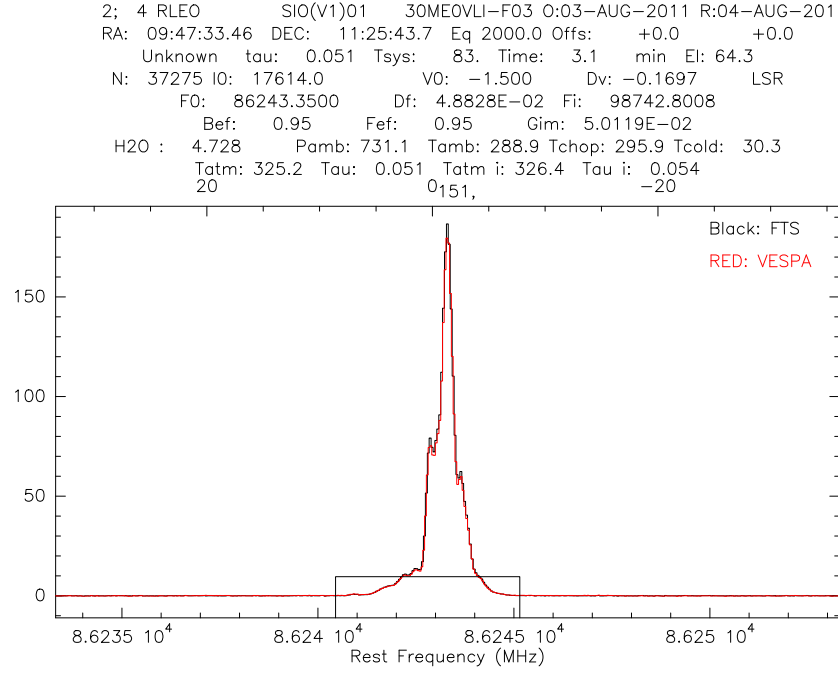


Figure 8: Comparing Vespa spectra smoothed to  $\sim 50$  kHz resolution with the corresponding narrow FTS spectra. Flux and position are consistent.

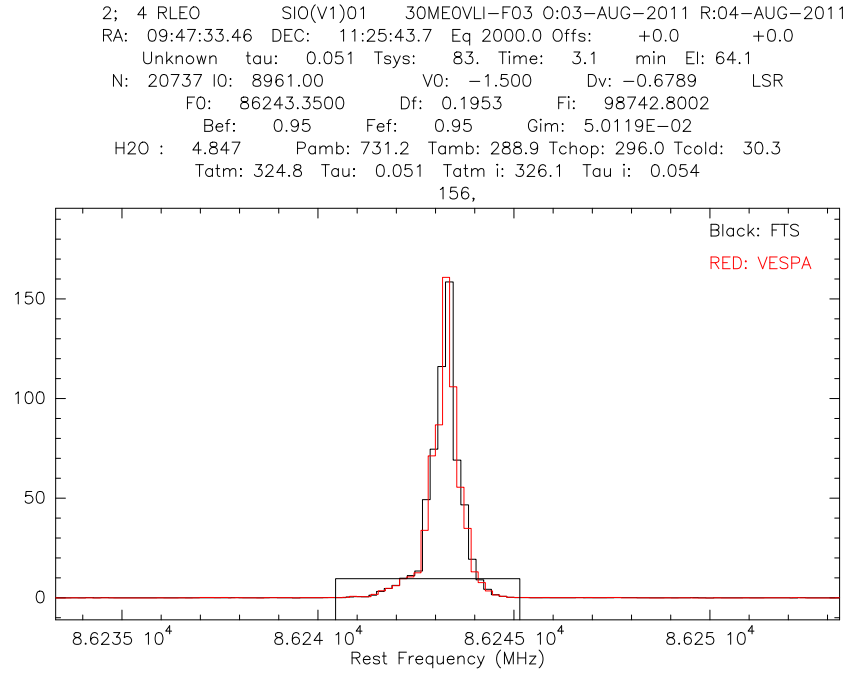


Figure 9: Comparing Vespa spectra smoothed to  $\sim 200$  kHz resolution with the corresponding wide FTS spectra. Flux and Position are consistent.

3; 4 RLEO SIO(V1)4 30ME0VUO-F07 0:03-AUG-2011 R:04-AUG-2011  
 RA: 09:47:33.46 DEC: 11:25:43.7 Eq 2000.0 Offs: +0.0 +0.0  
 Unknown tau: 0.088 Tsys: 171. Time: 6.4 min El: 36.7  
 N: 37275 I0: 17614.0 V0: -1.500 Dv: -0.1393 LSR  
 F0: 105103.350 Df: 4.8828E-02 Fi: 86244.1919  
 Bef: 0.95 Fef: 0.95 Gim: 5.0119E-02  
 H2O : 7.623 Pamb: 731.4 Tamb: 291.5 Tchop: 296.1 Tcold: 30.3  
 Tatm: 298.5 Tau: 0.088 Tatm i: 302.7 Tau i: 0.067  
 228,

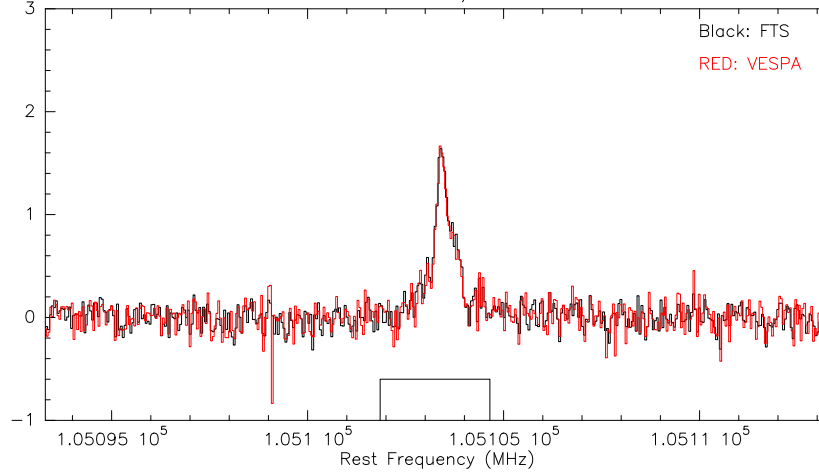


Figure 10: As Figure 8 but on a weaker line.

3; 4 RLEO SIO(V1)4 30ME0VUO-F07 0:03-AUG-2011 R:04-AUG-2011  
 RA: 09:47:33.46 DEC: 11:25:43.7 Eq 2000.0 Offs: +0.0 +0.0  
 Unknown tau: 0.087 Tsys: 191. Time: 6.4 min El: 34.3  
 N: 20737 I0: 8961.00 V0: -1.500 Dv: -0.5571 LSR  
 F0: 105103.350 Df: 0.1953 Fi: 86244.1924  
 Bef: 0.95 Fef: 0.95 Gim: 5.0119E-02  
 H2O : 7.207 Pamb: 731.4 Tamb: 291.9 Tchop: 296.1 Tcold: 30.3  
 Tatm: 297.1 Tau: 0.087 Tatm i: 301.0 Tau i: 0.065  
 235,

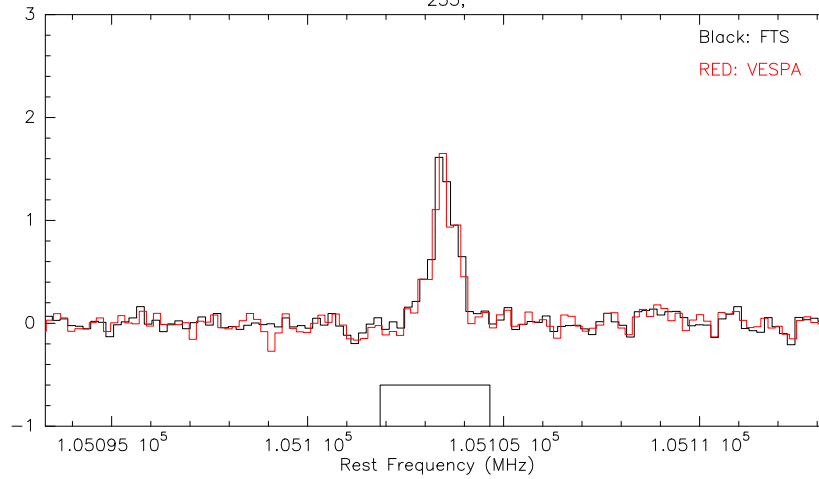


Figure 11: As Figure 9 but on a weaker line.



# C Comparison FTS narrow and FTS wide

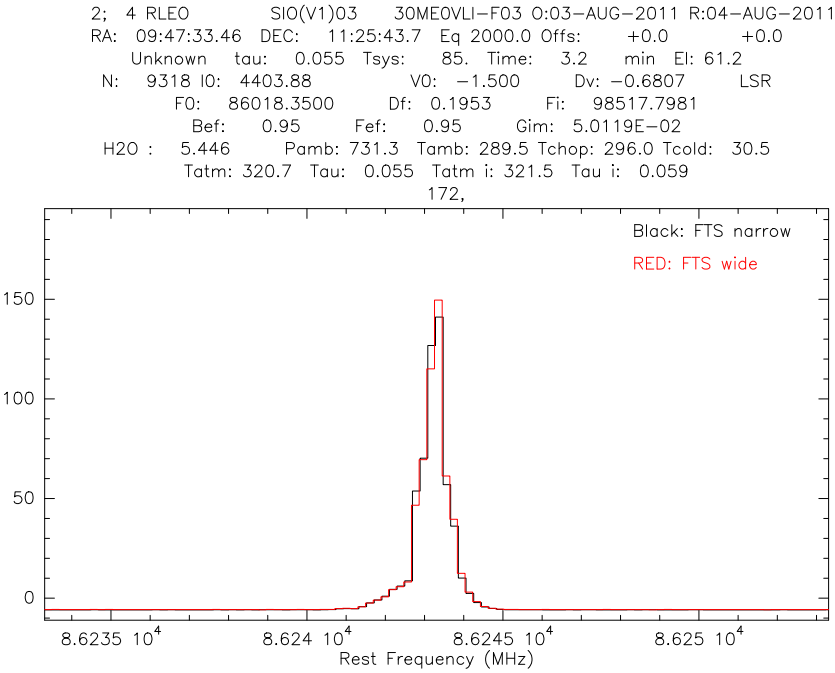


Figure 12: Comparing wide and narrow mode of the FTS. The narrow spectra has been smoothed to 200 kHz resolution to match the one of the wide mode.

## D PAKO Setups

### Line Catalogue

SIO(V1)	86.243350	LI
SIO(V1)01	86.243350	LI
SIO(V1)02	86.46835	LI
SIO(V1)03	86.01835	LI
SIO(V1)1	98.743350	UI
SIO(V1)2	89.42335	LI
SIO(V1)3	105.10335	UO
SIO(V1)4	86.243350	LO

### Setup: 0-1

RECEIVER E090	SIO(V1)01	- ! explicit options:
	/Horizontal UI LI	- ! SBs for Hori. polar.
	/Vertical UI LI	- ! SBs for Vert. polar.
	/dop dop	- ! Doppler correction
	/gain -13 db	- ! image gain ratio
	/eff 0.95 0.95	- ! forward and beam eff.
	/scale beam	!

Backend VESPA 1 0.0033 30 0 E0 horiz LI  
Backend VESPA 2 0.0033 30 0 E0 verti LI

backend fts /fine /default  
AND  
backend fts /default

### Setup: 0-2

RECEIVER E090	SIO(V1)02	- ! explicit options:
	/Horizontal UI LI	- ! SBs for Hori. polar.
	/Vertical UI LI	- ! SBs for Vert. polar.
	/dop dop	- ! Doppler correction
	/gain -13 db	- ! image gain ratio
	/eff 0.95 0.95	- ! forward and beam eff.
	/scale beam	!

Backend VESPA 1 0.0033 30 -225 E0 horiz LI  
Backend VESPA 2 0.0033 30 -225 E0 verti LI

backend fts /fine /default  
AND  
backend fts /default

**Setup: 0-3**

```

RECEIVER E090    SIO(V1)03
                  /Horizontal UI LI
                  /Vertical   UI LI
                  /dop dop
                  /gain -13 db
                  /eff 0.95 0.95
                  /scale beam
                  - ! explicit options:
                  - ! SBs for Hori. polar.
                  - ! SBs for Vert. polar.
                  - ! Doppler correction
                  - ! image gain ratio
                  - ! forward and beam eff.
                  !

```

```

Backend VESPA 1 0.0033 30 225 E0 horiz LI
Backend VESPA 2 0.0033 30 225 E0 verti LI

```

```

backend fts /fine /default
AND
backend fts /default

```

**Setup: 1**

```

RECEIVER E090    SIO(V1)4
                  /Horizontal LI UO
                  /Vertical   LI UO
                  /dop dop
                  /gain -13 db
                  /eff 0.95 0.95
                  /scale beam
                  - ! explicit options:
                  - ! SBs for Hori. polar.
                  - ! SBs for Vert. polar.
                  - ! Doppler correction
                  - ! image gain ratio
                  - ! forward and beam eff.
                  !

```

```

Backend VESPA 1 0.0033 30 0 E0 horiz UO
Backend VESPA 2 0.0033 30 0 E0 verti UO

```

```

backend fts /fine /default
AND
backend fts /default

```

**Setup: 2**

```

RECEIVER E090    SIO(V1)2
                  /Horizontal LI L0
                  /Vertical   LI L0
                  /dop dop
                  /gain -13 db
                  /eff 0.95 0.95
                  /scale beam
                  - ! explicit options:
                  - ! SBs for Hori. polar.
                  - ! SBs for Vert. polar.
                  - ! Doppler correction
                  - ! image gain ratio
                  - ! forward and beam eff.
                  !

```

```
Backend VESPA 1 0.0033 30 0 E0 horiz L0
Backend VESPA 2 0.0033 30 0 E0 verti L0
```

```
backend fts /fine /default
AND
backend fts /default
```

### Setup: 3

```
RECEIVER E090  SIO(V1)3          - ! explicit options:
                /Horizontal L0 LI - ! SBs for Hori. polar.
                /Vertical   L0 LI - ! SBs for Vert. polar.
                /dop dop        - ! Doppler correction
                /gain -13 db    - ! image gain ratio
                /eff 0.95 0.95  - ! forward and beam eff.
                /scale beam      !
```

```
Backend VESPA 1 0.0033 30 0 E0 horiz L0
Backend VESPA 2 0.0033 30 0 E0 verti L0
```

```
backend fts /fine /default
AND
backend fts /default
```

### Setup: 4

```
RECEIVER E090  SIO(V1)4          - ! explicit options:
                /Horizontal LI U0 - ! SBs for Hori. polar.
                /Vertical   LI U0 - ! SBs for Vert. polar.
                /dop dop        - ! Doppler correction
                /gain -13 db    - ! image gain ratio
                /eff 0.95 0.95  - ! forward and beam eff.
                /scale beam      !
```

```
Backend VESPA 1 0.0033 30 0 E0 horiz U0
Backend VESPA 2 0.0033 30 0 E0 verti U0
```

```
backend fts /fine /default
AND
backend fts /default
```

## Wobbler On-Off

```

SET ANGLE arcsec      !

SWWOBBLER      -120.0   120.0      - ! wobbler -/+ 120 arc sec
/TPHASE        2.0              - ! 2 seconds per phase
CALIBRATE      - !
/AMBIENT       - ! ambient load
/COLD          - ! cold   load
/SKY           -600.0   0.0      - ! sky at offsets -600.0 0.0
/SYSTEM        projection      - ! system for SKY offsets
/TCALIBRATE    5.0             - ! time per calibration subscan
START          - ! start

ONOFF /SWWOBBLER      - ! ONOFF for Wobbler switching
/NSUBSCANS     4       - ! number of subscans
/SYMMETRIC     - ! "symmetric" subscan sequence
/TSUBSCAN      30      - ! time per subscan

START          - ! start
START
START

```