CSO-FFTS & IF Commissioning

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Summary.
A novel wideband Fast Fourier Transform (FFT) spectrometer with 50-100 kHz spectral resolution has been made available to the CSO by MPIfR, with the necessary IF processor to interface to the nominal 4-8 GHz intermediate frequency.
The spectrometer has been successfully integrated and commissioned during Nov 26 – Dec 04 2007, and fully complies with specifications. Allan variance times are excellent (total power ~250 sec, spectroscopic ≥1000 sec). The equivalent noise bandwidth of the new core compares closely with the nominal channel spacing (61 - 122 kHz, depending on the bandwidth).

Change Record

REVISION	DATE	AUTHOR	SECTIONS/PAGES AFFECTED	REMARKS
0.1	01.12.07	Güsten	- all -	new issue
0.2	03.12.07	Güsten		Comments from team
0.3	05.12.07	Güsten		incl. 500 MHz mode

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1 Background & Scope

End of 2006 it was agreed between MPIfR (R. Güsten) and CSO (T. Phillips) that MPIfR shall deliver a high spectral resolution (~100 kHz) wideband (~1 GHz) FFT spectrometer for operation with the CSO facility heterodyne receivers. The delivery does include the IF processor unit to interface with a nominal 4-8 GHz IF.

In this document we describes the commissioning of this novel FFT spectrometer and associated IF processor.

2 Commissioning of the FFTS/ & IF at the CSO

Integration of the shipment in the backend room at the CSO started Nov. 26, 2007. After extensive debugging and optimization of the interfaces to the CSO hardware and control, a first spectrum on sky was recorded Nov.29 (because of mediocre weather conditions, all tests on sky were performed with the 230 GHz side cab receiver).

The commissioning team consisted of Rolf Güsten, Bernd Klein, Christoph Kasemann (MPIfR) and Hiroshige Yoshida (CSO).

3 Deliverables

Deliverables are a 4-8 GHz IF processor and power supply, and a 1x 1 GHz wide FFT spectrometer with control unit and external display. A set of documents is delivered:

RD-01	CSO-MPI-MAN-01	CSO-IF processor User Manual
RD-02	CSO-MPI-DSD-01	CSO-IF processor Design Description
RD-03	CSO-MPI-MAN-02	CSO-FFTS User Manual
RD-04	CSO-MPI-DSD-02	CSO-FFTS Design Description
RD-05	CSO-MPI-ICD-01	CSO-IF processor SCPI commands
RD-06		folder with electrical diagrams & data sheets

4 Specifications

The characteristics of the spectrometer are summarized in [RD-02] & [RD-04]. The FFTS provides

- 1 GHz bandwidth (for astronomical applications asking for high out-of-band signal rejection, the usable bandwidth is limited to ~950 MHz (10 dB) due to aliasing filtering the band edges – see Sect. 6.2) with
- 8192 channels (spacing: 122 kHz, equivalent noise bandwidth: 117 kHz).

The IF processor converts a 1 GHz wide segment out of the nominal 4-8 GHz IF output of the CSO heterodyne receivers to the 0 -1 GHz video input band of the FFTS.

5 Verification of the Hardware as installed at the CSO

The FFTS & IF units were installed on Nov.26 in the backend room of the CSO (App.A), connected to the CSO UPS. Basic functional tests with the internal noise source were performed, confirming the status of the system as recorded prior to shipment. Fig.1 displays a standard Allan variance test on the noise source, measured in the night of Nov.27, parallel to ZSPEC observations.

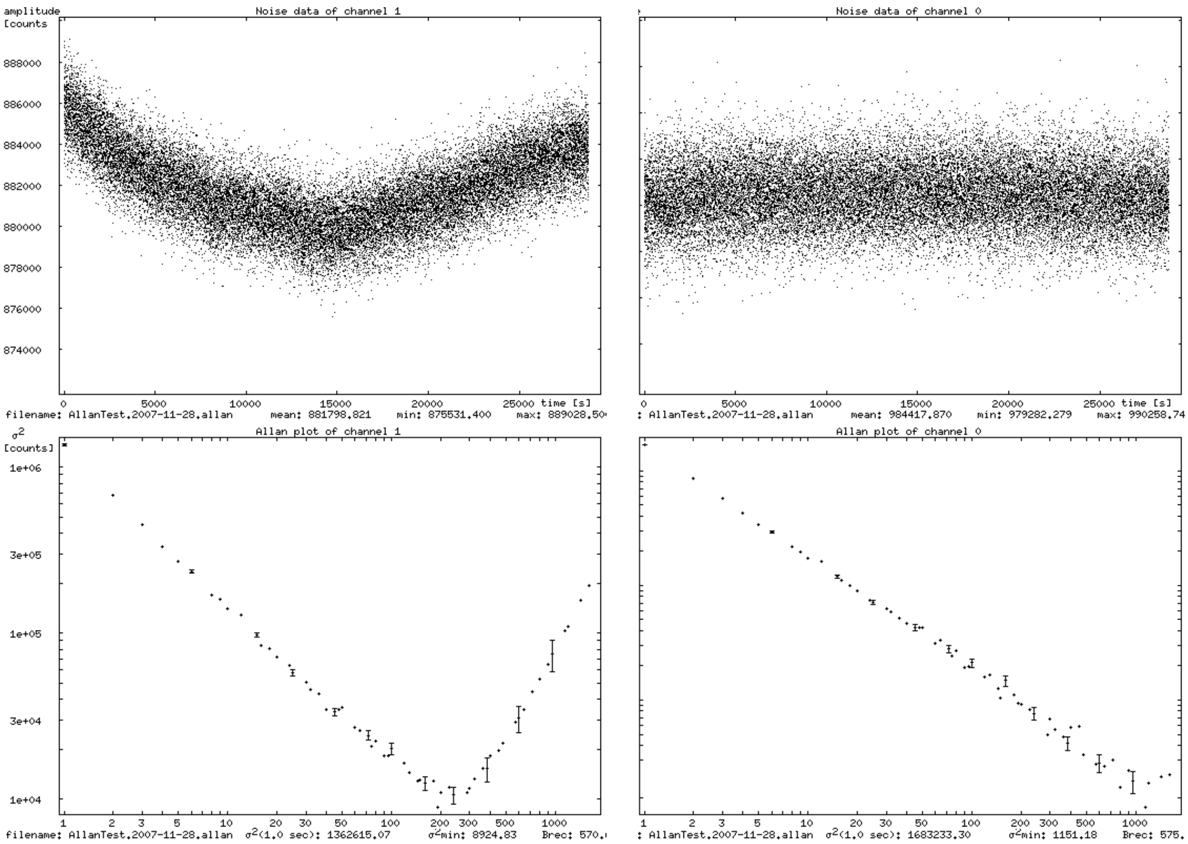

Fig.1. Measurement of the continuum (channel # 200) and spectroscopic (# 800 vs. 200) Allan variance of the FFT/IF spectrometer as installed at the CSO. Data were taken on the integrated 4-8 GHz noise source. The variance is calculated for two 1 MHz broad channels, separated by 600 MHz within the 1 GHz video band. Total power (continuum) AV times are ~250 sec, the spectroscopic AV time is ≥1000 sec.

The input of both, the 1-2 GHz IF of the 230 GHz side cab (after up-conversion) and the 4-8 GHz IF of the 270 GHz Cassegrain heterodyne receiver, was connected for these tests. Weather constrained, observations on-sky were performed at 230 GHz (CO2-1) only.

Control of the FFTS and the IF via the CSO UIP and successful data acquisition was established on Nov.28. A first position-switched CO(2-1) spectrum was measured towards W3(OH) in the evening of Nov.29 (Fig.2).

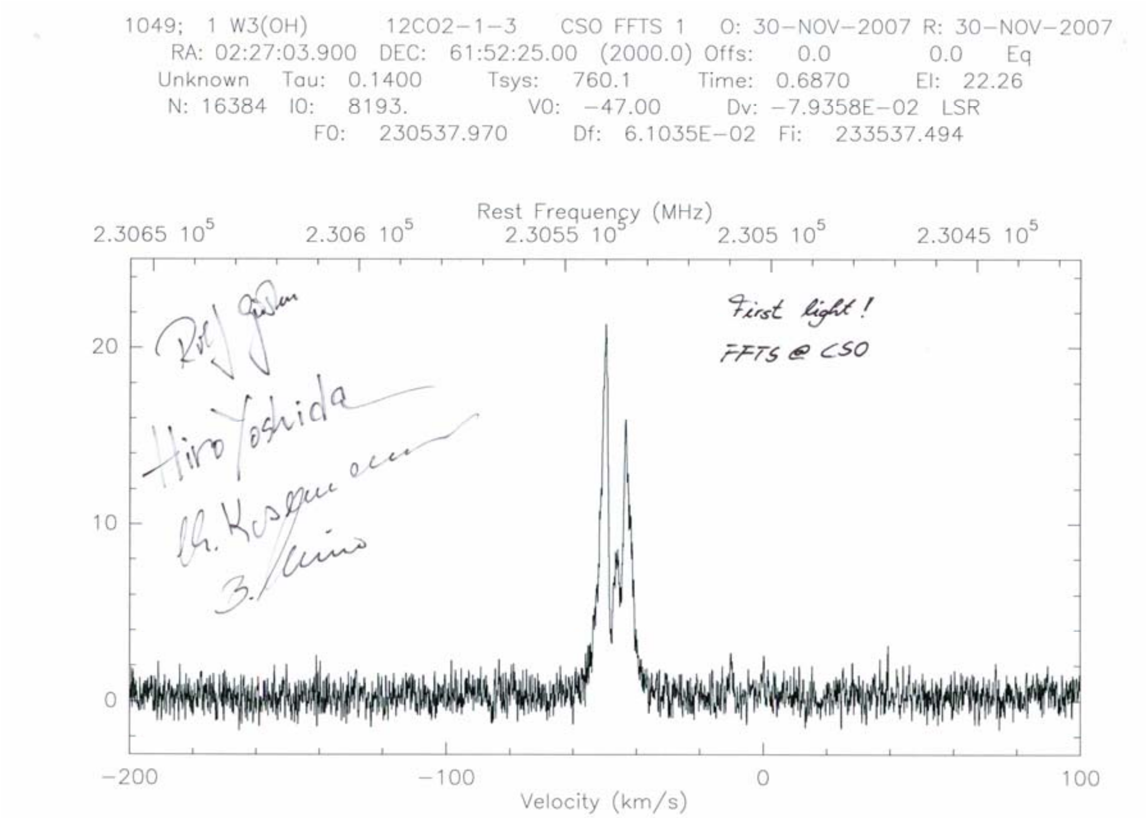

Fig.2. **First-light spectrum** with the CSO-FFTS & IF processor, recording a 1 GHz wide spectrum towards W3(OH). Frontend: side cab 230 GHz Rx, with the CSO up-converter. The integration time of this total power observation was 0 sec, the reference position was at 600” AZ (afterwards, a pointing offset of ca. 10” was determined).

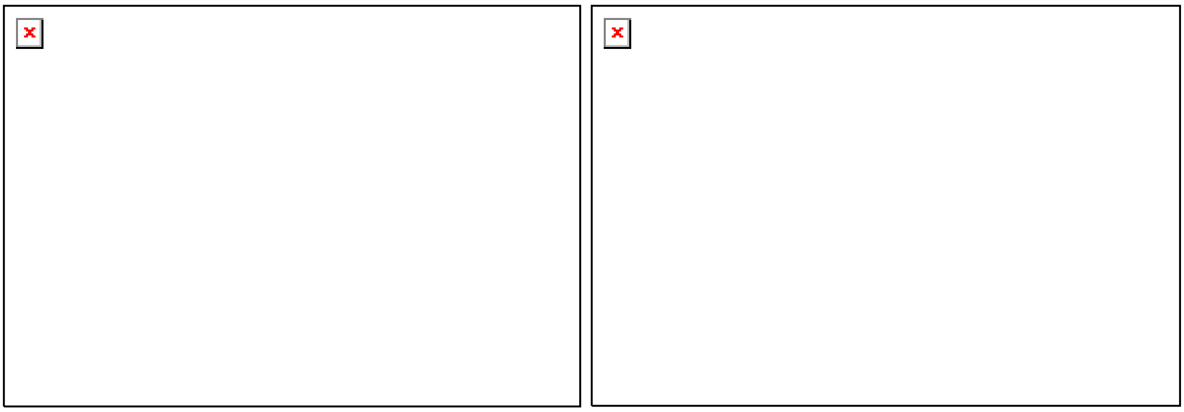

Fig.3. Our “second light” FFTS spectrum of CO(2-1) towards W3(OH), after peak-up on a nearly pointing reference. The on-source integration time was 6.8 min (with T_{sys} ~610 K). The right panel shows a blow-up of the same spectrum.

The next day, Nov.30, the wobbler was successfully integrated and 2-phase measurements were performed (Fig.4). Finally, on-the-fly data were taken during an RA slew across W3(OH), though during rather miserable atmospheric conditions.

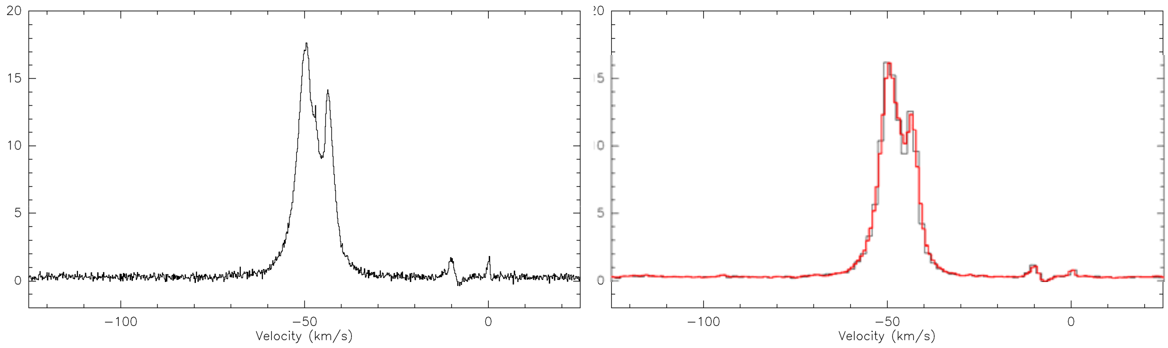

Fig.4. First FFTS spectrum observed in wobbler mode (300” throw, 0.5 Hz), during rather limiting atmospheric conditions (8 mm H_2O). The spectrum to the left displays the FFTS data in nominal resolution (120 kHz). In the right panel, this spectrum has been box-smoothed to the nominal resolution of the AOS (1.2 MHz), superimposed in red. The data agree pretty nicely, differences are likely due to the different effective resolutions/spectral responses of the two backends.

6 Verification of critical FFT /IF parameters

6.1 Spectral response of the FFT channels

The spectral response of the FFT spectrometer depends on the FPGA signal processing pipeline, which – in view of the rapid increase of FPGA performance – is a field of continuous optimization. As baseline (upon delivery) a windowed-FFT using a Blackman-Harris function was implemented (this core is also in routine operation at the APEX). Thanks to the miserable weather conditions, we took the opportunity to characterize and optimize more recent core developments (see references in RD-04).

Finally, we decided to install an optimized core, which instead of the BH window, uses a “4-fold weighted overlap add (WOLA)” pre-processing.[1]

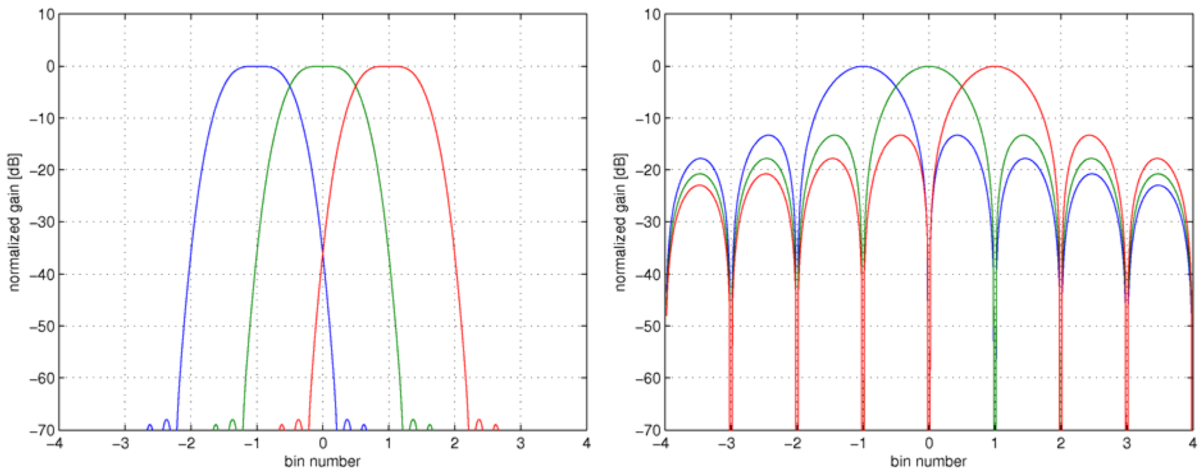

Fig.5. Frequency response of the FFT channels for the WOLA core (left panel). The response was confirmed with a narrow (few kHz) line that was injected via a power splitter (combining the

[1] Except for the first-light spectra (Fig.2,3) that were gathered with the Blackman-Harris windowed FFT, all data presented in this report have been taken with the WOLA core.

signal from the noise source) from an Agilent synthesizer E8257D. For comparison the response of an autocorrelator is given (right panel).

The channel spacing was confirmed during these measurements to 122 kHz, linear over the full spectral range spectral as predicted. For this core, the 3dB bandwidth was measured to 115 kHz, the equivalent noise bandwidth[2] is 117 kHz.

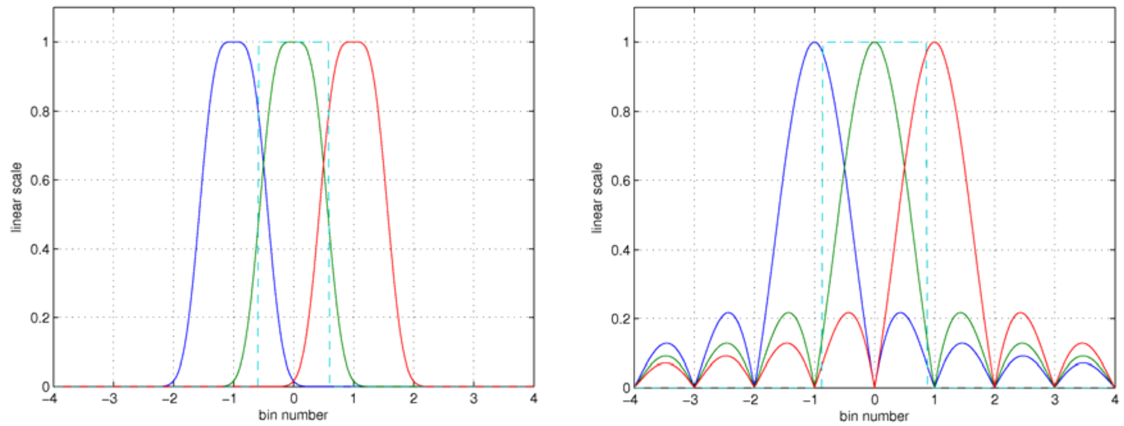

Fig.6. Simulation of the superior spectral response function of the FFT WOLA core, compared to an autocorrelator, which equivalent noise bandwidth is 1.7 times the channel spacing.

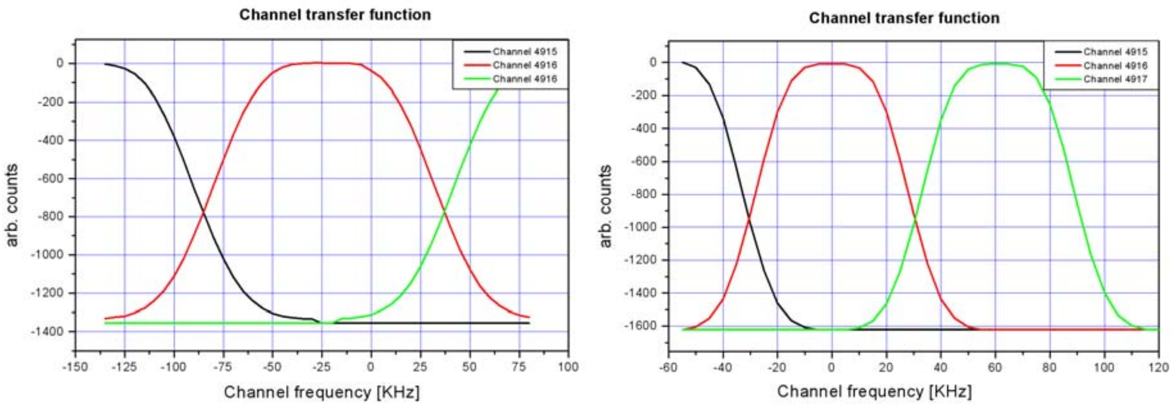

Fig.7. The spectral response of the CSO-FFT/IF as measured for both the 1000 and the 500 MHz core. The response functions are identical.

6.2 The effective bandwidth of the spectrometer

As explained in RD-02 & RD-04, due to the high dynamic range of the FFT spectrometer (48 dB of the 8-bit ADC) the IF processor has to limit the band edges with steep band pass filters to avoid aliasing by out-of-band signals. However, because of the limited steepness of any analog filter, residual aliasing is unavoidable, thereby limiting the usable bandwidth of the spectrometer. To characterize the actual response of the spec-

[2] The Equivalent Noise Bandwidth is the width of a fictitious rectangular filter such that the power in that rectangular band is equal to the actual power of the signal

trometer at the band edges, we measured the response again by injection of a narrow line signal (using the same set-up as explained in the previous section).

The transfer function has been measured to design (see Fig. 8):

- the transfer function at the lower IF edge is very steep, and the bandwidth of the spectrometer is limited by max. 20 MHz due to in-band roll-off. Out-of-band signals are suppressed by more than 20 dB.
- the upper edge is more critical (design-driven, filters are less steep), and aliasing must be taken into account by the careful observer. Depending on the astronomical application, the upper 30 (10 dB) to 60 MHz (20 dB suppression) shall be discarded.

This finding was confirmed on sky: during a CO(2-1) measurement towards W3(OH), the center frequency was offset by -550 MHz, so that the CO line was still detected in the wide(r) band AOS, but was 50 MHz outside the 1 GHz FFTS band edge. No line (0.1 K) was detected in the FFTS, from which we derive a min suppression of >23 dB (19/0.1).

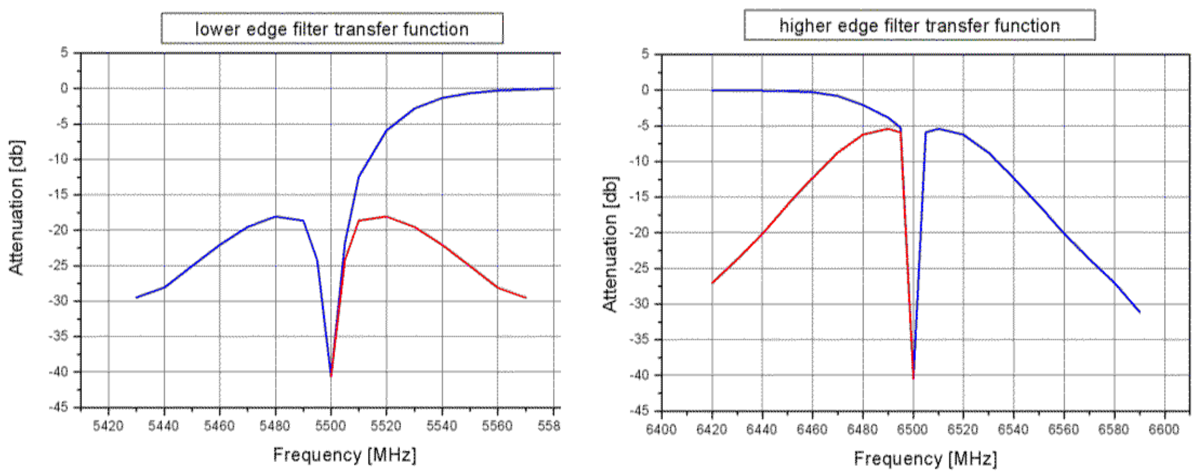

Fig.8. Transfer function of the FFTS/IF-processor. The lower half of the 1 GHz IF band is limited to -480 MHz, the upper half to +440 to 470 MHz for 20 (10) dB suppression, respectively.

6.3 Noise performance vs. time

Unfortunately, limited sky performance made a deep integration difficult. On Dec.01 we managed to acquire a short total of 45 minutes (on source) with the 230 GHz side cab receiver towards o-Ceti. Both, the AOS and the FFT spectrometer were operated in parallel. Observations were performed in wobbler mode (60”, 1 Hz, double beam switch, 4x10 sec on source per scan).

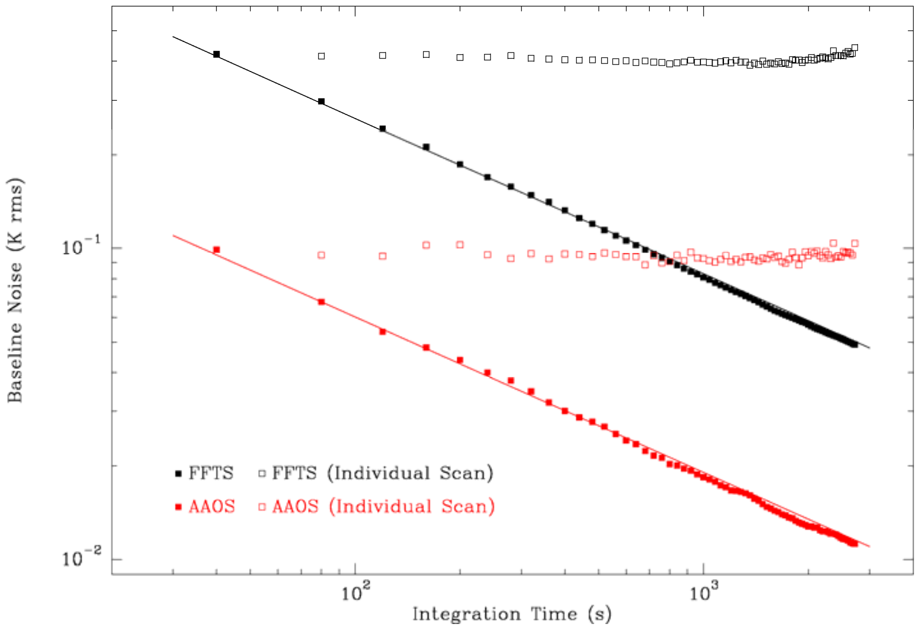

Fig.9. Noise of the cumulated spectra of a 46 min (on-source) long CO(2-1) integration towards o-Ceti, using the side cab 230 GHz receiver (FFTS: black dots, AOS: red dots). Open dots display the noise of the individual scans, reflecting unstable sky conditions.

Analysis of the noise in the accumulated FFTS spectrum reveals perfect agreement with the noise expected from the radiometer formulae ($T_{rms} = T_{sys}/\sqrt{0.5 \cdot \Delta\nu \cdot t_{on}}$):

- Because T_{sys} increases rapidly in the lower IF band (feature of the frontend), we limit our analysis to velocities -600 ≤ V_{lsr} ≤ +200 km/s: with T_{sys} = 580 K and 46 min on-source integration, an effective channel resolution of 120 kHz, we expect a rms noise of 45.1 mK.
- The noise rms actually measured in the spectrum (base 0) in this velocity window is 44.6 mK – in excellent agreement.

Note: we find a significant discrepancy between the FFTS noise and the noise derived in the AOS spectra, which – for its nominal resolution – reveals a too low noise level. It seems that the effective (receiving) bandwidth of the AOS has degraded as compared to the data sheets. With a receiving bandwidth of 1.55 MHz (data sheets) we expect a noise of 13.4 mK (using the formulae above), while we measure only 9.7 mK.

6.4 Upgrade to higher spectral resolution

With continuing subaqueous conditions we pursued further real-time software developments with the new WOLA core, thereby enabling an additional FFTS mode, providing higher spectral resolution:

- 500 MHz nominal bandwidth (for astronomical applications asking for high out-of-band rejection (10 dB), the usable bandwidth is ~450 MHz – Fig.10) with
- 8192 channels (frequency spacing: 61 kHz).

Following the set-up described above, we also measured the spectral response function of the channels in this mode (which, scaled to the frequency spacing, is identical to that of the 1 GHz mode):

- the 3 dB bandwidth is: 57 kHz; the equivalent noise bandwidth: 58 kHz.

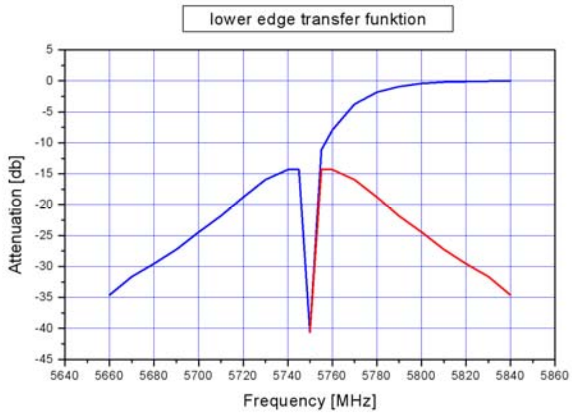

Fig.10. Transfer function of the spectrometer in the 500 MHz mode: suppression is good, the lower half of the IF band can be used up to -230 MHz or more, unless very high rejection is required (220 MHz for 20 dB). The performance of the filter at the upper band edge has not changed (Fig. 8).

7 Concerns & Actions Items

Overheating of the units is a potential operational risk. The ambient temperature in the CSO backend room is surprisingly high, both day and night. We run into temperature safety limits for the IF processor [RD-01] and, in particular, for the FFTS [RD-03] repeatedly (rather unexpectedly, because similar/identical units operate safely at the even higher APEX altitude). Additional fans were installed to lower the temperatures, but this can only be a temporary solution. R. Chamberlain took an action to re-locate major heat sources from the room like the water chiller of the AOS/IF processor.

Currently, the FFTS/IF is hooked up the CSO UPS. CSO shall establish a procedure to ensure that the units will always be and remain protected.

There is a concern about the number of switches of the relays controlling the attenuator in the IF processor. By the standard CSO calibration scheme (driven by the limited dynamic range of the AOS, adding 3dB for the hot calibration phase) we expect 100k cycles over a 5 yrs period, which is still well below the lifetime quoted by the manufacturer (1 million), but causes some worries about the actual performance of the relays (based on our experience at APEX). There are two ways to cope with this (potential) aging effect:

- optimize the calibration scheme to minimize the number of relay switches: except for - maybe - 1.3 mm observations at lowest sky temperatures, the dynamic range of the FFTS does not require adding (3 dB) attenuation in the (hot) calibration cycle. Auto-levelling “on-sky” only would bring the number of cycles into a safe regime.
- continue the calibration scheme “as is”, and be prepared to replace the relay(s) at some tbd time (costs are a few k€).

Given the dynamical range of the FFTS/IF, we recommend a modification of the CSO calibration procedure:

- for (submm)frequencies (300 GHz and beyond, where the sky contributes significantly to the system noise temperature) use autolevel “on-sky” only (the dynamic range of the FFTS/IF can handle the hot-phase counts), thereby reducing the number of relay cycles
- continue to perform the “classical” CSO calibration scheme with the 230 GHz receivers (3 dB in & out): with the excellent T_{Rx} of these receivers we may get into the dynamic range limits of the IF/FFTS system for the very best possible sky conditions. In a more sophisticated approach, the control system would monitor the TP counts (IF), and switch into the 3dB-add mode only if necessary.

App. A

The FFTS & IF units were installed on Nov.26 in the backend room of the CSO (Fig.A1), connected to the CSO UPS. Because of potential overheating of the units (see Sect.7), additional fans have been attached to the IF processor and the housing of the Acqiris board.

Fig.A1. The CSO-FFT/IF spectrometer as installed in the backend room at the CSO. The left panel shows the (from top), the Acqiris FFT board, the IF processor and the IF power supply. To the right: the FFT control computer with its flat screen.