INTERNAL REPORT

Spectroscopic observations with the SRT using the NODDING technique

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Report N. 72, released: 15/03/2018
Reviewer: V. Vacca

Osservatorio Astronomico di Cagliari

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Abstract

In radio astronomical spectral line observations a number of observing techniques are employed to remove the contribution of the Earth's atmosphere. For receiving systems that have, at least, two feeds, the technique known as nodding has shown excellent results both in terms of observational efficiency and good spectral baselines. In the following, we will report on measurements, performed on October 2016 on the water maser emission in the Galactic star-forming region W 51 using the K-band receiver with the XARCOS spectrometer, aimed at testing the implementation of the nodding mode for spectroscopic measurements at the SRT. The details of the observing strategy adopted, the data reduction and the main results are here described. The test has been successful opening the possibility to exploit soon this technique with the SRT also with the broad-band spectrometer, SARDARA.

1. Introduction

Radio astronomical measurements are affected by various systematic effects that need to be characterized and/or mitigated. One severe problem in radio observations, in particular of spectral lines, is produced by the variable emission and absorption due to the Earth's atmosphere. In order to try reducing the negative effect of the Earth's atmosphere, a number of observing techniques are employed. In particular, three main switching methods are commonly used at radio telescopes (other 'switching modes' exist but are not reported here, being either less common or not related to the topic of this report):

- Position Switching: on-source observations (ON) are interleaved with off source measurements (OFF), made by moving the telescope onto a portion of sky, thought to be devoid of emission. Usually, the OFF position will be chosen a few beam widths away from the ON position and, possibly, at the same elevation or declination as the ON, in order to minimize the difference in atmospheric conditions (typically, elevation-dependent).
- Frequency Switching: during an observation, the center frequency is alternated between two values. The ON measurement is taken at the frequency of interest while the OFF is taken at a frequency offset w.r.t. the ON frequency by a few times the expected width of the spectral line. Also in this case, the user will usually spend half of the observing time OFF and half ON frequency. When the difference in frequency between ON and OFF is smaller than about one half of the observing bandwidth, the mode is called 'in-band' frequency switching. In such a case, it is possible to increase the signal-to-noise ratio (SNR) of the observations by a factor of 2 by 'folding' the ON and OFF frequency measurements.
- Beam Switching: this mode requires a subreflector nutation (chopping) at a rate of one to several Hz, and a small movement of the telescope at a prescribed rate (typically every 30-90 seconds). In this way, two positions can actually be observed, one for which the beam position sees the source (ON) and another for which only the 'sky' (OFF) is observed. Then, it is thus possible to obtain an (ON-OFF) spectrum (for more details, please see Magnum et al. 2006).

All the three methods described above have pros and cons. In particular, the in-band frequency switching increases the on-source integration time and imply less system overheads, and is particularly suitable for more spatially-extended sources. However, it also leaves significant residual standing waves in the final spectrum. In addition, the exact frequency of the line has to be known in advance with relatively high accuracy (a condition that is not fulfilled in line searches/surveys). While the beam switching mode provides optimal (i.e. flat) spectral baselines and reduces telescope movements, it has hardware constraints, and hence, it is not available for all telescopes/receivers. In addition, this method can only be applied for sources whose angular diameter is smaller than the subreflector throw. The position-switching is indeed an excellent technique to remove the 'sky contribution', especially for relatively compact targets but it has the dramatic drawback of entailing significant telescope movements, with corresponding large slewing time. Indeed, more than half of the total observing time is not spent on-source.

In this framework, for receiving systems that have two or more beams (or, better, feeds), the nodding technique can be used. Nodding is nothing more than a form of position switching done via commands provided through the observing schedule without, however, the need to cyclically move the telescope and integrate on the ON and OFF position, respectively. Indeed, for dual or multi beam systems there are always two beams, e.g., A and B, on the sky. When A is on source, B is off source (on blank sky), thus providing a simultaneous ON and OFF measurement. Then, for calibration reason (see Sect. 5), the telescope is moved so that B is on source and A is on blank sky for an equal time. By producing, for each beam (see also Sect. 4), the two (ON-OFF/OFF) spectra and then averaging them, we obtain a final spectra with an on-source integration time, almost (minimal overheads in the observing cycle are naturally present) equal to the total observing time, hence with no lost time while performing the off-source observations and very little slewing time.

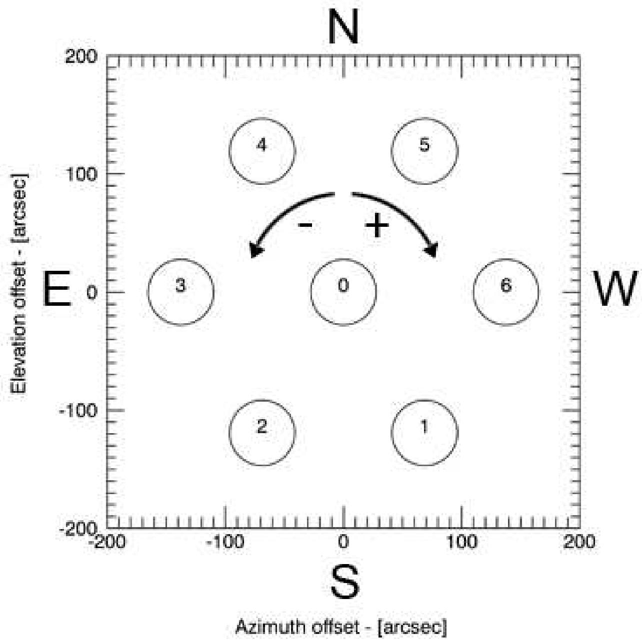

Figure 1: Scheme of the feeds locations of the SRT 7-feed K-band receiver, when the dewar angle is set to 0° (from http://discos.readthedocs.io/en/latest/user/srt/source/Derotator.html).

2. Spectroscopy at the SRT

Thorough descriptions of the Sardinia Radio Telescope (SRT) project and its receivers and backends suites are already reported in a number of papers and technical reports (e.g., Bolli et al. 2015, Prandoni et al. 2017, and references therein), and hence, they will not be repeated here. In the following, we will only provide the basic information relevant for the topic of this report.

Spectroscopic measurements at the SRT can now be routinely performed, using different techniques (e.g. positions, switching, on-the-fly, etc...), with the three first-light receivers, the 7-feed K-band (18-26.5 GHz), the single-feed C-band (5.7-7.7 GHz) and the coaxial dual-feed L and P band (1.3-1.8 GHz and 0.305-0.41 GHz, respectively).

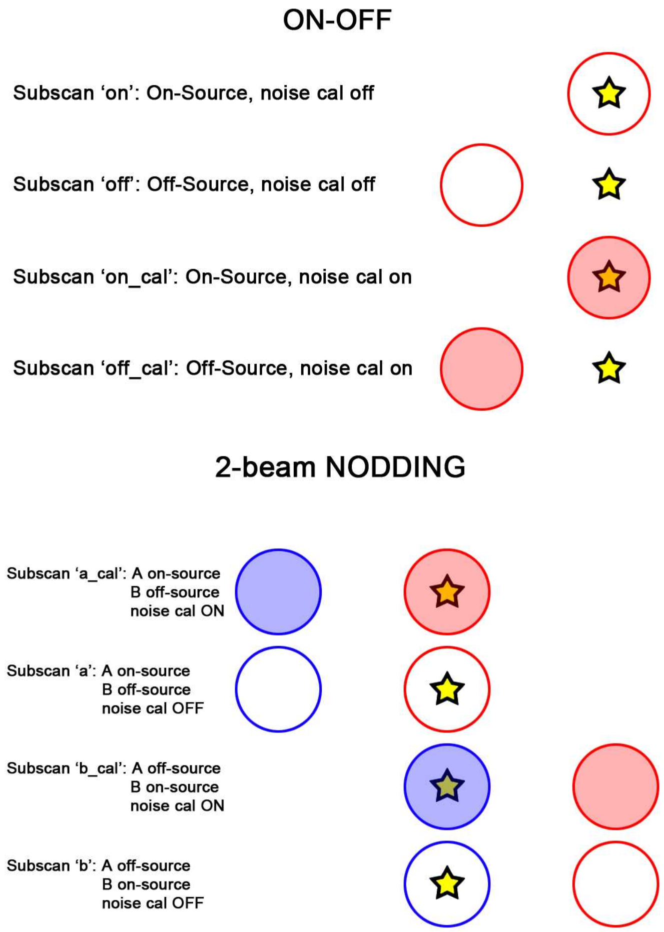

Figure 2: *Upper panel* Scheme of a standard cycle of position switching (ON-OFF) acquisition with the use of the calibration mark (two last rows). *Lower panel* Scheme of a standard cycle of 2-beam NODDING acquisition with the use of the calibration mark (first and third rows). Taken from Bartolini & Righini (2016).

The C and K band receivers can be used, for spectroscopic observations in position switching mode with either the narrow-band digital spectrometer, XARCOS (Melis et al. 2015), or the broad-band ROACH 2-based digital backend, SARDARA (Melis et al. submitted), while L/P band observations can only be performed using the latter backend. Presently, XARCOS is the only backend that provides 7-feed information making it, so far, the most suitable spectrometer for multi-feed K-band observations (a development of SARDARA is in rapid progress aimed at upgrading the system toward multi-feed capabilities).

So far, however, the nodding mode for spectroscopic observations was never operated at the SRT, despite the presence of a multi-feed K-band receiver. Hence, in the following, we report the first spectroscopic observational test performed at the SRT using the Nodding mode at K band with XARCOS.

3. Observations and Data reduction

Test observations with the SRT were performed in October 3, 2016. We observed the water maser emission in the well-known star forming region W 51. We used the feed labeled as 0 (the central one) and 3 that are properly (see Sect. 1 for the reason) at the same elevation. A second possible option is offered from the system, that of using the feed pair 0 and 6, also at the same elevation (see Fig. 1 for a scheme of the feeds locations). The observational scheme is illustrated in Fig. 2 (lower panel) where only Subscan ’a’ and ’b’ (second and fourth rows) are considered here, since the calibration mark was not used for the flux calibration. For comparison, in Fig 2 (upper panel) a standard position

Table 1: Details of the Observations

Target	Date	Obs. Freq. [GHz]	Backend	Config.	Obs. Time [s]	Spectrum Noise [mJy/bm/chan]	Flux Cal.
W 51	2016-10-3	22.2	XArcos	XK03	120	150	3C286

switching measurements is also displayed.

The nodding scheme implies a two-step cycle: a) the FEED A (feed 0) is ON-source, FEED B (feed 3) is OFF-source (Fig. 3, top-left and top-right panels); b) the situation is reversed, with FEED B pointing to the source, while FEED A is on the 'empty' sky (Fig. 3; bottom-left and bottom-right panels). The Target observations were interleaved, with the same setup, by measurements of the source 3C 286, used for flux calibration purposes. The integration time was of 1 minute per step.

XARCOS was configured using the 'XK03' mode, that provides two bands of 62.5 and 3.9 MHz, split into 2048 channels, yielding a channel spacing of 30.5 and 1.9 kHz, respectively, and full polarization information. For the sake of conciseness, only results for the broader band will be reported and discussed in the following but the positive outcome and main details also apply to the narrower band measurements.

The data were converted into GILDAS format using the converter developed by A. Trois (Trois et al., in prep) and reduced using CLASS (part of the GILDAS package). 'ON-OFF/OFF' spectra were created using the method described in Sect. 5 in order to remove the contribution from the sky and significantly reduce the ripples present in the baselines, and clearly visible in Fig. 3. The flux density scale was calibrated (from counts to Jy) by estimating the average value of counts of the continuum in the (on-off)/off spectrum of the well-known calibrator 3C 286 and considering its flux density (2.53 Jy) at the observed frequency (22.2 GHz), computed by using the coefficients determined by Perley and Butler (2017). The spectra were averaged together (both polarizations and both feeds) to increase the SNR.

The main details of the observations are summarized in Table 1.

4. Results

Figure 4 shows the final spectrum of the water maser in W 51 obtained with the SRT using the nodding technique. The final noise in the spectrum is of ~ 150 mJy/chan, higher than the expected theoretical noise (~ 100 mJy/chan) due to the non optimal atmospheric conditions at which the K-band test was conducted ($\tau_{22GHz} \sim 0.12$). However, it is evident that the quality of the baseline in the spectrum is optimal and all the main features, known to be present, are confidently detected with SNR between 10 (weakest feature) and 10000 (emission peak). Accounting for the known high variability of the water maser emission, the flux density of the main features is consistent with those reported in literature (e.g., Comoretto et al. 1990).

5. The choice of the feeds for the nodding technique.

As explained in Sect. 1, the choice of using two feeds at the same elevation when performing the nodding is due to the larger difference in atmospheric conditions between two locations at different elevation than that at different azimuth. Indeed, the (two) setups made available for the nodding mode at the SRT exploit feeds at the same elevation (when the derotator is in 'park position', at 0 degrees rotation and fixed). However, another important issue concerning the feeds, is the way we couple the ON and OFF position from the two steps in the nodding cycle. Fig. 5 shows what happens if the ON-OFF subtraction is done using two different feeds. In particular, if the ON spectrum is taken from the feed 0 and the OFF one comes from the feed 3 (and viceversa), the final ON-OFF/OFF spectrum presents still quite dramatic residual ripples (Fig. 5, top-left and bottom-left panels). This is due to the different response of the feeds to the incoming signal (either sky or sky+source). Differently, if one uses ON and OFF positions from the same feed the final spectrum has evident flatter baselines (Fig. 5, top-right and bottom-right panels). Hence, a reasonable way to proceed is to produce the ON-OFF/OFF spectrum for the feed 0 and that for the feed 3, and then averaging the two to obtain a more sensitive spectrum[1] Noticeably, the final integration time on-source is still the double w.r.t. to a position switching observations, thus significantly minimizing all overheads.

[1] If the duty cycle between the two steps a) and b) (see Sect. 3) is relatively fast (in our case the integration time was of one minute for each step), the difference in the atmospheric conditions is less significant than the difference in the response of the two feeds (see, e.g., O'Neil 2002; Nasir et al. 2013).

6. Final remarks and Expected Follow-ups

The present work testifies the possibility to successfully lead spectroscopic observations using the nodding technique at the SRT, taking profit of its multi-feed K-band receiver. At the time of writing this report, XARCOS is the only backend that has multi-feed capabilities for this kind of observational mode. However, given that the main bases toward the use of nodding (i.e., the scheduling creation, the data conversion and data reduction procedures), have been successfully set, there is no evident obstacle toward the extension of this observing mode also at the wide-band backend, SARDARA, when its extension to multi-feed (or, at least, two-feed) capabilities will be completed (as mentioned before, this effort is already in an advanced stage).

In addition, the nodding mode is clearly a relevant possibility for the 32-m Medicina antenna, that is equipped with a dual feed K-band receiver. Indeed, exploiting the advantages, in terms of observing efficiency, offered by this mode will make this antenna even more attractive, among other goals, for (sensitive) spectral line measurements, like emission/absorption line searches and monitoring, in compact/point-like targets, for which the nodding is particularly suitable.

Acronyms

ON	On-source
OFF	Off-source
SARDARA	SArdinia Roach2-based Digital Architecture for Radio Astronomy
SNR	Signal-to-Noise Ratio
SRT	Sardinia Radio Telescope
XARCOS	X ARcetri COrrelation Spectrometer

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Acknowledgments

We would like to thank J. Braatz for inspiring suggestions on the nodding data processing. We are also indebted with F. Buffa for sharing information on weather parameters at the SRT site during the observations, and with A. Navarrini for useful discussions.

Appendix A

In the following, we give an example of the two configuration files necessary to produce a schedule (using the 'schedule creator' Basie, version 0.6.4; Bartolini & Righini 2016), to perform the Nodding observations with the SRT similar to those described and discussed in this report.

- The **configuration file** ('configuration_NOD_test_XK03.txt'):

```
projectID = nod
observer = AT
```

```
scheduleLabel = W51

# SRT, MED or NOTO
radiotelescope = SRT
# for Medicina receivers can be:
# C, CL, X, K
# for SRT receivers can be:
# P, L, C, K, KM
receiver = KM
# default repetitions value for each scan
repetitions = 1
# default tsys value for each scan
tsys = -1
#optional restFrequency in Mhz, can be a list
restFrequency = 22235.08
#restFrequency = 22000
#restFrequency = 21587
ftrack = True

# File name of the target specs in this same directory
targetsFile = targets_NOD_test_XK03.txt

[backends]
# Here we configure which backend we are using in this schedule.

[[XK03]]
    type = XARCOS
    # one of XK77 XK03 XK06 XK00 XC00
    configuration = XK03

[scantypes]

    #NODDINGNAME = NODDING FEED_A FEED_B DURATION [4a,4b,4a_cal]
    Nodding03 = NODDING 0 3 60.0 [1a,1b,1a_cal,1b_cal]
```

- The **targets file** ('targets_NOD_test_XK03.txt')

```
# Comment lines to exclude them from the schedule computation
#
# Mandatory params:
# LABEL SCANTYPE BACKEND TARGET_FRAME LONGITUDE LATITUDE
# where:
# SCANTYPE is defined in configuration file
# BACKEND is defined in configuration file
# TARGET_FRAME = [EQ, GAL, HOR]
#
# Optional params:
# [tsys, repetitions, offset_lon, offset_lat, offset_frame, vref, vdef,
# rvel]
# where:
# vref = [BARY, LSRK, LSRD, GALCEN, TOPCEN]
# vdef = [OP, RD, Z]

W51    Nodding03 XK03 EQ  19:23:42.0h +14:30:33 vref=BARY vdef=OP rvel=7.6
```

In the next lines, we also give an example of the outputs produced by the 'schedule creator' Basie (version 0.6.4; Bartolini & Righini 2016), i.e., the four files of the schedule. The observations refer to a simple a,b,a_cal,b_cal cycle (see Sect. 3 for details) in Nodding mode on W51. In red, we point out those points that will be changed in the new version of Basie. In particular, the 'initialize' command will be likely removed from by .bck file in order to not repeat this unnecessary initialization (that can be done once before lunching the schedule) at every cycle. In addition, more important, in our .lis file, the sign of the offset (in red) for moving the lateral feed (feed 3) on-source, was edited by hand and changed from negative to positive. In the next Basie release, the sign of the offset (in HOROFFS) for the lateral feed 3 employed for nodding measurements, as appears in the .lis file, will be corrected (the same also for the other lateral feed, feed 6, that, is presently associated to a positive HOROFFS offset, while it should be a negative one).

Command typed:

> schedulecreator -c configuration_NOD_test_XK03.txt .
Files produced:

- The **schedule file** ('W51.scd')

```
# Generated with basie version 0.6.4
# compatible nuraghe version: nuraghe-0.6
# compatible escs version: escs-0.6
PROJECT: nod
OBSERVER: AT
SCANLIST: W51.lis
PROCEDURELIST: W51.cfg
BACKENDLIST: W51.bck
MODE: SEQ
SCANTAG: 1
INITPROC: PROC_INIT_RESTFREQUENCY

SC: 1 W51 XK03:MANAGEMENT/FitsZilla
1_1 60.000000 1 PROC_FTRACKLO_DEROTATORFIXED PROC_NULL
1_2 60.000000 3 PROC_NULL PROC_NULL
1_3 60.000000 5 PROC_CALON PROC_CALOFF
1_4 60.000000 7 PROC_CALON PROC_CALOFF
```

- The **backend configuration file** ('W51.bck')

```
XK03:BACKENDS/XBackends{
initialize=XK03
}
```

- The **scan file** ('W51.lis')

```
#W51
1 SIDEREAL W51 EQ 19:23:42.0000h 14:30:33.0000 j2000 -HOROFFS 0.0000d 0.0000d -RVEL 7.600000
BARY OP
3 SIDEREAL W51 EQ 19:23:42.0000h 14:30:33.0000 j2000 -HOROFFS 0.0382d 0.0000d -RVEL 7.600000
BARY OP
5 SIDEREAL W51 EQ 19:23:42.0000h 14:30:33.0000 j2000 -HOROFFS 0.0000d 0.0000d -RVEL 7.600000
BARY OP
7 SIDEREAL W51 EQ 19:23:42.0000h 14:30:33.0000 j2000 -HOROFFS 0.0382d 0.0000d -RVEL 7.600000
BARY OP
```

- The **configuration file** ('W51.cfg')

```
PROC_NULL{
}
PROC_INIT_RESTFREQUENCY{
nop
restFrequency=22235.08
}
PROC_CALOFF{
calOff
}
PROC_CALON{
calOn
}
PROC_FTRACKLO_DEROTATORFIXED{
fTrack=LO
derotatorSetPosition=0d
derotatorSetConfiguration=FIXED
}
```

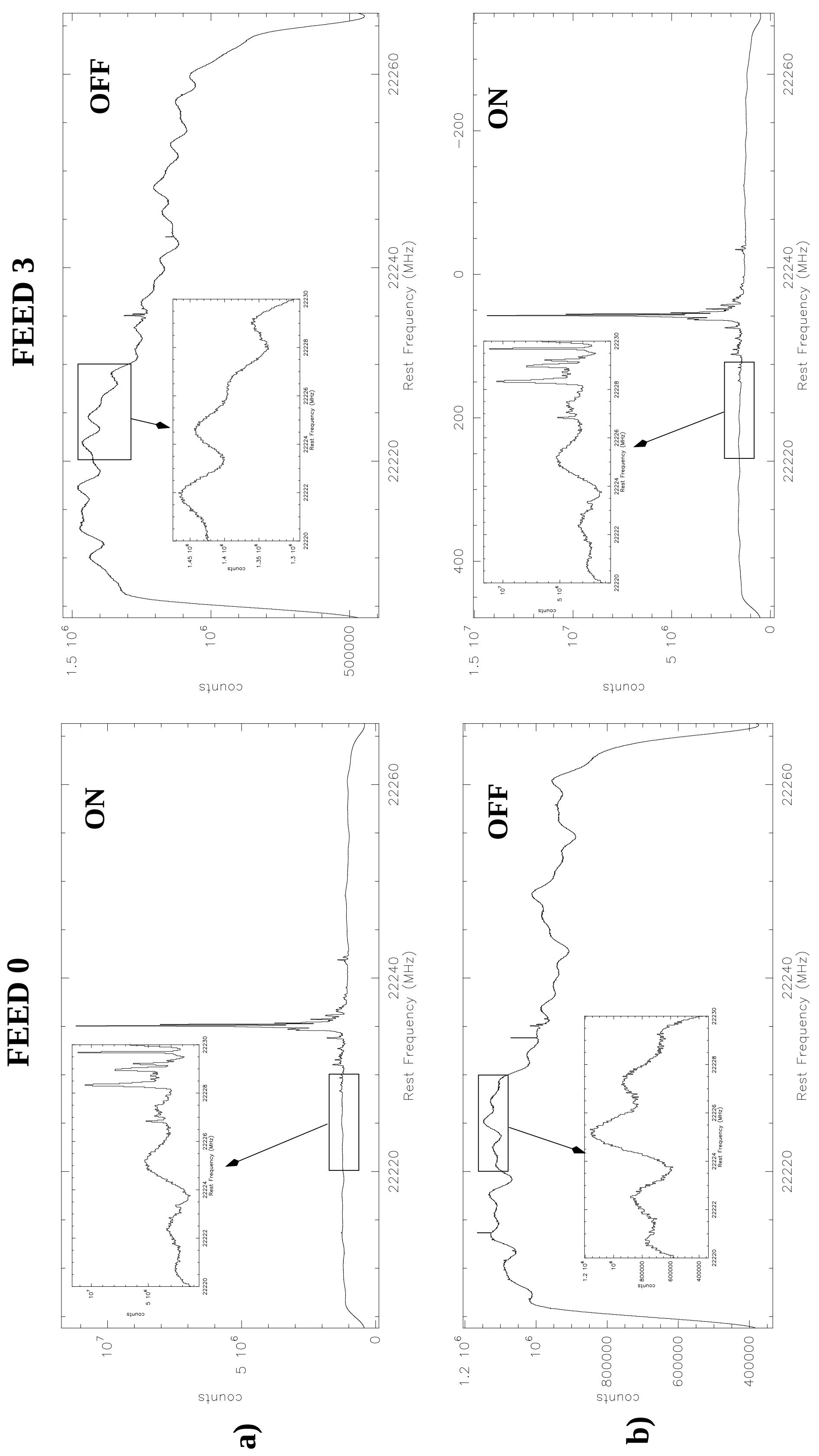

Figure 3: The nodding scheme used for the test described in the report: a) ON and OFF positions taken with the feeds 0 and 3, respectively; b) the situation is reversed, and ON and OFF positions are now taken with the feeds 3 and 0, respectively.

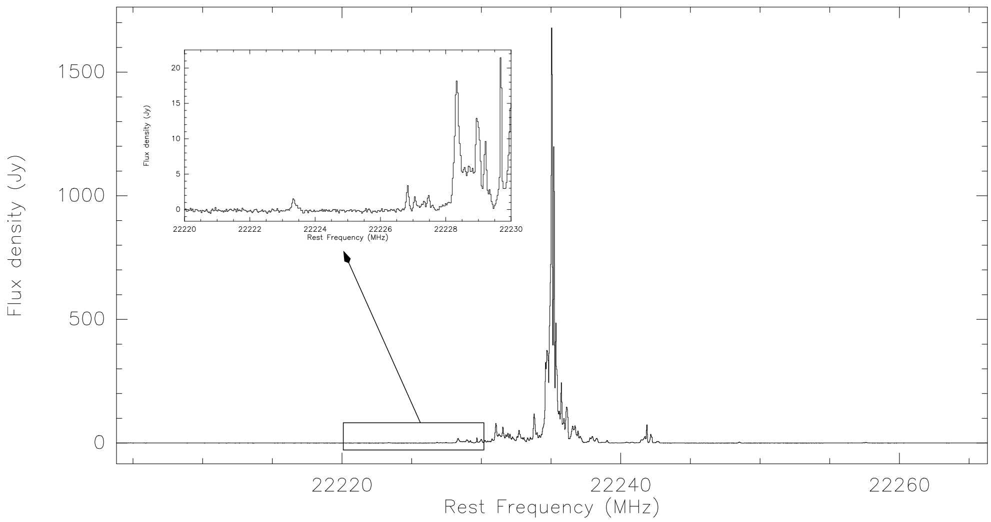

Figure 4: K-band water maser spectrum of W 51 obtained with the SRT using the NODDING mode. The spectrum is the average of the two spectra obtained with the two feeds, and both polarization. The inset clearly shows the quality of the baseline.

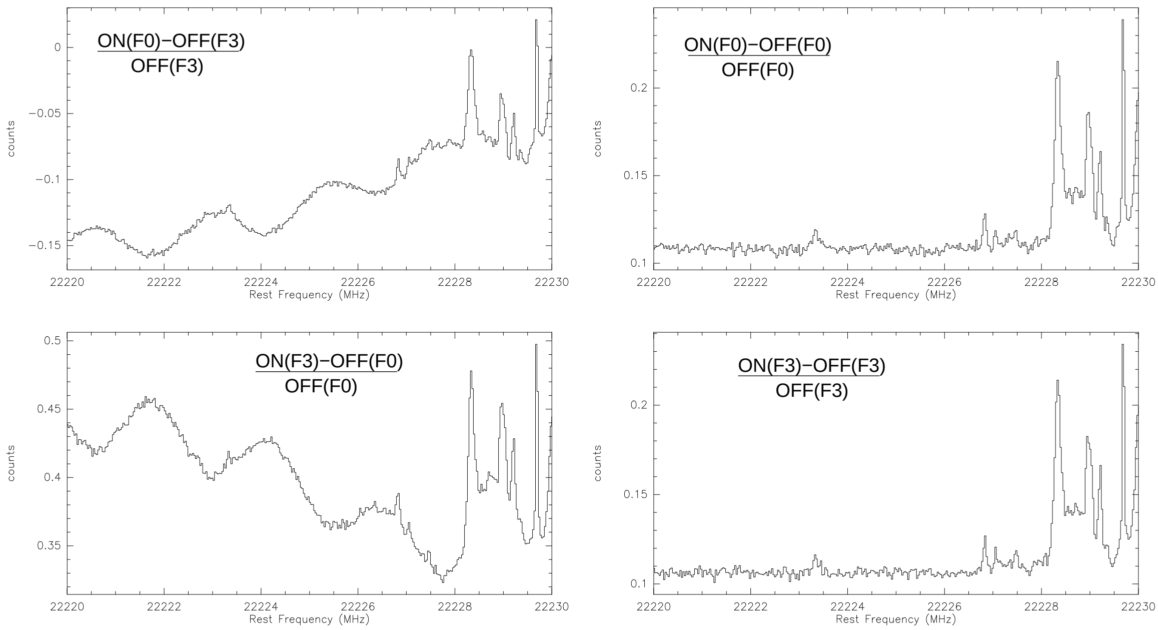

Figure 5: Zoom-in of the ON-OFF/OFF (uncalibrated) spectra obtained by using the ON and OFF from different beams (upper-left and lower-left panels) and from the same beam (top-right and bottom-right panels). The different quality of the baselines is evident.