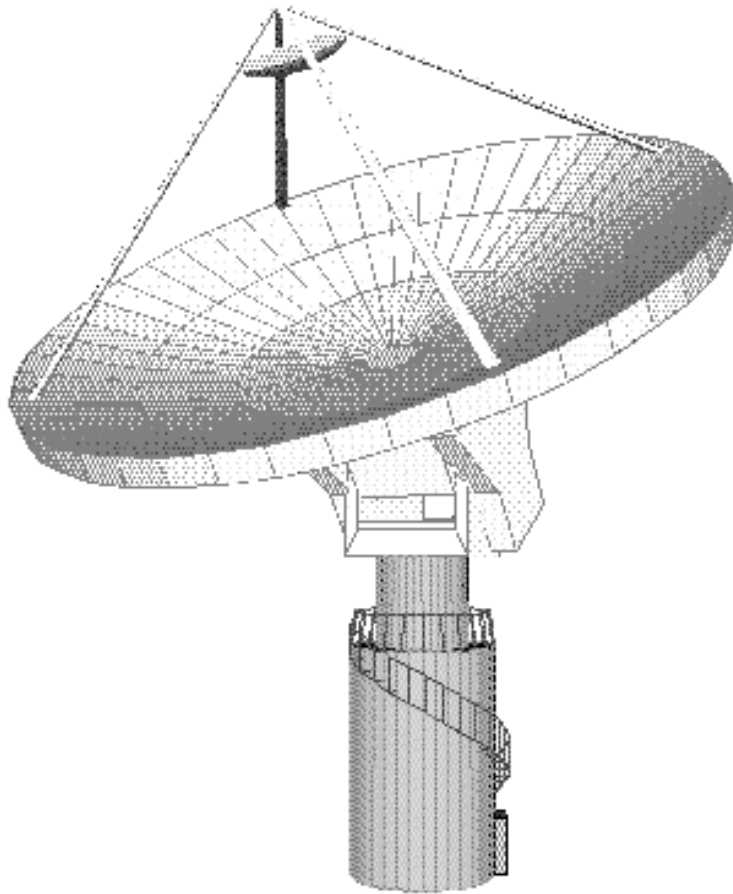


# OSO 20 M TELESCOPE HANDBOOK



**Onsala Space Observatory  
August 31, 2016**

The latest version of this handbook can be found [here](#).

Original version by Lars E.B. Johansson.

Latest revisions by A.O.H.Olofsson and E. De Beck.

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# CHAPTER 1

## INTRODUCTION

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This manual gives a description of the observing system for the 20 m telescope at the Onsala Space Observatory (OSO) and is supposed to be used as a guide for planning and conducting an observing run. Additional information about the telescope, system parameters and OSO in general can be found on our web page:

[www.chalmers.se/en/centres/oso/radio-astronomy/20m/Pages/Description.aspx](http://www.chalmers.se/en/centres/oso/radio-astronomy/20m/Pages/Description.aspx)

The OSO 20 m telescope is a mm- and cm-wave antenna for astronomical and geodetic research. It is enclosed by a radome which was renewed in the summer of 2014. The telescope is located at sea level some 50 km south of Göteborg, at

LATITUDE	57°23'45.0046" N
LONGITUDE	11°55'34.8719" E
ELEVATION	22.758 meter

The telescope is both used as a single-dish instrument and as a part of global VLBI (Very-long-baseline interferometry) networks. It is operated by the Swedish National Facility for Radio Astronomy, Onsala Space Observatory at Chalmers University of Technology.

We warn the reader that, although considerable effort has been made to update the content of this manual, there may be occasional *legacy numbers* left. However, any discrepancy between historical and actual numbers should not exceed  $\sim 10\%$ .

### 1 Quick system overview

The receivers (Chapter 2, Sect. 2) available at present – summer 2016 – are

- an SIS-mixer for the range 85–116 GHz ("3mm"; Chapter 2, Sect. 2.1),
- a HEMT amplifier for the range 67–87 GHz ("4mm"; Chapter 2, Sect. 2.2),
- three HEMT amplifiers in the range 18–50 GHz,
- and two HEMT amplifiers used for S- and X-band VLBI observations.

The backend instrumentation (Chapter 2, Sect. 3) includes

- a Fast Fourier Transform spectrometer (FFTS) for resolutions of 12 and 61 kHz at 100 and 1000 MHz bandwidths, respectively, and
- a new FFTS, with a maximum  $2 \times 4$  GHz bandwidth at 76 kHz resolution, or  $2 \times 156$  MHz at 4.8 kHz resolution. This system will soon be upgraded to cover 4, instead of 2, backend windows.

All spectrometers can be run simultaneously. Keep in mind that they will all be centred at the same frequency. A higher-resolution ( $<1$  kHz) spectrometer can possibly be made available upon request. Technical discussion with staff is needed for this.

The main component of the control system is a Linux PC running a graphical user interface (GUI) programme, PEGASUS, which runs the telescope, the subreflector, receiver tunings and the spectrometers (aided by various peripheral computers and control units). PEGASUS was originally developed at the Canada France Hawaii Telescope (CFHT) and modified at OSO for radio astronomical observations. PEGASUS is very easy to operate and allows the observer to send essentially *all* observing commands from GUI control windows via mouse clicks. These windows are presented and discussed in this manual. The data obtained are saved in single-dish FITS format and various programmes, e.g. XS and CLASS, are available to reduce and analyse them.

## 2 Observing

The year is divided into two observing semesters: April 1 – September 30 and October 1 – March 31. Deadlines for proposal submission are usually October 15 and April 15, but can be subject to changes. The exact dates will be released with the *Call for proposals*. Proposal submission is handled by the NorthStar system, which is available [here](#).

The observing systems at OSO are designed to be user-friendly and fail-safe, allowing observers to set up and perform their own observations after a short introduction on-site. The visiting observers are advised to arrive one day early, to prepare for the observing run. The support astronomer (SA) will assign a computer account to the observer and help them prepare and set up the observing run. The SA will also be available to discuss the best way to perform the proposed observations. When the observations commence, the SA will introduce the visitor to the observing procedures and explain e.g. the receiver tuning.



### 3 Staff

The team supporting single-dish observations consists of:

Chief telescope scientist	<a href="#">A. O. Henrik Olofsson</a>
Telescope scientist	<a href="#">Per Bergman</a> , <a href="#">Michael Olberg</a>
Astronomer-on-duty (AoD) / support astronomer	<a href="#">Per Bergman</a> , <a href="#">Roger Hammargren</a> , <a href="#">Michael Olberg</a> , <a href="#">A. O. Henrik Olofsson</a> , <a href="#">Javier Rodón</a>
Hardware engineer	<a href="#">Leif Helldner</a>
Software engineer	<a href="#">Mikael Lerner</a>
Logistics responsible	<a href="#">Paula Rosell</a>

The engineers and logistics responsible are available Monday to Friday during office hours. Click on any of the above names to contact these people through email.

### 4 Communication

Questions and remarks about technical matters or scheduling should be addressed to the telescope scientists. For reservations of rooms at OSO please contact Paula Rosell ([Paula.Rosell\[at\]chalmers.se](mailto:Paula.Rosell@chalmers.se)). General information about accommodation and travel to OSO can be found on our web page under the header [Contact > Visitor Information](#). Maps of the area, including the observatory grounds, are available through e.g. [Contact > Visitor Information > Maps](#).

A number of computers are available to the observers and, upon request, laptops can be connected and assigned guest accounts. Note that any wireless radio-frequency connections (e. g. from mobile phones and bluetooth devices) are not allowed and must be turned off while inside the observatory grounds.

# CHAPTER 2

## TECHNICAL DESCRIPTION

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### 1 The telescope

The 20 m telescope was designed and built by Electronic Space Systems Corporation (ESSCO) in 1975. It is enclosed by a radome, which was fully upgraded in the summer of 2014. This radome protection leads to the absence of any observational restrictions concerning sun-avoidance or wind speeds. The presence of the radome causes some losses owing to imperfect transmission and reflections. Optimal conditions are achieved around 95 GHz, with total losses of only 5%.

The telescope is an elevation-azimuth mounted Cassegrain antenna. The subreflector tilt and position are computer controlled to compensate for the gravitational deformation of the main reflector. Pointing and focus observations are easily performed to add corrections to existing model fits. These pointing and subreflector position models are updated on a regular basis.

The main telescope parameters, such as beamwidths and efficiencies, are given in Table 2.1. Figures 2.1 and 2.2 show the main beam efficiencies and receiver temperatures of two of the receivers.

### 2 Receivers / frontends

The 3 mm and 4 mm bands are part of a new receiver installed and commissioned at the OSO 20 m telescope in 2014 and 2015. The two bands share the same optical layout and work at a physical temperature of 4 K, with receiver temperatures of about 50 K. The local oscillator (LO) system is based on a Gunn oscillator with a phase lock loop (PLL) and four mechanical tuners for broadband operation, providing independently tunable LO power for each polarisation. Detailed information on the receiver and the commissioning of the 3 mm band can be found in Belitsky et al. 2015, *Astronomy & Astrophysics* 580, A29, available [here](#). An in-depth paper on the details of the 4 mm band is forthcoming.

TABLE 2.1 – Main 20 m telescope parameters.

Longitude	11° 55' 35" (E)	
Latitude	57° 23' 45" (N)	
Altitude	22.758 m	
Diameter	20.1 m	
Surface accuracy (rms)	140–220 $\mu\text{m}$	(elevation dependent)
Pointing accuracy	3" rms in Az and El	
Half power beamwidth (FWHM):		
22 GHz	157"	
43 GHz	88"	
86 GHz	43"	
115 GHz	33"	
Main beam efficiencies <sup>1</sup>		
22 GHz	0.61	(at 40° elevation)
43 GHz	0.56	(at 31° elevation)
86 GHz	0.53	(at 54° elevation)
110 GHz	0.36	(at 47° elevation)
Aperture efficiency		
22 GHz	0.55 (16 Jy/K)	
86 GHz	0.40 (22 Jy/K) <sup>2</sup>	

<sup>1</sup> Sample measured values from planetary observations (mainly on Jupiter). The efficiencies should be accurate to within 10% for similar elevations. The main beam efficiency applicable to your observations is dependent on frequency and elevation and is listed in the FITS headers of the individual data sets.

<sup>2</sup> At elevation 50°. This applies at both 3 mm and 4 mm.

## 2.1 3 mm: 85 – 116 GHz

The 3 mm band employs sideband separating (2SB) SIS mixers with a separation of 12 GHz between the centres of the LSB and USB. Currently, each sideband in effect has an IF bandwidth 4 GHz (IF at 4 – 8 GHz), although the 2SB mixers are able to provide 4 – 12 GHz. There are four IF outputs, from the dual polarisation in combination with the two sidebands. A planned upgrade will allow one to record both polarisations in both sidebands at 2.5 GHz bandwidth in each sideband. Currently, this is limited to 4 GHz in both polarisations in one sideband, or 4 GHz in both sidebands in one polarisation. The sideband rejection ratio is typically  $\sim 15$  dB or better. The baseline was shown to be extremely stable, even under poorer weather conditions.

The 3 mm band was installed in the spring of 2014, received some upgrades during the summer of 2014, and was fully commissioned by the end of 2014. Under good weather conditions a system temperature of approximately 100 K can be achieved. Example spectra from the early commissioning observations and an overview of the observed SV projects can be found [on our web pages](#). Again, more in-depth technical information on this receiver band is found in Belitsky et al. 2015, *Astronomy & Astrophysics* 580, A29, available [here](#).

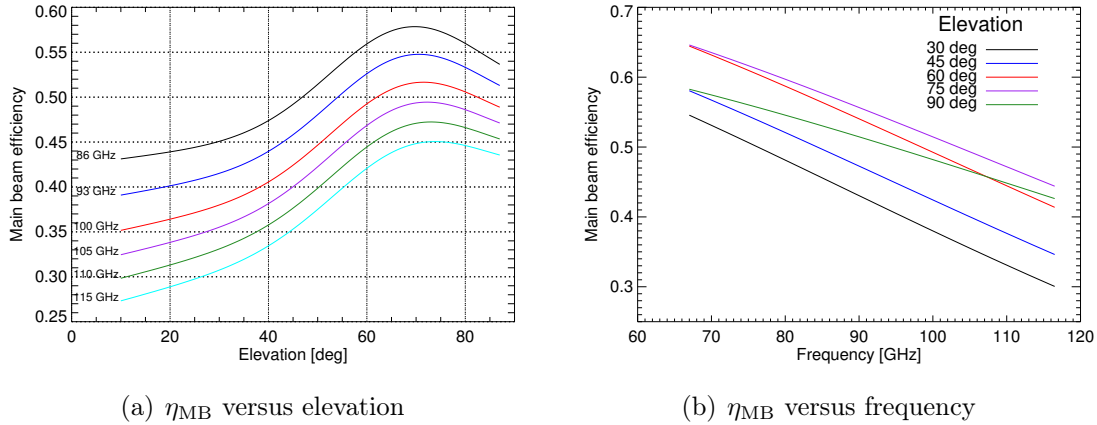


FIGURE 2.1 – Main beam efficiencies  $\eta_{MB}$  at 3/4 mm depend on both frequency and elevation.

## 2.2 4 mm: 67–87 GHz

The HEMT amplifier receiver operational at 67–87 GHz ("the 4 mm receiver") is a dual polarisation sideband separating (2SB) receiver with a separation of 12 GHz between the centres of the upper sideband (USB) and the lower sideband (LSB). Each sideband has an IF bandwidth of 4 GHz. Analogous to the 3 mm band, there are 4 IF outputs, from the dual polarisation in combination with the two sidebands. With upgraded backend capabilities, one will be able to record both polarisations in both sidebands at 2.5 GHz bandwidth in each sideband. Currently, this is limited to 4 GHz in both polarisations in one sideband, or 4 GHz in both sidebands in one polarisation. The sideband rejection ratio is typically 15 dB or better.

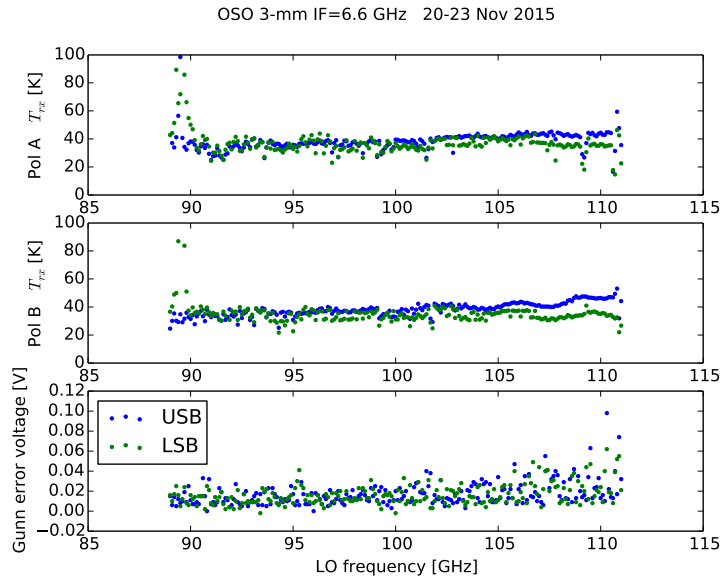
This receiver was installed at the telescope in October 2015. Science verification (SV) observations were performed during the first months of 2016. Example spectra from the early commissioning observations and an overview of the observed SV projects can be found [on our web pages](#).

## 2.3 100 GHz receiver

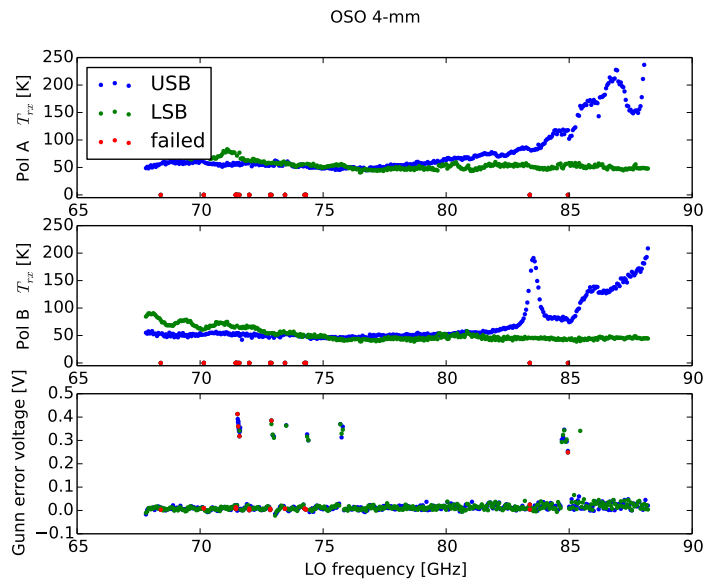
**NB:** The text below describes the Onsala 3 mm receiver which was available up until March 2014. The new 3 mm receiver has been available since mid-2014 and is described above, in Sect. 2.1.

The old 3 mm receiver was based on a cryogenically cooled SIS sideband separating mixer. It consisted of two complementary SIS mixers wherein the output from each one is used to suppress the image band of the other. For stability reasons, only one of the sidebands was retrieved at a time, so it effectively worked like a normal single-sideband (SSB) receiver.

The system covered the range 84–116 GHz, with a typical SSB receiver temperature of 100 K (see Fig. 2.3 for the frequency dependence). The IF bandwidth was 1.2 GHz and the image sideband suppression generally in the range 10–20 dB. At certain frequencies, this rejection may have been worse but that could often be overcome by using another LO frequency and/or manually switching sideband.



(a) 3 mm



(b) 4 mm

FIGURE 2.2 – Receiver temperatures at 3/4 mm versus LO frequency.

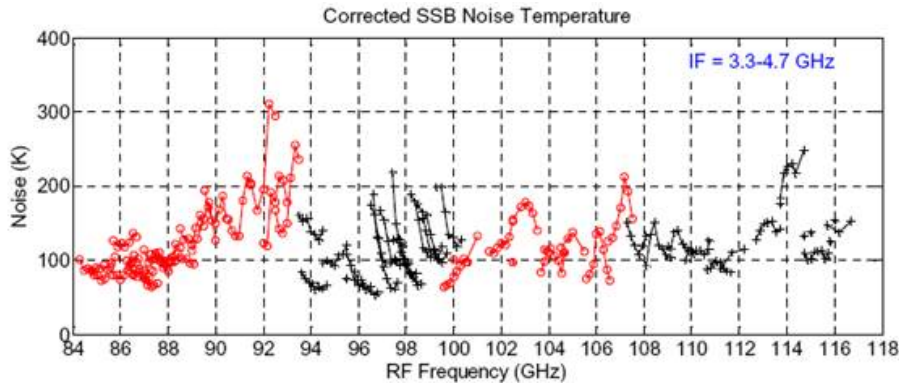


FIGURE 2.3 – Receiver temperatures for the old 100 GHz receiver. Since March 2014, this receiver is no longer in use.

The mixer voltage and current biases were tuned remotely under computer control but could be optimised manually within the GUI. A test signal could be injected at the signal frequency to verify a correct tuning. The LO phase-lock and attenuation procedures were highly automated and normally done by simply clicking two buttons.

### 3 Spectrometers / backends

Two fast Fourier transform spectrometers (FFTS) are available for observations: SPE (1 GHz max. width) and OSA (4 GHz max. width). Table 2.2 gives an overview. A higher-resolution ( $<1$  kHz) spectrometer can possibly be made available after technical discussion with observatory staff.

It should be noted that the sensitivity of continuum observations is low and such observations are basically only done to determine beam efficiencies and pointing corrections. The maximum bandwidth is 1280 MHz (corresponding to a velocity coverage of  $3300 \text{ km s}^{-1}$  at 115 GHz). The highest spectral resolution available is 30 Hz. However, the latter (available only when using the HRC) has limited availability at present and can only be used upon special request. On a regular basis the highest resolution is 12.2 kHz with the FFTS (bandwidth 100 MHz). All spectrometers can be used simultaneously but they cannot be offset within the IF bandpass; they are always centred at the tuned frequency.

Dual-polarisation observations are available for the HEMT receivers covering 18–26 and 36–50 GHz. The RCC is then used with a configuration that only returns half the number of channels per spectrum for each bandwidth mode, i.e., the spectral channel separation is doubled. The SPE (FFTS) retains its high-resolution options but the maximum bandwidth is reduced from 1 GHz to 500 MHz.

A sampling window function can be applied to the FFTS to reduce the effects of unstable conditions, e.g. power fluctuations caused by radio-frequency interference (RFI). Such conditions are typically manifested in FFTS spectra by a multitude of spikes across the bandpass. Normally, the window function is not used (or rather it is set to a rectangular profile) because it has some drawbacks (discussed more in Sect. 2.2.15 in Chapter 5).

TABLE 2.2 – Spectrometer characteristics.

	Total band- width (MHz)	Number of channels	Resolution (kHz)
<b>FFTS</b>			
SPE	1000 / 500 / 100	16384/8192/8192	61.0 / 61.0 / 12.2
OSA	4000*	52429	76.294
	2500 / 625 / 156.25	32768 / 32768 / 32768	76.294 / 19.073 / 4.7684

\* 4 GHz backend width is achieved by combining two backends of 2.5 GHz with 1 GHz of central overlap.

## 4 Telescope and instrument control system

The telescope, its receivers, and other instrumentation are controlled by a Linux PC, `munin`, which uses a graphical user interface called `PEGASUS`. In general, the system allows access to a single user only, although a multiple user environment is possible if required. Under certain circumstances, remote observations using a VNC interface are allowed. All data are stored on a main disk and can easily be accessed by a second workstation, `brune`, used for data reduction and dedicated to the on-going project. The data may be dumped at any time by the observer to an external storage medium, such as DVD or USB stick.

The antenna and subreflector tracking – corrected according to the latest pointing and subreflector position models – are run by `jupiter`, a separate computer located in the telescope cabin. All relevant information from the control software (ACAPS) about source coordinates, current sky pointing etc. is displayed in a special terminal window on `munin`. The correlator is run by a CPU-board, `mars`, which also has a dedicated terminal window on the `munin` display. Most other functions are controlled by (or from) `munin/PEGASUS` directly. Weather data, used to calculate the atmospheric refraction and for data intensity scale calibration, is distributed via the observatory network to `munin` from a weather station located at the site.

The time information that controls the antenna tracking comes from an internal clock in ACAPS synchronised to the local hydrogen maser standard. The real-time time deviation is also shown in a small window on the `munin` display.

Coarse receiver tuning is done automatically through servo units according to predefined look-up tables. These units include the mechanical tuning of the Gunn diode that generates the LO output. Phase-locking and fine-tuning (if needed) of the Gunn diode are then done using the GUI in `PEGASUS`.

All of the above is described in more detail in the following chapters.

# CHAPTER 3

## SPECTRAL-LINE OBSERVATIONS

---

### 1 Observing modes

A common feature of all spectral line observations is that the final spectrum is a difference of data containing the useful signal and some reference spectrum. The reason is that the raw power spectrum suffers from a rather non-linear frequency dependence with amplitudes that effectively hide weak signals. Such variations should disappear when the reference spectrum is subtracted from the signal spectrum, provided that the switching between the two phases is faster than atmospheric fluctuations or receiver instabilities.

The OSO system provides three observing modes: beam switching, position switching, and frequency switching. The choice depends basically on source size and baseline requirements and is in general a compromise. If equal amounts of time are spent on the on- and off-positions, the noise penalty for the switching scheme is a factor of  $\sqrt{2}$  in the radiometer formula, which is used for sensitivity/time estimates. Certain observing modes can however improve on this noise penalty: when employing frequency switching one always remains on-source and when employing position switching in mapping mode one and the same off-measurement can be used for several on-positions. We describe the different observing modes in more detail below.

#### 1.1 Beam switching

Beam switching (BSW) gives the best baselines since the switching is relatively fast and the frequency band is the same in the two phases. In single beam switching mode (SSW) there is a slight difference between the two beams, causing the baseline to generally show some curvature. A flatter baseline is obtained in the dual beam switch mode (DSW) where two beam-switched spectra are subtracted from each other, one taken with the source in the signal beam and one with the source in the reference beam.

Beam switching is achieved by rotating a mirror at the secondary focus which switches two beams symmetrically displaced in azimuth by about  $11'$  on the sky to each side of the optical axis. The corresponding beam switch speed is 1.5 Hz with a total blanking time of 7%. The rotating mirror can be stopped to allow



position-switching and frequency-switching observing modes.

Beam switching should be used for observations of weak and broad lines with spatial extents smaller than the beam throw of  $11'$ .

## 1.2 Position switching

Position switching (PSW) is used in regions with complex spectra and large source extents. The reference (off-source) position is reached by moving the antenna, implying a slow switching of typically one cycle per minute. The quality of the baseline is strongly dependent on the stability of the atmosphere during that cycle.

The reference position can be defined in absolute coordinates or relative to the source position.

## 1.3 Frequency switching

Frequency switching (FSW) is the most efficient observing mode for a given observing time, with the on-source integration time being doubled in comparison to BSW or PSW observations. The switching is done by changing the tuned frequency to two alternating values, according to an offset (frequency throw) defined by the observer. Subtraction of the corresponding spectra will lead to a spectrum with the observed line appearing at two different places in the bandpass, once as a positive signal and once as a negative signal. A folding procedure must then be carried out by the observer in order to average the two together. The frequency throw should be large enough to prevent the line components from blending with each other. At the same time, one must be careful to keep the two positions of the line in the spectrum within the bandpass of the spectrometer.

The switching speed can be fast since no mechanical units are involved; it is 5 Hz for the present receivers. A drawback to FSW observations is the baseline curvature inherent to the method. This is caused by the imperfections in the band pass curve which are shifted by the frequency throw before the difference spectrum is formed. Frequency switching is therefore less useful for weak or broad lines and BSW or PSW is preferential.

For the currently available receivers the frequency switching is obtained by alternating the LO frequency directly. This means that the phase lock in the spectrum analyser does not shift as the switching proceeds (see Sect. 2.2.12 and 2.2.17 in Chapter 5).

Typical frequency throws at 3 mm are 10 MHz but even larger throws are generally feasible. As the line widths observed towards a given source are fixed in velocity rather than in frequency, the throws can be halved when the 6–15 mm systems are used. Note that the telluric (mesospheric) CO lines are not cancelled in the frequency switching mode.

## 1.4 Mapping

Standard mapping routines are available, where the default setup gives a rectangular, regularly spaced grid. The map editor (Sect. 2.2.20 in Chapter 5) allows for the design of arbitrary grid points to be mapped and maps can e.g. be tilted by specifying a position angle. All observing modes described above can be used for mapping. For PSW a relative or absolute reference position can be given and

one reference spectrum can be used for several on-source spectra, increasing the time-efficiency of the mapping procedure.

## 2 Calibration

Intensity calibration is obtained by inserting an absorber at ambient temperature in the signal beam. This chopper wheel method leads to an intensity scale for a spectrum in  $T_A^*$ , the antenna temperature corrected for atmospheric contribution and other losses. The second order chopper wheel correction term (see Ulich & Haas, 1976 ApJS 30, 247) is also calculated and applied. To convert the intensity scale to main beam brightness temperatures  $T_{MB}$ , divide the  $T_A^*$  intensities by the main beam efficiencies  $\eta_{MB}$ .

$$T_{MB} = T_A^*/\eta_{MB} \quad (3.1)$$

We refer back to Chapter 2 for an overview of the efficiencies and their dependence on frequency and elevation.

## 3 Pointing strategy

Pointing runs are conducted regularly at OSO to maintain a pointing accuracy of 3" rms in azimuth and elevation. The pointing model adopted is essentially the one described by Ulich (1981) with expanded corrections in Azimuth (Az) and Elevation (El). A limited number of pointlike 86 & 43 GHz SiO maser sources (AGB stars) are available for spectral line pointing. These are listed in a catalogue available to the observer in the telescope's software system. Mars, Jupiter, Saturn and Venus may also be used for continuum pointing measurements.

To check and possibly improve the pointing accuracy during observations, the observer is advised to perform pointing checks in regular intervals. In case such a pointing source is within 10° to 15° from the observed source, the obtained pointing offsets should be applied as they reflect the current observing and telescope conditions. If there are no nearby pointing sources the pointing model itself will most likely yield a more reliable correction for such a sky position. However, we advise the observer to always perform pointing and focus measurements at least twice a day, in order to check the present pointing model and correct for day/night tendencies and weather changes.

## 4 Velocity systems

It is possible to observe in the local standard of rest (LSR), heliocentric, geocentric, and topocentric velocity systems. Note that different conventions for the Doppler correction can be used in the literature: e.g. relativistic, radio, or optical. The observer has to know which convention was used to determine the velocity of the source. For a given radial velocity the calculated sky frequency can be different depending on the convention used. At velocities  $>1000 \text{ km s}^{-1}$  it becomes important to know in which convention the radial velocity of a source is given.

At OSO we use the radio convention, where the sky frequency is given by

$$f_{\text{sky}} = f_{\text{rest}} \left( 1 - \frac{v_{\text{radio}}}{c} \right) \quad (3.2)$$

where  $f_{\text{sky}}$  is the sky frequency,  $f_{\text{rest}}$  the rest frequency of a given line of interest,  $v_{\text{radio}}$  the radial velocity of the source in the LSR reference frame, and  $c$  the speed of light. The relativistic Doppler correction uses the form

$$f_{\text{sky}} = f_{\text{rest}} \sqrt{\frac{1 - \frac{v_{\text{rel}}}{c}}{1 + \frac{v_{\text{rel}}}{c}}} \quad (3.3)$$

The optical convention is the correct one for a velocity obtained from an optical redshift  $z$  by defining  $v_{\text{opt}} = c \cdot z$ . When optical redshifts are to be used, it can be handled in the following manner in the telescope control system (see Fig. ??): a heliocentric velocity scale is chosen with the velocity set to zero and the rest frequency of interest (without any velocity correction) should be replaced with the appropriate sky frequency calculated by

$$f_{\text{sky}} = \frac{f_{\text{rest}}}{1 + \frac{v_{\text{opt}}}{c}} = \frac{f_{\text{rest}}}{1 + z} \quad (3.4)$$

Alternatively, using the relations above, we can leave the  $f_{\text{rest}}$  unchanged and calculate  $v_{\text{radio}}$  according to

$$v_{\text{radio}} = c \frac{z}{1 + z} \quad (3.5)$$

However, this option should only be used for small redshifts, if at all. Also note that this option will give a frequency axis oriented to the rest frame of the source which may not be desired for some measurements.

See also Sect. 2.2.10 in Chapter 5.

## 5 Time estimates

Below we describe how the observing time needed to achieve a certain sensitivity can be estimated. However, in order to simplify writing and reviewing of OSO 20 m proposals, we strongly advise interested observers to use a web-based tool for the time estimates instead. This tool is available through

[www.oso.chalmers.se/oso/calc/ObservationTimeEstimate.php](http://www.oso.chalmers.se/oso/calc/ObservationTimeEstimate.php)

The equivalent system temperature outside the atmosphere is calculated as

$$T_{\text{sys}} = \left[ T_{\text{rec}} + T_{\text{gp}} + T_{\text{atm}} \left( 1 - e^{-\tau_0 / \sin(\text{El})} \right) \right] \cdot e^{\tau_0 / \sin(\text{El})} \quad (3.6)$$

where  $T_{\text{rec}}$  is the receiver temperature,  $T_{\text{gp}}$  is the ground pick-up (some 20 K),  $T_{\text{atm}}$  is the effective atmospheric temperature (about 15 K below air temperature at ground level),  $\tau_0$  is the atmospheric zenith opacity, and El is the elevation of the source. Table 3.1 lists typical values of the atmospheric zenith opacity at OSO. These are only rough estimates, but good enough for most applications.

The rms noise in the spectrum is calculated from

$$\Delta T = C \frac{T_{\text{sys}}}{\sqrt{Bt_{\text{int}}}} \quad (3.7)$$

TABLE 3.1 – Typical zenith opacities at OSO

$\nu$ (GHz)	86	100	115
$\tau_0$	0.2	0.3	0.8

where  $C$  is a factor depending on the observing method used, with  $C = \sqrt{2}$  in the case of the time-symmetric BSW and PSW modes and  $C = 1$  in the case of FSW.  $B$  is the noise bandwidth per channel of the spectrometer, and  $t_{\text{int}}$  is the integration time on-source. To estimate the antenna temperature of the target line  $T_{\text{A,line}}$ , multiply its expected brightness temperature with the main beam efficiency (or with the moon efficiency if the source is very much larger than the main beam). The desired spectral rms noise,  $\Delta T$ , is then often a fraction of line strength, such as  $T_{\text{A,line}}/3$  for a  $3\sigma$  detection.

To calculate the actual observing time, as opposed to the on-source integration time  $t_{\text{int}}$ , you should add the time spent in the reference phase (in BSW and PSW equal to the time spent in the signal phase). You should also add overhead for intensity calibration and processing time of the spectra. Typically, the former is less than 3% of the total observing time and, the latter takes some 5 seconds per spectrum. An additional 5 seconds per spectrum should be included when in PSW mode, to allow for telescope movement. On the other hand, in FSW or BSW modes, up to 10% of the time per spectrum is lost due to data blanking during transition between switched states. Finally, the total telescope time should include contributions also from receiver tuning, and pointing and focussing tests. For most frequencies, a receiver tuning only takes a few minutes (seconds only when the HEMT receivers are in use). A typical pointing and focussing check requires 5 to 10 minutes. Note however that in general multiple tunings and source changes are required to carry out such checks. Thus a complete pointing cycle (source change, tuning, observations, source change, retuning) takes some 15 minutes.

## 6 Atmospheric transmission

Figure 3.1 shows the receiver temperature, atmospheric temperature, and the system temperature in the 3–4 mm range. From the plot, it is clear that observations below 70 GHz and above 112 GHz are very dependent on the atmospheric/weather conditions.

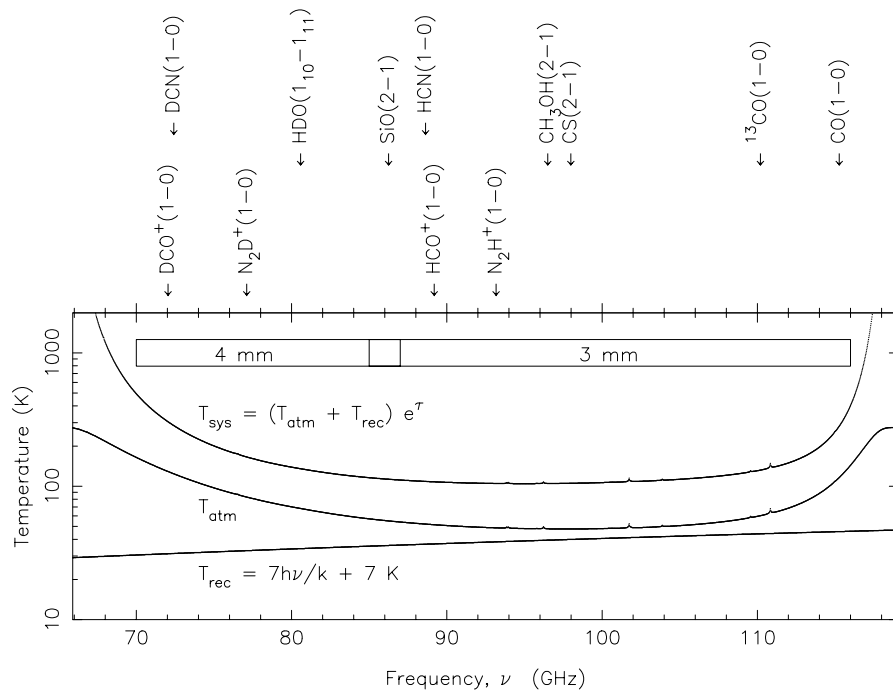


FIGURE 3.1 – Receiver, atmospheric, and system temperatures of the 3/4 mm receivers versus frequency.

# CHAPTER 4

## DATA

---

### 1 Backups, retrieval and transfer

All telescope data are written in FITS format, with the header as described in Sect. 3 of this chapter. At the end of an observing run the data can be written to a DVD, USB memory, or the user's own laptop for transportation. This usually is a compressed file (g-zipped tar-file) of FITS spectra. The data can also be made downloadable upon request. If daily backups are required it will be the responsibility of the observer. The actual raw observing data will be backed up by the OSO staff at the end of the observing run and kept in the OSO archive. We plan to make this archive browsable, with open access to scientific data in mind.

### 2 File names

Data are stored as FITS-files with names starting with a scan number followed by either a lower-case or an upper-case suffix, e.g. 1234567s.fits. These different file type extensions and their meaning are

- s** — calibrated, but otherwise unprocessed, scientific integrations for single position staring observations
- m** — calibrated, but otherwise unprocessed, scientific integrations for mapping observations
- a** — averages of the two polarisations, if appropriate. One pair of s- or m-files, for two polarisations in one spectrometer, are combined into one a-file.
- A, M, S** — system averages of multiple spectra based on radiometer formula weights. Should typically not be used in final scientific reduction since no other quality filtering is taking place.
- c** — system temperature spectra (c for calibration)
- r** — off-position raw total power spectra. These are produced in PSW mode, or during the calibration phase in FSW mode.
- x, X, p, P** — spectra taken during pointing and focussing, where the upper case refers to the centre position.

## 3 Fits header

We explain some of the relevant FITS header entries below and give an example of a FITS header in Sect. 3.2.

### 3.1 Selected entries

#### 3.1.1 Project identifier: PROJECT

This entry lists the project identifier, typically something like e.g. O2015b-01. This is entered when logging into the project account for the first time.

#### 3.1.2 Observer: OBSERVER

The person who observed the spectra. This has to be entered when logging into the system and can be changed throughout the observing session.

#### 3.1.3 Astronomical target: OBJECT

The astronomical target/object of the observation. This is automatically logged by the system when pointing the telescope at an object. This name is taken from the source catalogue specified by the observer. See also Sect. 1.2.

#### 3.1.4 Line or setting: LINE

The atomic/molecular line name, or any other "setting name" that has been entered by the observer when tuning the system. In the below example this is SiO, for the 86 GHz SiO transition.

If the IF-SWITCH was configured to deliver data from two different sidebands (USB and LSB) at once, the sidebands can be distinguished by the LINE entry. The main sideband, selected by choosing a transition or custom frequency while tuning with LINES (see Sect. 2.2.9 in Chapter 5) will contain a database transition label (or an alternate string selected by the observer) as normal. The data files with spectra from the other sideband will have the string "osb\_" appended to the beginning of the normal LINE string, signifying "other sideband".

#### 3.1.5 Receiver: FRONTEND

The receiver information is specified in the FRONTEND header entry. In the example below, this is SIS 3-mm, i.e. the new SIS receiver functional at 3 mm wavelength. The new HEMT receiver functional at 4 mm would analogously be described as HEMT 4-mm.

#### 3.1.6 Spectrometer: INSTRUME

The spectrometer origin of a spectrum is specified in the INSTRUME header entry. This is SPE1 or SPE2 for spectra obtained with the older FFTS. This normally reflects the two polarisations called PolA and PolB but it depends on how the IF-SWITCH was commanded during the observations. The actual polarisation is given in the POLARIZA keyword (below). The newer FFTS (Omnisys A, or OSA) similarly produces pairs called either OSA1 and OSA2, or OSA3 and OSA4.

For pre-averaged products of polarisation, such as the found in the a-files (Sect. 2),

INSTRUME will be set to e.g. OSA1+OSA2.

### 3.1.7 Polarisation: POLARIZA

In case the new FFTS (OSA) is used in the broadest 4 GHz bandwidth mode, the first pair (OSA1 and OSA2) will typically contain the two polarisations for one half of the band (actually 2.5 GHz wide), and the other pair (OSA3 and OSA4) will contain the two polarisations for the other half. This can, however, be changed to some degree by the observer when setting up the IF-switch during the observations. See also Sect. 2.2.29 in Chapter 5.

### 3.1.8 Observing mode: OBSMODE

The OBSMODE entry refers to the observing modes described in Sect. 1 in Chapter 3.

### 3.1.9 Frequency and velocity information

Information on the frequency coverage and resolution of the spectrum is given in the entries CRVAL1 (offset frequency), CDELTA1 (frequency resolution), CRPIX1 (reference channel), and RESTFREQ (rest frequency). The frequency array of the spectrum can then be reconstructed as

$$f(i) = \text{RESTFREQ} + \text{CRVAL1} + \text{CDELTA1} \times (i - \text{CRPIX1}) \quad (4.1)$$

The observed sky frequency, accounting for any Doppler shift, is given in OBSFREQ.

The corresponding velocity resolution and reference channel velocity are listed under DELTAV and VLSR.

### 3.1.10 Observing conditions

The entries HUMIDITY, TAU-ATM, and TSYS give the humidity, atmospheric optical depth, and system temperature at the time of the observations.

### 3.1.11 Efficiencies

The header also lists BEAMEFF and APEREFF. The latter can be ignored, and only BEAMEFF should be used. This is the frequency and elevation dependent main beam efficiency  $\eta_{\text{MB}}$  needed to convert the intensity in the obtained spectrum (in  $T_{\text{A}}^*$ ) into main beam temperature ( $T_{\text{MB}}$ ) – see Sect. 2 in Chapter 3.

## 3.2 Example

Below you find a sample FITS header from a dual beam-switched measurement of the SiO maser transition near 86 GHz in the source NML Cyg. Note that the precision of the data values – described by the keyword BITPIX below – changed at some point between April 2004 and February 2010, from 16 (16-bit integers) to -32 (32-bit floats). At some point between 2012 and 2016 there was also the addition of the FRONTEND keyword, to include information on the receiver (frontend) used for the observations (see above).

```
SIMPLE =          T / Basic FITS format
BITPIX =         -32 / number of bits used for pixel value
NAXIS  =          3 / number of axes, first one defines spectrum
```



```

NAXIS1 =          32768 / number of frequency channels in spectrum
NAXIS2 =              1 / longitude axis
NAXIS3 =              1 / latitude axis
ORIGIN = 'OSO-PEGASUS' / at Onsala Space Observatory, Sweden
TELESCOP= 'OSO-20M '   / data aquisition telescope
PROJECT = '02015a-04'  / project
OBSERVER= 'De Beck '   / observer
OBJECT = 'NMLCyg '     / object of observation
LINE = 'SiO '          / molecule line
POLARIZA= 'PolB '      / polarization (LCP/RCP/LCP+RCP)
FRONTEND= 'SIS 3-mm'   / receiver
INSTRUME= 'OSA4 '      / backend
OBSMODE = 'DSW SIG '   / mode of observation (PSW/BSW/DSW/FSW/SSW)
OBSTYPE = 'signal '    / type of observation (SIG/REF/CAL/COM/AVE)
SCAN-NUM=          3059201 / scan sequence number 1-999999
SEQUENCE=              0 / observation sequence number 1-99
COMMENT = ' '
BSCALE =              1.0 / real = tape*BSCALE + BZERO
BZERO =                0.0 / bias added
BUNIT = 'K '          / brightness units
DATAMAX =          3.426122E+00 / maximum amplitude of data
DATAMIN =         -2.451166E+00 / minimum amplitude of data
CTYPE1 = 'FREQ '      / f(i) = RESTFREQ + (Hz)
CRVAL1 =              0.0 / CRVAL1 + offset frequency
CDELTA1 =          7.629395E+04 / CDELTA1 * frequency resolution
CRPIX1 =           16384.000 / (i-CRPIX1) reference channel
CTYPE2 = 'RA '        / longitude at reference (epoch) = (deg)
CRVAL2 =           311.606414 / CRVAL2 + reference position
CDELTA2 =           0.000000 / CDELTA2/cos(DEC) * sky offset
CRPIX2 =              0.000 / (1-CRPIX2)
CTYPE3 = 'DEC '       / latitude at reference (epoch) = (deg)
CRVAL3 =           40.116500 / CRVAL3 + reference position
CDELTA3 =           0.000000 / CDELTA3 * sky offset
CRPIX3 =              0.000 / (1-CRPIX3)
OBSTIME =             60.0 / true observed integration time (sec)
INTTIME =             75.318 / effective integration time (sec)
TAMB =                274.8 / ambient temperature (K)
PRESSURE=            99730.0 / air pressure (Pa)
HUMIDITY=             0.86 / relative humidity (fractions)
TLOAD =               276.80 / load temperature (K)
TCOLD =               80.00 / liquid nitrogen load temperature (K)
TREC =                55.00 / receiver noise temperature at feed horn (K)
TSYS =                267.76 / chopper wheel system noise temperature (K)
TCOMP =               300.00 / comparison system noise temperature (K)
DBLOAD =              3.2360 / load attenuation (dB)
CHOPPERW=             1.0783 / chopper wheel factor
TAU-ATM =             0.3900 / optical depth of the atmosphere (neper)
DATE-OBS= '2016-02-11' / date of data acquisition (ccyy/mm/dd)
UTC = '15:56:54.00'   / universal time at start of observation
LST = '02:09:14.10'   / sidereal time at start of observation
JDATE =           2457430.164514 / julian date at start of observation
EQUINOX =             2000.0000 / equinox of coordinates
RA =                 311.750576 / object apparent right ascension (deg)
DEC =                 40.176154 / object apparent declination (deg)
RAOFF =                0.000000 / offset in right ascension (sky deg)
DECOFF =                0.000000 / offset in declination (sky deg)

```

```

AZIMUTH =          108.035530 / telescope azimuth readout          (deg)
ELEVATIO=          37.709976 / telescope elevation readout        (deg)
AZOFF    =           0.000000 / offset in azimuth                (sky deg)
ELOFF    =           0.000000 / offset in elevation              (sky deg)
AZPOINT  =           0.268364 / total pointing offset in azimuth  (instr.deg)
ELPOINT  =          -0.212314 / total pointing offset in elevation (instr.deg)
AZCORR   =           0.000250 / pointing correction in azimuth    (sky deg)
ELCORR   =          -0.000611 / pointing correction in elevation  (sky deg)
REFRAC   =           0.023036 / refraction angle at current elevation (deg)
BEAMEFF  =           0.403 / antenna beam efficiency             (fraction)
APEREFF  =           0.0 / antenna aperture efficiency           (fraction)
VLSR     =           2000.0 / velocity of reference channel       (m/s)
DELTAV   =          -2.310354E+02 / velocity spacing of channels  (m/s)
RESTFREQ=          99000000000.0 / rest frequency                (Hz)
OBSFREQ  =          99000398769.1 / observed sky frequency at ref. channel (Hz)
IMAGFREQ=          87000398769.1 / image sideband freq corresp. to OBSFREQ (Hz)
FSW-THRO=           0.0 / frequency switch throw                 (Hz)
FSW-OFFS=           0.0 / frequency switch offset                (Hz)
GAINIMAG=           13.000 / image sideband gain ratio (Image/Signal)
RELEASE  = '9402 ' / linux 3.2.0 & xubuntu 12.04
HISTORY  = -----
HISTORY  = TRACK_RMS 0.0008270 0.0004090 (deg)
HISTORY  = SUB_OFFSET 0.700 5.000 0.800 (mm)
HISTORY  = ANT_TEMPS 3.60 0.00 0.00 0.00 0.00 0.00 0.00 0.00(C)
HISTORY  = INCLINOMETER 0.067 0.360 1.412 EW/NS/CW (V)
HISTORY  = -----
END

```

## 4 Data Reduction

There is a computer called `brune` at the observer's disposal in the control room for data reduction and other needs such as email checking, weather monitoring, etc. The display is located directly to the right of the `munin` control computer display. Normally, a common user named 'observer' is always logged in here so no login procedure is required. Your data files will be available in the directory `~/<colour>/online/data/`. This directory is instantly updated as the observations progress, meaning that one always has access to the most recently obtained FITS files for inspection and reduction.

Several basic data reduction programmes are available at OSO for simple on-line analysis and final data reduction. We describe these below. Upon request, other packages could possibly be made available on `brune`.

### 4.1 XS

XS is an easy-to-use graphics oriented programme developed by Per Bergman at OSO, to reduce and analyse single-dish FITS data. It has a large selection of tools and is based on visual feedback through menu options and point-and-click control in the various plots such as spectra, contour maps, statistics, file selections, etc. No complete manual exists but short help cues are present for every function. It is also available for download by anonymous ftp at `yggdrasil.oso.chalmers.se`. XS is the official data reduction software supported by the staff at OSO and we recommend that it be used as the first choice.

Using XS for data reduction and/or inspection, one can filter on any of the FITS header keywords for selection.

## 4.2 CLASS

The Continuum and Line Analysis Single-dish Software (CLASS) is an internationally recognised data reduction and analysis tool developed at Observatoire de Grenoble and IRAM. It allows easy reduction of large volumes of data and is mainly script oriented, although it also has a GUI component. Full documentation is available at OSO. For the latest version, information, and updates, please consult the GILDAS web page at [www.iram.fr/IRAMFR/GILDAS/](http://www.iram.fr/IRAMFR/GILDAS/).

Using CLASS for data reduction and/or inspection, the FITS header information as written at the OSO 20 m telescope will not be retrieved in its totality. For example, CLASS expects all information on frontend, backend, and polarisation to be located in the INSTRUMENT entry in the header. CLASS will be able to discern between the two sidebands in the broadband 2SB spectra based on the LINE keyword.

## 4.3 DRP

The Data Reduction Package (DRP) is a number of small programs to be used for the reduction of single-dish spectral line data, developed by Michael Olberg at OSO. One advantage is that individual commands can be combined into more powerful ones by using shell scripts. Software documentation for DRP is available at OSO.

# CHAPTER 5

## A TYPICAL OBSERVING RUN

---

This chapter provides an overview and (illustrated) description of the steps involved in a typical observing run at the OSO 20 m telescope. As a visiting observer, you will of course be introduced to the software by the OSO support staff. This manual should, however, serve as the observer's technical guide throughout an observing run, since the observers are supposed to observe, i.e. command and steer the telescope, independently. Thus, if arriving early to the observatory, it is advisable to watch the previous observers, and learn about e.g. the start-up and tuning procedures. Throughout an observing run, a support astronomer will be available on-site during office hours in case of problems. At other times, staff assistance is offered over the phone by support staff according to an updated priority list put up in the control room.

This chapter contains a description of preparatory work that can/should be done by the observers before starting the observing session, a comprehensive overview of the PEGASUS user interface and its many functionalities, a summary of a typical observing run, and tips for troubleshooting.

### 1 Preparations

#### 1.1 Account

A guest account will be assigned to the observing project upon arrival, and the user name will normally be that of a colour, e.g. "green". The account allows access to the PEGASUS control programme running on `munin`, a Linux PC. All observed scans will be saved under this account, and each account will contain one project at a time only. The data files are easily accessed from the data reduction machine `brune` (physically located next to `munin` in the control room) as described in Sect. 4 in Chapter 4.

#### 1.2 Source catalogue

The only file(s) needed from the observer to be prepared onto the assigned PEGASUS account is/are the source list(s). These source lists, or source catalogues, should contain the source names, epoch, coordinates, and source velocities. The files can be created on-line in PEGASUS using a text editor or can be sent to the

PEGASUS guest accounts via sftp/scp or equivalent. In the latter case, the observers need to make sure that the file formatting described below is used throughout the file.

### 1.2.1 Formatting

A typical source catalogue entry looks similar to the following:

```
Orion A    EQ 1950.0    05:32:47.0 -05:24:23    LSR  8.0
```

Note that there must be at least *two* white spaces between the source name and epoch since we have opted to allow single spaces in the source name. An off-source coordinate for position switching observations may be defined by appending the word REFERENCE, followed by RA/Dec values, at the end of the line above. An example catalogue file is shown below.

### 1.2.2 Sample source catalogue

```
# -----
#          #####    ##    #####    #####
#          #   #   #   #   #   #   #
#          #       #   #   #   #####
#          #       #####    #   #
#          #   #   #   #   #   #   #
#          #####    #   #   #   #####
#
#-----
# object      KEYWORD columns in any order
#-----
# Source A    EQ 1950.0  04:56:41.4  56:06:30
# "object"    EQ 2000.0  04h56m41.4s  56d06'30"
#             GALACTIC  1.2345d    2.3456d
#             OFFSET           0.0    180.0
#             OFFSET           0.0"   180.0"
#             REFERENCE 05:32:00.0  22:00:00
#             REFERENCE 05h32m00.0s  22d00'00"
#             ROFFSET           4.1    4.2
#             LSR    0
#             VLSR   0
#             GEOCENTRIC 0
#             HELIOCENTRIC 0
#             NONE
#             VRANGE  -2.0 -1.0 1.0 2.0
#-----
# Notes:
# * All keywords for one source must be on the same line
# * The object name must be followed by at least 2 white spaces
# * The exclamation mark can also be used as a comment symbol
# * Many keywords can be abbreviated such as REF for REFERENCE and
#   HEL for HELIOCENTRIC
# * Galactic coordinates (GAL) are given by longitude first
# * ROFFSET defines a reference position in horizontal coordinate
#   offsets (azimuth followed by elevation)
# * VRANGE is only used for pointing sources
# * NONE means no Doppler correction at all (sky frequency)
```

```

#-----
Orion A      EQ 1950.0 05:32:47.0 -05:24:24 VLSR +8.0
DR21(OH)    EQ 1950.0 20:37:14.2 42:12:10 VLSR -3.0 REF 20:37:46.6 42:12:10
W_Cyg       EQ 2000.0 21:36:02.5 45:22:29 HEL -14.0
NGC7538     GAL 111.5421d 0.7770d LSR -56

```

### 1.3 Observing log

We point out that there is no on-line observing log kept for the 20 m telescope. The observers are responsible for keeping track of e.g. the weather conditions and which files correspond to which observations. Log sheets that can be filled out manually will be at the observer's disposal in the control room.

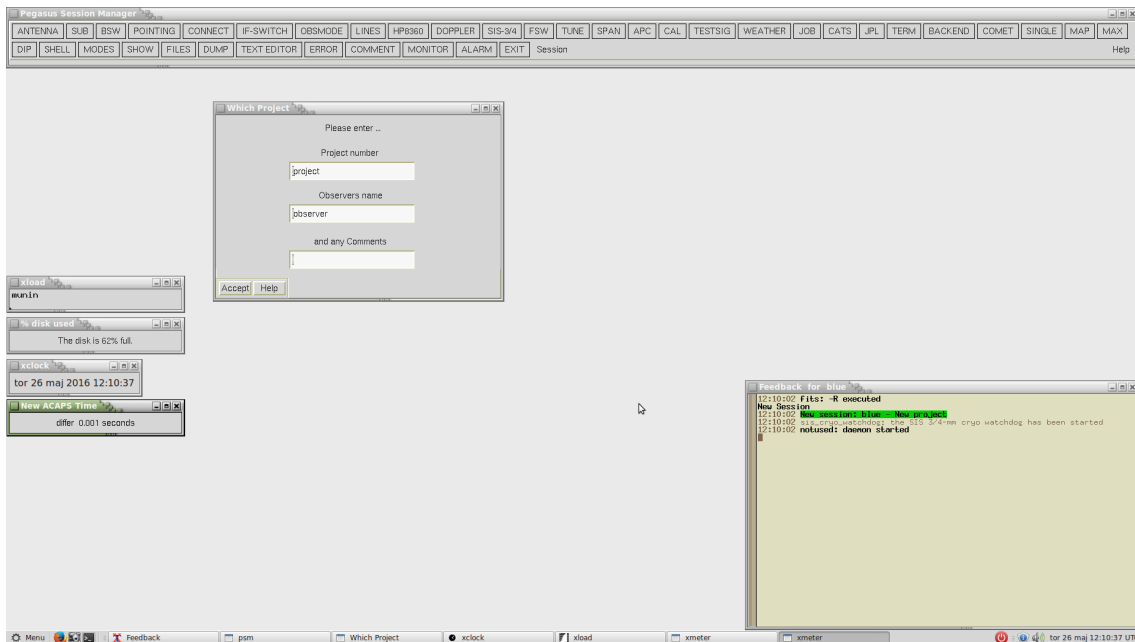


FIGURE 5.1 – Screen at start-up of PEGASUS.

## 2 The PEGASUS system

The basic philosophy of the PEGASUS GUI is that each window gives a variety of options, which are activated by clicking on the small selection boxes next to the corresponding fields. A red selection box indicates that an item has been selected and activated. Some boxes may be mutually exclusive and thus cancel other previous selections, others may be used in combinations. Small red diamonds may also be used to select settings, but in some cases, as outlined below, they are only indicators of previously selected options and thus will not change any status when clicked.

The following sections will show and explain each PEGASUS window accessible to the observer from the PEGASUS top level menu bar (Fig. 5.1). We refer to the name of each window in SMALL CAPS for easy identification. Selection fields or other options in general will be written in “quotes”. Once a PEGASUS window setup is finished, a row of buttons toward the bottom edge is then used to process the selected options. We refer to these buttons in boxes.

`Accept` will result in accepting the options entered and immediately starting any processes needed to implement these choices. `Save values` will only save the current settings of the window in question and close the window without actually starting any processes yet. `Defaults` puts all of the selection boxes and any numerical values within parameter fields to their default settings and values. `Cancel` will close the window without accepting any changes that may have been made. Finally, `Help` will open a window, which gives some brief explanation about the functions of the PEGASUS window.

## 2.1 Start-up

Before starting a session, the observer should always make sure that the antenna is ready for use, and in particular that no one is present in the cabin or riding the skylift or otherwise doing maintenance work interfering with antenna operation inside the radome. Only if the cardboard sign mounted on the upper right of the glass window in the control room towards the radome is green with the text "ANTENNA IS READY TO OPERATE", is it safe to proceed.

The observing session starts by logging onto `munin` under one of the assigned guest accounts. This will automatically launch the PEGASUS GUI. The user will then first be prompted for some details on the observing project in a small pop-up window – Fig. 5.1. After entering project number, PI name, and an optional comment, followed by clicking the `Accept` button, the actual start-up procedure will begin. Towards the left on the screen, four small windows are present, monitoring the date and UT, disk space, workload and the time difference between the hydrogen maser standard and the `jupiter` clock used for tracking the telescope position.

Towards the bottom right, the `FEEDBACK` window will be open. During observations this window will serve as a feedback to the observer allowing them to monitor the system status when issuing commands via the PEGASUS control windows. Observing modes, system temperatures, pointing results, scan numbers, etc. will all be displayed in this window as the observations progress. Most of this information is also available through the different PEGASUS control windows, meaning that a continuous monitoring of the feedback window as it scrolls through this information is not necessarily required.

After this first part of the start-up procedure, a window labelled `CHECKIT` appears automatically – Fig. 5.2. This shows a list of the necessary actions to enable the antenna tracking, pointing corrections, receiver selection and so on. This list should be followed from top to bottom. To the right of each instruction there is a clickable button to carry them out. Note that the buttons merely are shortcuts to some of the items in the top bar menu labelled `PEGASUS SESSION MANAGER` – this menu is visible in Fig. 5.1.

The individual steps in the start-up (`TERM`, `ANTENNA`, `CATS`, `POINTING`, `SUB`, `CONNECT`, and `OBSMODE`) are explained further below, in separate sections. When finished going through all these steps, press the `Done` button. If you need to repeat any step later on, use the top bar menu. You can also bring back the `CHECKIT` window by opening a Linux terminal window (`SHELL` in the top menu bar) and running the command `checkit` at the prompt.

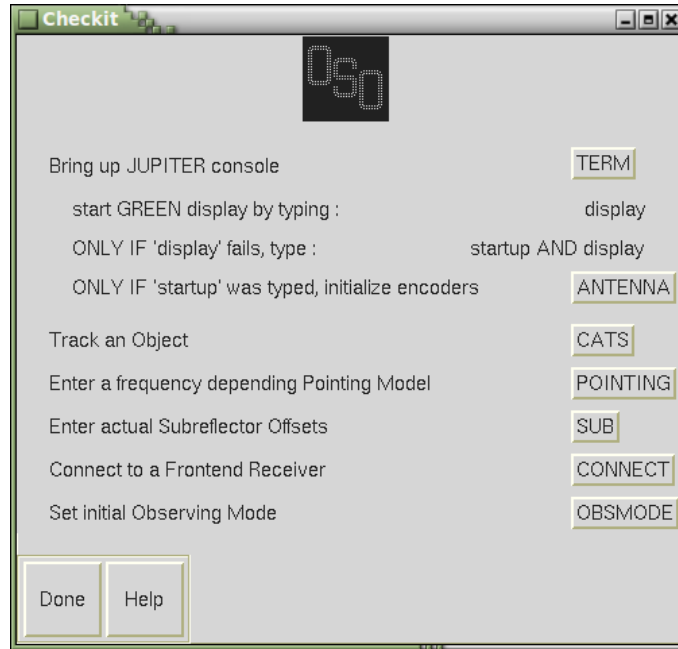


FIGURE 5.2 – CHECKIT window.

## 2.2 GUI windows: an overview

### 2.2.1 TERM

TERM gives the observer the option to open console windows for certain hardware/computers as shown in Fig. 5.3. Normally, this is only used to provide feedback from “ACAPS” (Antenna Control and Positioning System, running on `jupiter`), and “WEATHER” using `munin` as the host screen.

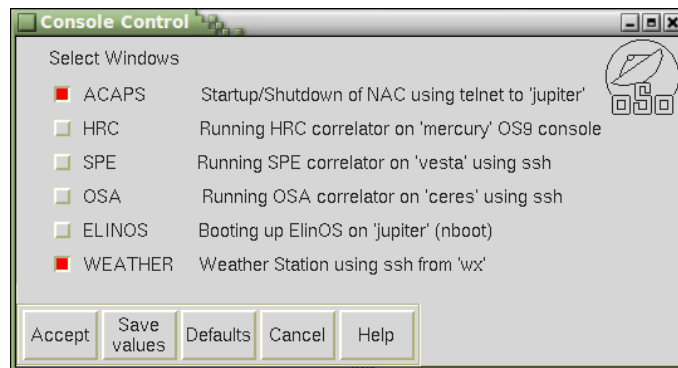


FIGURE 5.3 – TERM brings up the CONSOLE CONTROL window.

After `Accept` has been pressed in CONSOLE CONTROL (Fig. 5.3), the ACAPS CONSOLE and OSO WEATHER DISPLAY windows appear – Figs. 5.4 and 5.5. The ACAPS CONSOLE is an interface to the `jupiter` computer which is used to run the telescope tracking software. Type `display` at the prompt of the ACAPS CONSOLE. In case this does not bring up the telescope tracking info, enter `startup`, followed by `display` to enable monitoring of the antenna tracking. Now, information about the antenna tracking in descriptive coordinates, the commanded



and actual position in azimuth and elevation, tracking errors and pointing offsets, the setting of the subreflector, etc., should appear. The values shown at this stage are however only initial and will not be properly updated until the “Initialisation” manoeuvre has been conducted, see further below. In case the antenna was put into "Stop" mode after a previous observing session, the background colour of the window is red to signify that this has not yet been done. In case it was left in "Run" mode, or once the initialising steps are taken and the antenna is put into "Run" mode and tracking a source, the ACAPS CONSOLE should look similar to that in Fig. 5.4. Not all of the information displayed in this window is relevant to the observer and most of it can also be obtained through the PEGASUS windows explained in the following sections.

At the end of the observing session, but only when instructed by staff to do so, the antenna monitoring can be turned off. You do this by hovering over the ACAPS CONSOLE with the mouse pointer to make it active and typing <Ctrl-C>, followed by issuing the command `shutdown`.

### 2.2.2 ANTENNA

ANTENNA opens the 20M NEW ANTENNA CONTROL window shown in Fig. 5.6. It is mainly used for starting or stopping and parking the antenna or initialising the incremental encoders. The observer will typically only use this window at the beginning and at the end of the observing session. To enable antenna tracking for the first time after logging in, select “Encoder initialization” followed by `Accept`. The antenna will now move in a certain pattern in order to pass encoder calibration points in azimuth and elevation. This may take a minute or so. The background of the ACAPS CONSOLE window (Fig. 5.4) will go from red to black when the operation is successfully completed. When finished, choose “Run” and `Accept`. Only the latter step needs to be taken in case initialisation was performed earlier, e.g. by a previous observer of a different project.

At the end of the observing run, or if the antenna needs to be parked temporarily mid-observation, bring up this window by clicking on `ANTENNA` in the top menu bar and select “Stop” and `Accept`. This turns off the power to the antenna drive

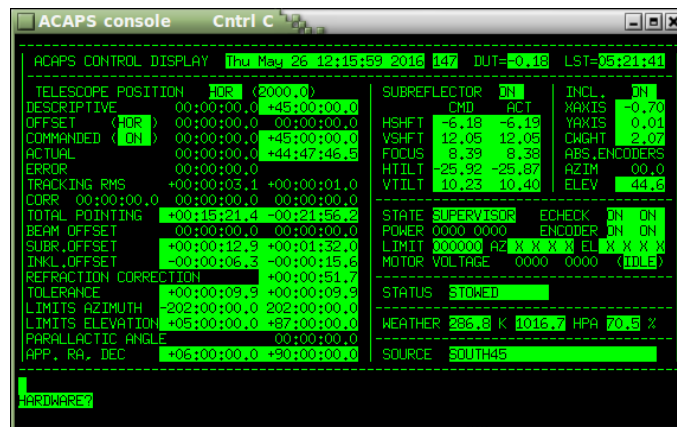


FIGURE 5.4 – The ACAPS console, allowing to track e.g. the telescope’s movements and other basic information.

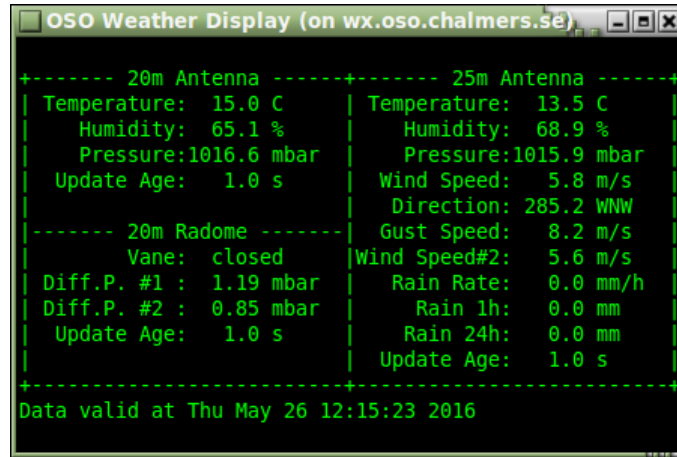
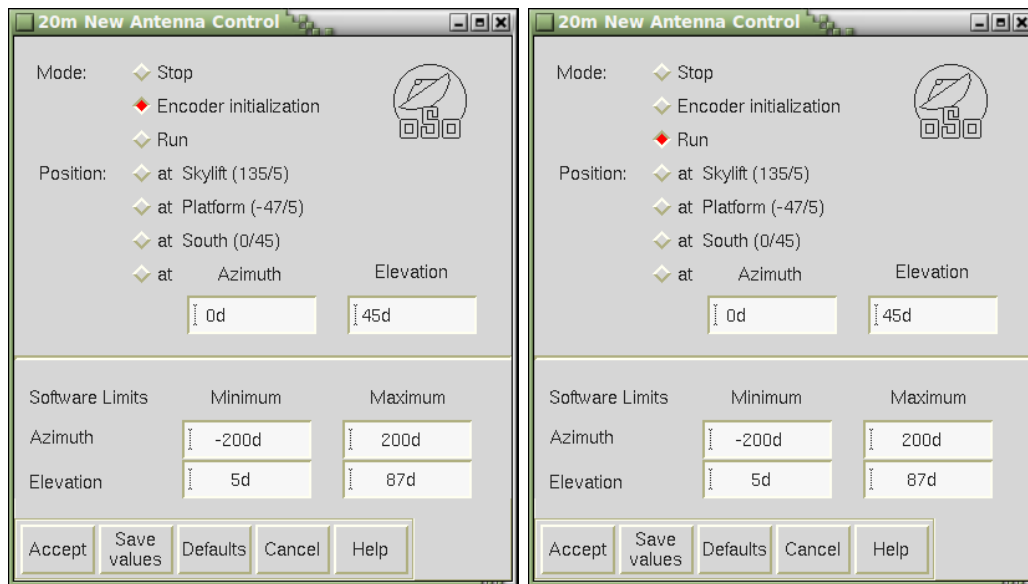


FIGURE 5.5 – The OSO WEATHER DISPLAY is usually kept running in the background on munin.

and activates the brakes. The antenna can also be directed to a certain predefined position (e.g. skylift, platform), used for maintenance and/or cabin access reasons. If this is necessary, first direct the antenna to the appropriate position, and only after that, put the antenna in "Stop" mode.

The 20M NEW ANTENNA CONTROL window also shows the azimuth and elevation software tracking limits applied by ACAPS. These numbers should not be altered by the observer.



(a) Encoder intialisation

(b) Run

FIGURE 5.6 – 20M NEW ANTENNA CONTROL brought up by ANTENNA.

### 2.2.3 CATS

CATS opens the SOURCE CATALOGS window shown in Fig. 5.7. It is used to select sources from existing pointing and calibration catalogues or the user's

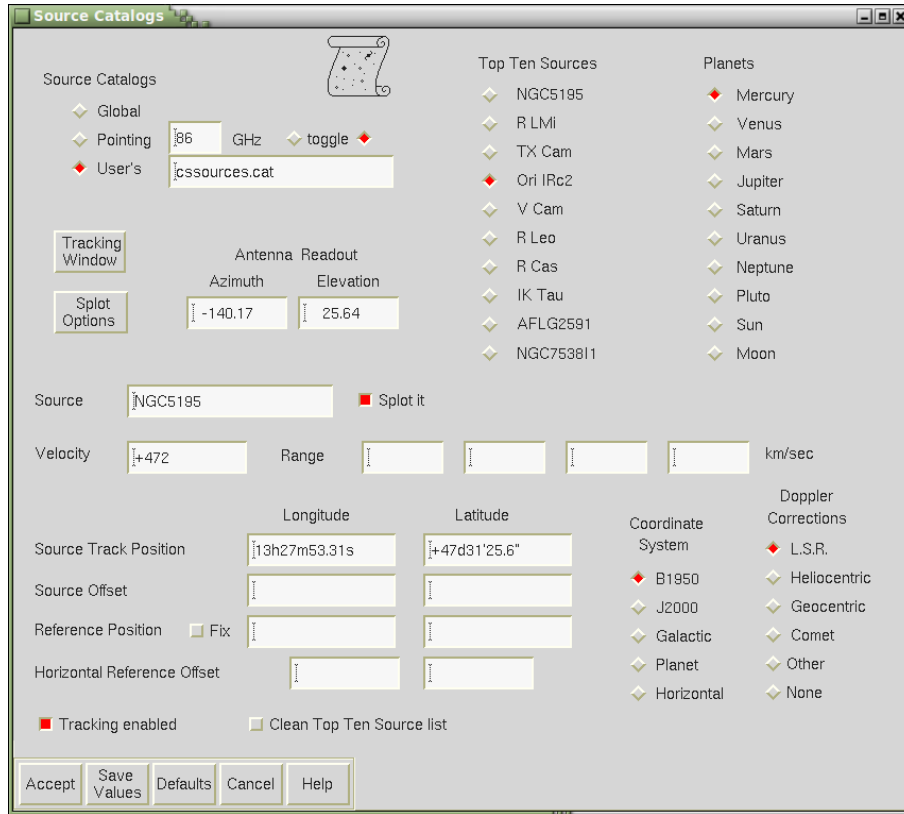


FIGURE 5.7 – The SOURCE CATALOGS window, brought up with CATS.

source catalogue, to set or modify source parameters, and to command the telescope to track the selected source. The most convenient way to track a source is to select it from a prepared source list (see Sect. 1.2), but the coordinates, coordinate system, and source velocities can also be entered manually. In addition, any “Source Offset” position, “Reference Position”, or relative “Reference Offset” in horizontal or descriptive coordinates can also be entered manually.

Clicking on the diamonds next to “Global”, “Pointing” or “User’s” will automatically open the corresponding catalogue. In the latter case the name of a correctly formatted .cat-file must be entered in the text field before clicking – see Sect. 1.2. Figure 5.8 shows a foreground window with a source list that has appeared after clicking the diamond in front of “User’s” – see Fig. 5.8. Click on a source to check its current azimuth and elevation values: the box with the azimuth value turns yellow when the source has started setting; the box with the elevation will turn red in case of a negative value. You can also click “Plot a Graph” in the bottom right corner to see the evolution in time of the selected source’s elevation. When you have decided on a source, click **Accept**. To close the window, click on **Cancel** or the cross at the top right corner of the window frame. Once a source has been selected from a catalogue, all relevant information will automatically be copied into the fields in the lower half of the SOURCE CATALOGS window. The source velocity, Coordinate system and Doppler corrections are normally transferred here from your selection in the source file, but may also be set manually. By clicking **Accept**, the telescope will be sent to track the source if it is within the tracking limits and “Tracking enabled” is active

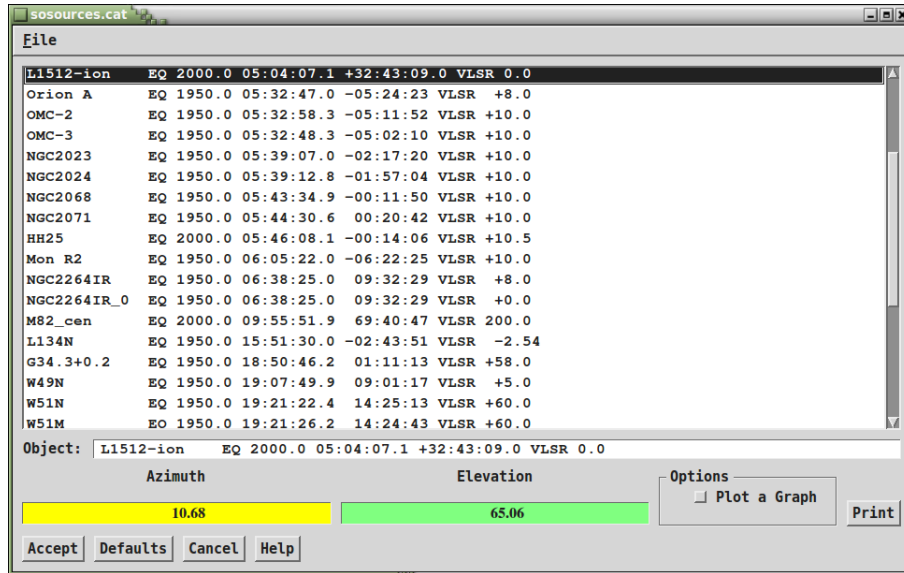


FIGURE 5.8 – Example of a source catalogue in the GUI.

(tracking limits may be modified by pressing the `Tracking window` button). Once a source is being tracked, all relevant information which has been given in the SOURCE CATALOGS window will be saved to the list of “Top Ten Sources”, at the top of the SOURCE CATALOGS window. By clicking on the diamond next to the source name in this list, all of the previous settings will then automatically be recalled, updating only the sky position of the source.

To track a planet, simply select a planet from the list “Planets” and make sure that you are in Coordinate System “Planet” (bottom right in the window), before you click `Accept`.

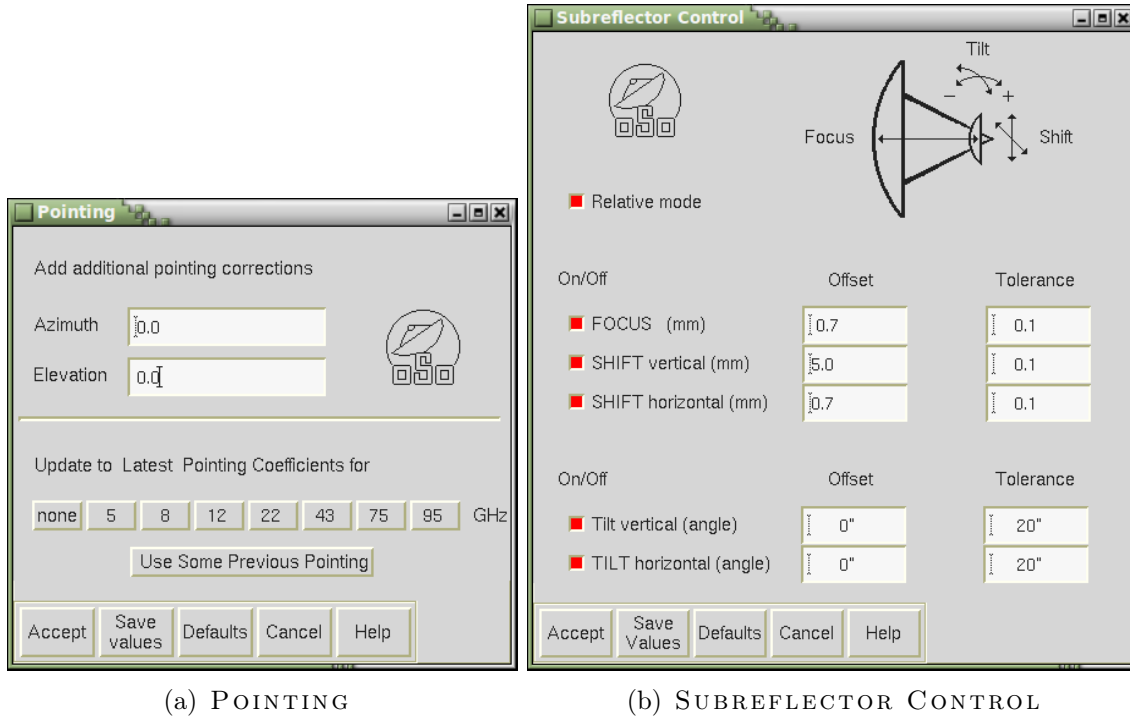
In the SOURCE CATALOGS window, there are also a few options related to a tool called Splot. Splot can show visibilities for sources as a function of time and is therefore useful when planning your observations. Please ask the staff if further information is required.

## 2.2.4 POINTING

POINTING opens the POINTING window – see Fig. 5.9(a). This window shows the pointing corrections currently applied to the telescope. The observer should select the pointing model to be applied to the observations by clicking on the button with the centre frequency of the receiver you are using. For the 3mm and 4mm receivers, this is 95 GHz and 75 GHz, respectively. This must be done at the start of every observing session. It is advisable to set the “Add additional pointing corrections” values to zero at this point. Press `Accept` to make the changes take effect.

## 2.2.5 SUB

SUB opens the SUBREFLECTOR CONTROL window – see Fig. 5.9(b). This window shows the subreflector (focus) offsets currently applied. As is the case with



(a) POINTING

(b) SUBREFLECTOR CONTROL

FIGURE 5.9 – POINTING and SUBREFLECTOR CONTROL windows.

POINTING, this must be done at the start of every observing session. It is advisable to set the “FOCUS” offset field in the SUB CONTROL window, to zero at the start of your observation. Press  to make the changes take effect.

### 2.2.6 CONNECT

CONNECT brings up the FRONTEND RECEIVER CONNECT CONTROL window – see Fig. 5.10. This window is used to select a receiver. Simply click the diamond button next to the frequency range description corresponding to your observations, and then . Selecting a receiver has to be done as part of the start-up process every time the observer logs into their project account.

### 2.2.7 OBSMODE

OBSMODE brings up the OBSERVATIONS MODE CONTROL window – see Fig. 5.11. The main use of this window is to select an observing mode (Chapter 3, Sect. 1) by clicking the appropriate diamond button in the upper left portion of Fig. 5.11. Even though the observing mode must be stated again when an observation is actually launched (see SINGLE, MAP, or MAX in Sects. 2.2.19, 2.2.20, and 2.2.18 in this chapter), there are some benefits to doing it here, which are related to tuning and spectrometer power levels.

The backends can also be configured from the lower left portion of this window. Click the button(s) below “Setups” to open a window where you can set bandwidth(s) and spectral resolution(s) of the spectrometer(s) you want to use. The  button in the top menu bar can be used to change the spectrometer configuration at any time later on – see Sect. 2.2.15.

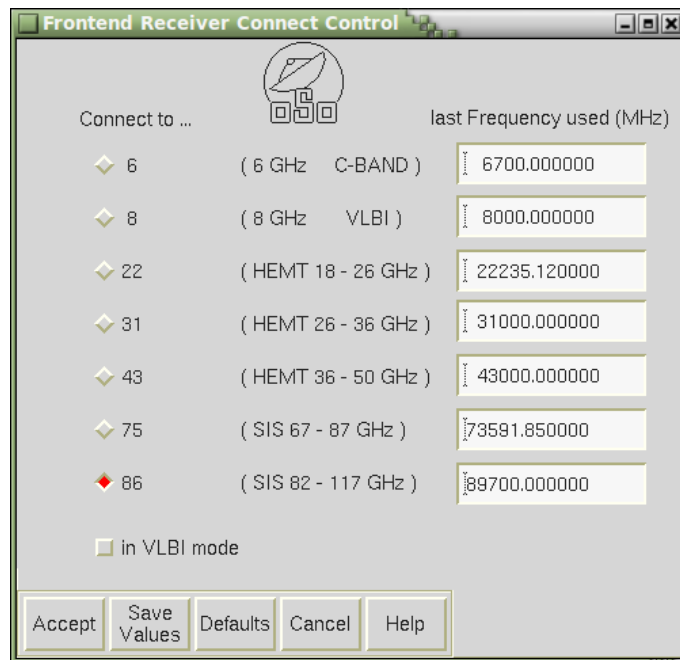


FIGURE 5.10 – The FRONTEND RECEIVER CONNECT CONTROL window, brought up by CONNECT.

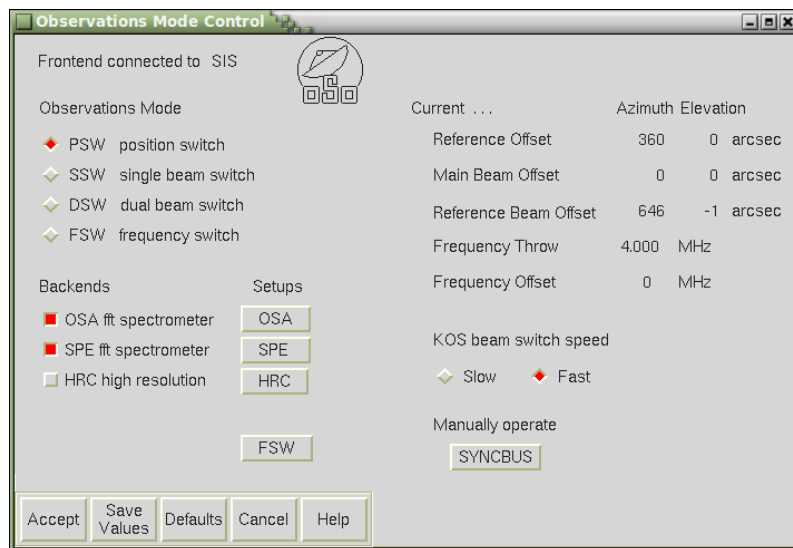


FIGURE 5.11 – The OBSERVATIONS MODE CONTROL window, brought up by OBSMODE.

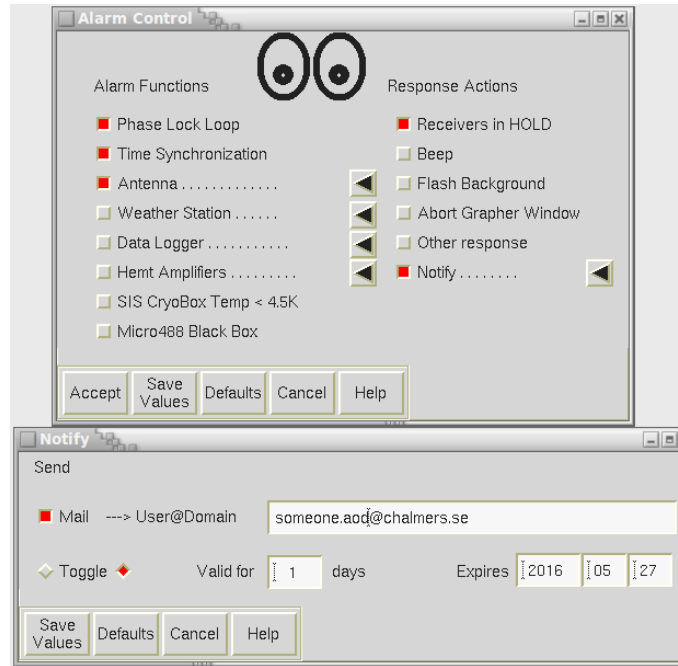


FIGURE 5.12 – The ALARM CONTROL window, brought up by ALARM.

### 2.2.8 ALARM

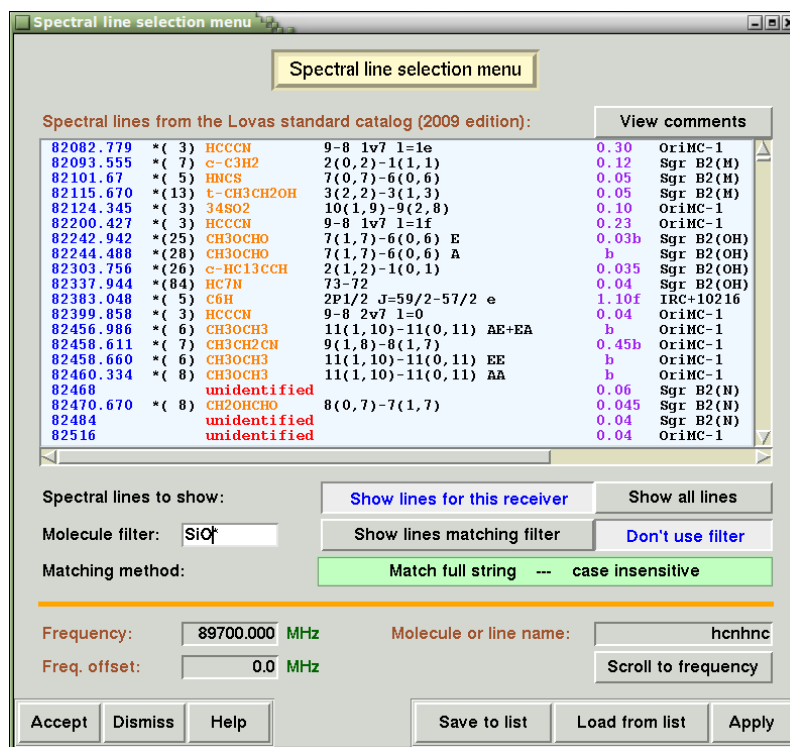
The alarm should be started just before an astronomical observation starts, i.e., after pointing and tuning have been performed.

ALARM opens the ALARM CONTROL window shown in Fig. 5.12. An ALARM STATUS window will be activated when `Accept` is clicked, and will continuously monitor the items marked in the selection boxes listed under “Alarm Functions”. Certain items have a subset of options shown if the respective filled black triangle is clicked. It is recommended that all items selected in the Figure are used routinely.

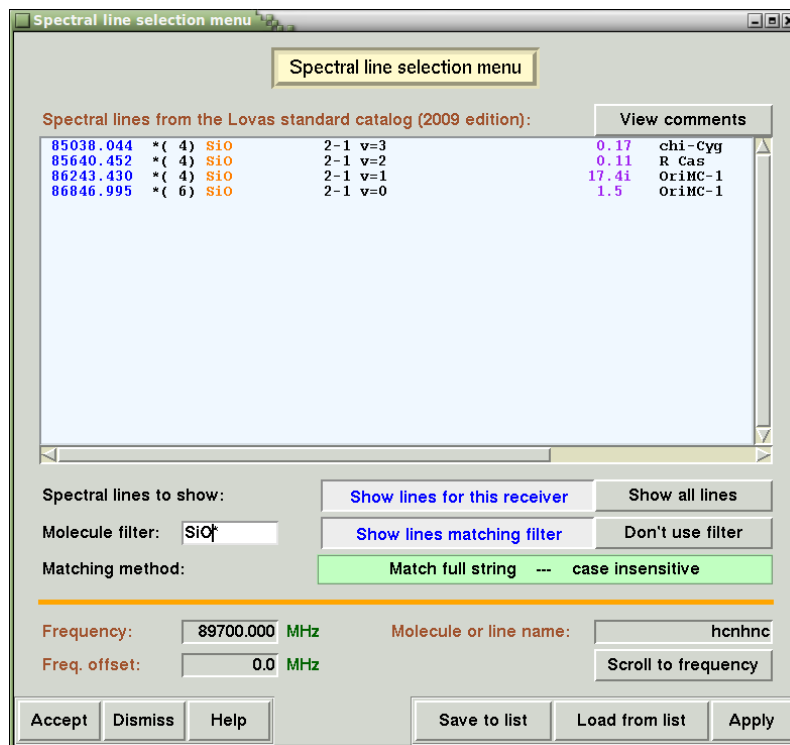
If an alarm is triggered, a number of *response actions* selected from the ALARM CONTROL will be invoked. Usually, the background color of the PEGASUS GUI will change to red, an audible beep will warn the observer, and an alarm message in the feedback window will indicate the source of the problem. If the system is currently integrating, the integration is temporarily paused until the alarm has been reset. Press `Hold` in the ALARM STATUS window until the problem is understood and solved, then `Reset` to continue observing. Most problems can easily be dealt with by the observer, but in case you do not understand the nature of the problem, ask the staff for help. The observer can set up an automatic email notification in case of an alarm, by under "Notify" specifying the relevant email address.

### 2.2.9 LINES

LINES invokes the SPECTRAL LINE SELECTION MENU shown in Fig. 5.13(a), which is based on the LOVAS molecular line catalogue. The observer first puts the name of the desired molecule into “Molecule filter” and then clicks on `Show lines matching filter`. To select a line from the catalogue, simply click on



(a) General appearance.



(b) Appearance after filtering for SiO\*.

FIGURE 5.13 – The SPECTRAL LINE SELECTION MENU, brought up via LINES.



it, followed by . At this point, a window appears from which you choose whether you want to tune the receiver immediately or cancel the tuning process. Tuning at a later stage is done by clicking TUNE (see below).

There is a large list of possibilities to search for/filter for molecules or listed transitions:

- From a dropdown list following "Matching method" one can select whether matching should be done on the full molecule name or on any part of it, i.e. whether 'CO' should just give you 'CO' or everything which has the string 'CO' somewhere in the name, and whether the search should be case sensitive or not.
- The system supports a wild-card syntax and right-clicking on the 'Molecule filter' line will give you the syntax list and a set of examples:

```
'*' is a wildcard for zero or more arbitrary characters
'#' is a wildcard for one digit
'.' is a wildcard for one arbitrary character
'?' means that the previous character can appear once or not at all
'&' means that the previous character can appear once or more
'%' means that the previous character can appear zero times or more
'[XYZ]' matches one of the characters in the brackets
'<XYZ|QWY>' matches either of the two sequences of characters
```

Here are some examples using full string matching:

```
'*' matches all molecules
'HCO*' matches 'HCO', 'HCO+', 'HCOOH' and 'HCOOD'
'H.O' matches 'HCO', 'HNO', 'HDO' and 'H2O'
'H*O' matches the ones above and many more like 'HCCCHO'
'HNC?O' matches 'HNO' and 'HNCO'
'HN[CO]' matches 'HNC' and 'HNO'
'HC#N' matches 'HC3N', 'HC5N', 'HC7N' and 'HC9N'
'HC#&N' matches the ones above and also 'HC11N' and 'HC15N'
'HC#%N' matches the ones above and also 'HCN'
'[HD]#%CO+' matches 'HCO+', 'DCO+', 'H13CO+' and 'D13CO+'
'CH*<CN|NH>' matches 'CH3CN', 'CH2NH', 'CH2CHCN' and many more
```

- Note that some molecules may be written in a different form than you expect, for example,  $\text{HC}_3\text{N}$  is listed in the catalogue as 'HCCCN'.

One can also manually enter a tuning (rest) frequency in the bottom left corner, next to "Frequency" and give that setting a freely chosen name in the box next to "Molecule or line name". This name will be passed on to the FITS header under the LINE keyword. There is also the possibility to add a frequency offset to the selected/defined frequency. This can be useful when one is interested in a broader window that is not centred around the given rest frequency, but still keeping the velocity scale defined w.r.t. that rest frequency. It can also be used in case instabilities would occur at the centre of the spectrometer. The line of interest can then be moved away from the "problem area", again without changing the velocity definition.

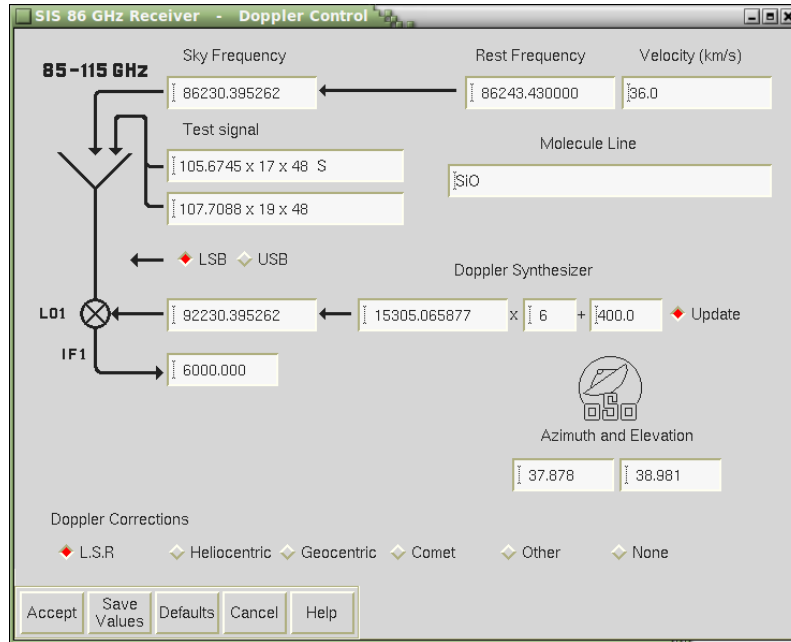


FIGURE 5.14 – DOPPLER CONTROL for 3mm receiver. In this particular example, the receiver will be tuned to the SiO transition at 86243.43 MHz, with a (radio) velocity shift of 36.0 km/s in the LSB.

The buttons `Save to list` and `Load from list` allow one to respectively save or load a certain frequency or transition with an arbitrary name to or from a list. This list can be used throughout the entire observing run, as it is saved to the project account. This can be useful in case several settings or transitions will be observed repeatedly for e.g. a list of sources.

The Doppler-corrected sky frequency will be calculated automatically, in accordance with the at that time available source velocity and velocity system, and `FREQUENCY CONTROL` will be updated. In order to avoid retuning to correct for a faulty Doppler-shift, it is therefore advisable to track the source of interest *before* selecting the line frequencies.

### 2.2.10 DOPPLER

*We advise the observer not to use this window unless absolutely necessary.*

An alternative to using `LINES` is to enter the rest frequency in the `FREQUENCY CONTROL` window shown in Fig. 5.14. The velocity and Doppler corrections then have to be adjusted as needed. In general, any other parameter should have the default setting defined by the rest frequency. `Accept` sets the HP synthesizer in the L01 chain which corrects for the Doppler shifts. The frequency applied also appears in the `FEEDBACK` window.

### 2.2.11 BSW

The beam switch mechanism does not need to be configured manually. Its operation can be monitored by using the BSW button in the top menu bar. In normal operation, only the `BEAM SWITCH MONITOR` button is of interest here. By clicking it, a schematic drawing of the real-time signal path will appear by, see

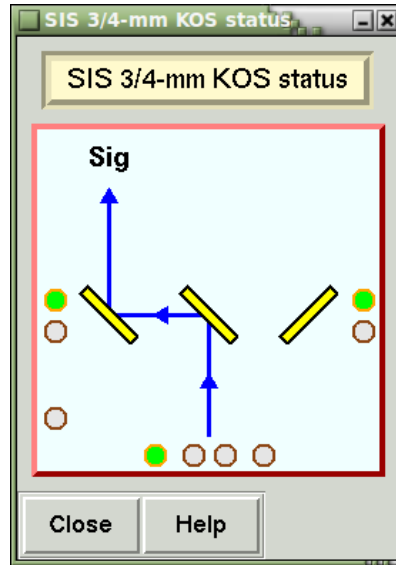


FIGURE 5.15 – Beam switch monitor showing the current position of mirrors and loads. The switch procedure can be followed as it proceeds.

Fig. 5.15. This is a useful tool to understand how the optics are configured on the 20 m telescope.

### 2.2.12 FSW

To configure the frequency switching mode, click on FSW in the top menu bar and enter numbers for "Frequency Throw" and "Frequency Offset". The latter parameter is normally set to zero meaning that a line will appear in the middle of the spectrum after a folding procedure has been applied (assuming that the gas is emitting exactly at the velocity set for the current astronomical target). Select "Start FSW" and  to start the switching. We note that the spectrum analyser window (see Sect. 2.2.17, Fig. 5.21) will not show a moving spike of the phase lock, since the LO frequency itself is changed during FSW.

### 2.2.13 TUNE

In case of the HEMT systems below 50 GHz, all receivers are tuned fully autonomously when a spectral line is selected in  or when a frequency is entered manually in .  in this case will do no more than resend the current settings. The tuning process of the other receivers is almost completely automated, with still a few steps for the observer to go through.

The broadband receivers at 3 mm and 4 mm can be tuned in several ways. The SIS 3 MM AUTO-TUNE DISPLAY and SIS 4 MM AUTO-TUNE DISPLAY windows are shown in Figs. 5.16 and 5.17. These inform the observer on the status of the different receiver components (synthesisers, mixers, amplifiers, ...) throughout the different tuning procedures.

One can use , , go into the , , and . The frequency information (sky frequency, sideband, LO frequency, and frequency offset) which will be/is/was used for the tuning

is specified in blue towards the bottom of the display window.

The auto-tune procedure can take up to a few minutes in the case of the 3 mm receiver. This can be sped up by first clicking on `Select alternative parameters` and selecting the tuning parameters from a recent tuning similar to the desired one and then clicking on `Quick-tune`. It is possible that certain receiver parts still need optimising after a quick tuning, which will be visible in the `AUTO-TUNE DISPLAY` as boxes that have not turned green.

The changes to the local oscillator (LO) as the tuning procedure progresses can be monitored in the `SPECTRUM ANALYZER DISPLAY`, see Sect. 2.2.17.

#### 2.2.14 CAL

`CAL` in the top menu bar opens the `CALIBRATION CONTROL` window shown in Fig. 5.18. It displays the temperature used for the calibration load, the receiver temperature as measured by the selected spectrometers, and updates the system temperatures, chopper wheel correction factors, and optical depths at the current elevation and zenith after each calibration spectrum. The receiver and system temperatures are also printed in the feedback window, but the observer may find it easier to get all the calibration values from `CAL`.

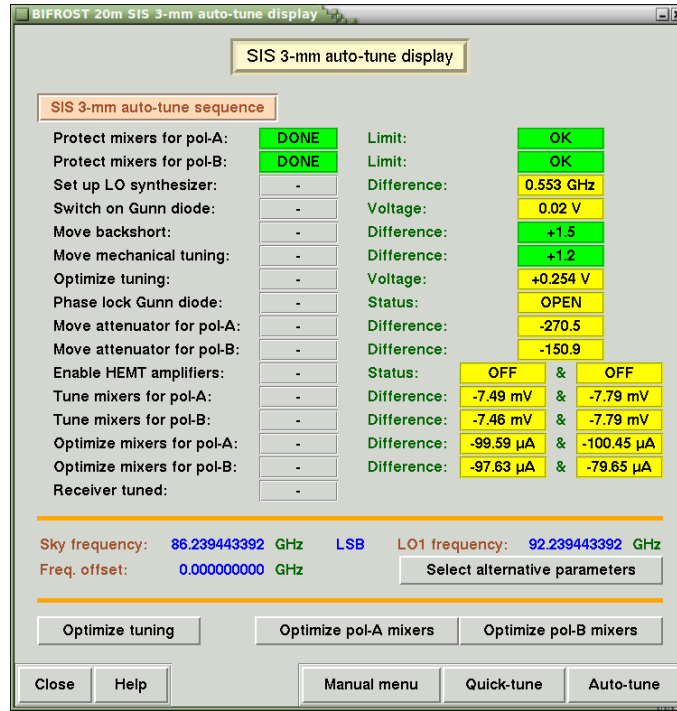
#### 2.2.15 BACKEND

`Backend` opens the window shown in Fig. 5.19(a). From here, the observer can configure the spectrometers and adjust their input levels. This should be done after source changes, weather changes, retunings, and in general at regular intervals. The `Adjust` task takes up to 30 seconds for the new FFTS (OSA), and 7 seconds for the old FFTS (SPE). The `FEEDBACK` window will show when the adjustment is completed.

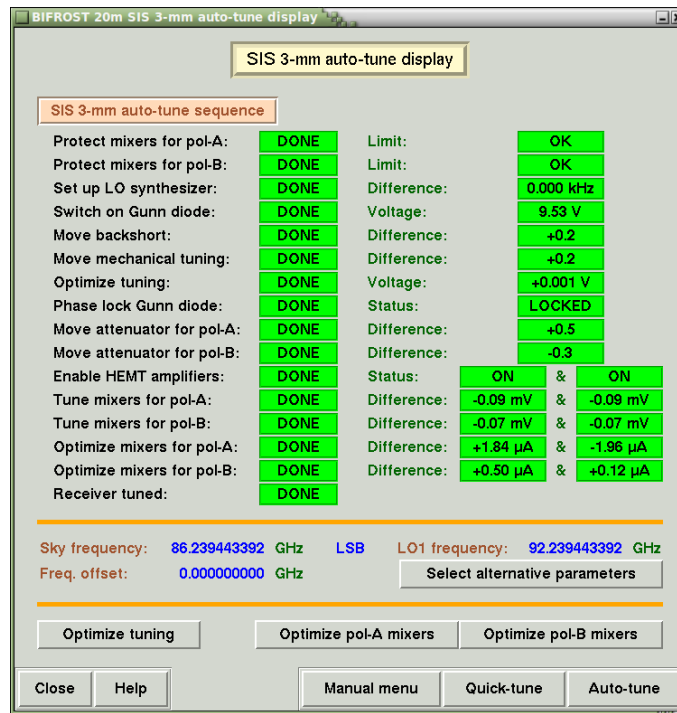
The `Setup` buttons open a window for the appropriate backend from which it can be configured. Figure 5.19 shows the corresponding window for the FFTS, which vertically lists four possible configurations involving different bandwidths and resolutions:

- ◇ 1 × 16k channel A
- ◇ 1 × 16k channel B
- ◇ 2 × 8k low resolution A+B
- ◇ 2 × 8k high resolution A+B

In single-polarisation observations, only the first and last option are meaningful: the first gives 1 GHz bandwidth and 61 kHz channel separation, and the latter 100 MHz bandwidth and 12.2 kHz channel separation. In dual polarisation, options three and four are the ones normally used: 2 × 500 MHz bandwidth and 61 kHz channel separation, or 2 × 100 MHz bandwidth and 12.2 kHz channel separation. If option one or two is used in dual-polarisation mode, it will give 1 GHz bandwidth spectra of *one* of the two polarisation components exclusively (i.e., the other is lost for this spectrometer). In single-polarisation mode, options one and two should be completely redundant since the spectra produced in the two configurations are taken from the same IF-signal. Nevertheless, we recommend to always use option one in this case to avoid confusion.



(a) Auto-tune display before tuning



(b) Auto-tune display after successful tuning

FIGURE 5.16 – SIS 3 MM AUTO-TUNE DISPLAY before and after tuning.

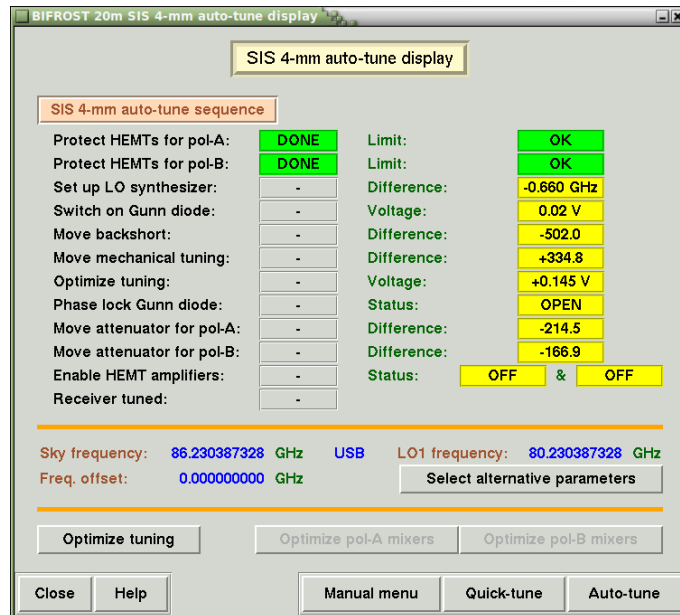


FIGURE 5.17 – SIS 4 MM AUTO-TUNE DISPLAY before tuning.

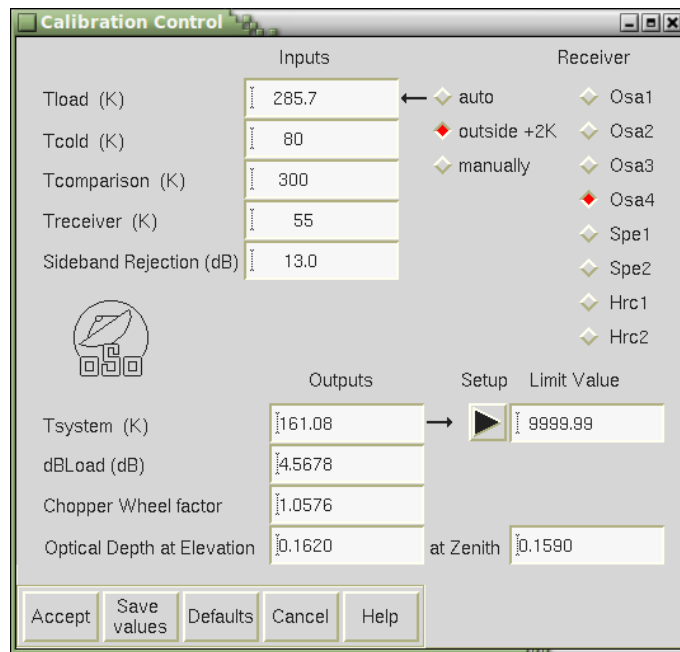


FIGURE 5.18 – The CALIBRATION CONTROL window brought up by CAL in the top menu bar.

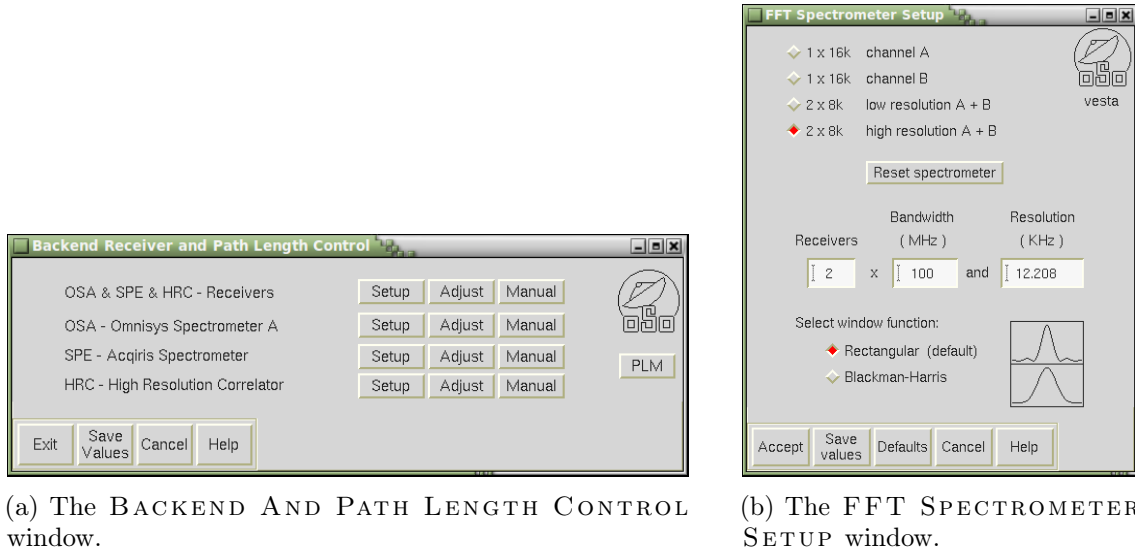


FIGURE 5.19 – Windows relevant to backend configuration.

There is an additional choice in the FFTS setup window, namely “Select window function”. This should normally be set to “Rectangular”. The other option, “Blackman-Harris”, can have some effect to suppress spikes if the input power levels are fluctuating, e.g., in bad cases of RFI. It also has a somewhat smoother channel filter profile curve. There are however significant drawbacks: the ENBW (Equivalent Noise BandWidth) of the spectrometer goes up without the actual channel noise RMS going down, meaning that a fraction of the observation time is effectively lost when this option is used.

### 2.2.16 SIS 3/4 CONTROL

The SIS-3/4 button in the top menu bar opens the SIS 3/4 CONTROL window, shown in Fig. 5.20. This control window gives access to a list of procedures, e.g. tuning or shutting down the receiver, and a list of tools to monitor and control e.g. the mixers or the receiver status.

Clicking `Status monitor` brings forward a window where different receiver stability parameters are monitored. Most important are the three values listed on the first line: a phase lock flag, an error voltage, and the AGC voltage (in that order of importance). The phase lock alarm (which can be activated at any time by the observer by invoking `ALARM`) continuously checks all three parameters to ensure good tuning stability. Observers should check the status monitor window immediately after a successful tuning. If the listed currents are orange/red already right after a successful tuning, retuning will most likely not solve the issue. In this case, the observer should make sure the values do not drift outside the range  $25 - 50 \mu\text{A}$ . If the reported currents are blue after successful tuning, we advise the observer to retune in case the numbers have turned red after some time.

### 2.2.17 SPAN

The SPAN tool is a graphical interface to a spectrum analyser physically located in a rack opposite to the control computer display – Fig. 5.21. Here one can see the

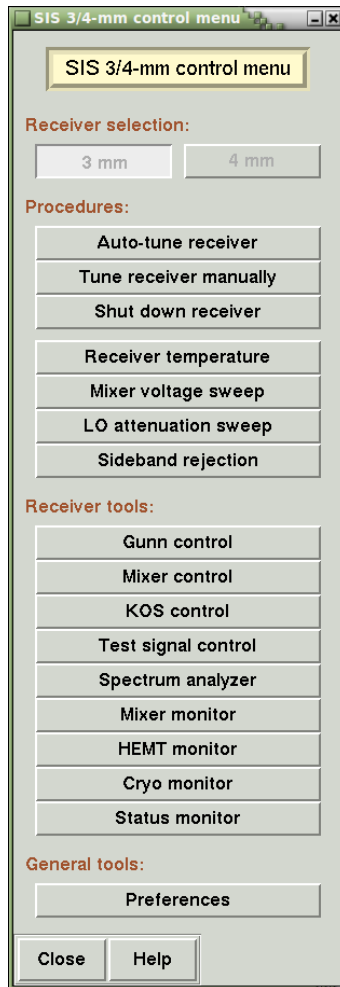


FIGURE 5.20 – The SIS 3/4-MM CONTROL MENU, brought up by clicking SIS-3/4 in the top menu bar.



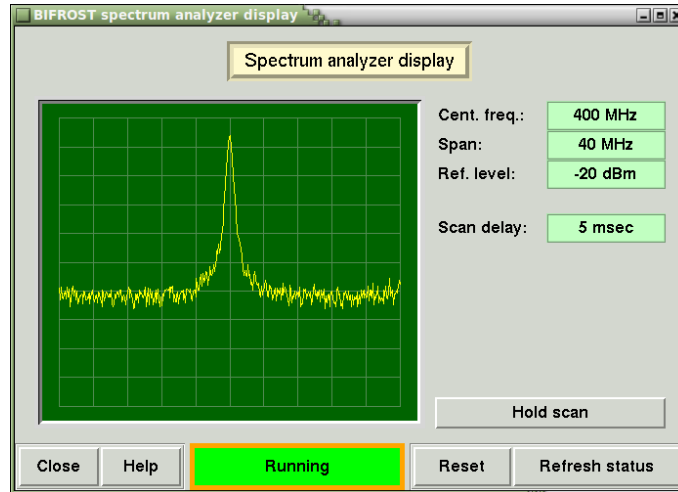


FIGURE 5.21 – The SPECTRUM ANALYZER DISPLAY, brought up by SPAN in the top menu bar.

IF-band or the phase lock loop signal in real-time. The bandwidth of the current view can be changed, which can be of particular use when trying to lock the phase as part of the tuning procedure.

### 2.2.18 MAX

Good pointing accuracy for radio telescopes can only be achieved if pointing runs are conducted regularly to account for long term changes of climate conditions and/or slow elastic gravitational deformation of the dish. At OSO, 24-hour long pointing runs, observing point-like SiO masers distributed throughout the sky, are done whenever needed to ensure a good pointing to within a few arcseconds rms.

To account for short term changes in weather conditions and/or thermal deformation of the dish or the subreflector supports due to temperature changes, observers are advised to check the pointing and focus throughout their observing runs. Especially during drastic temperature changes between day and night the focus can change as much as 2 mm in extreme cases. For point sources, such a change implies an intensity loss of 20% and 30% at 85 GHz and 115 GHz, respectively. We advise observers to conduct a pointing/focus measurement at least twice a day, after sunrise and sunset.

Typically, pointing and focus observations are carried out towards point-like SiO masers, available in the system in a pointing-source catalogue. Once the receiver is tuned to the correct frequency, the MAX CONTROL window is opened by pressing `Max` in the top menu bar – Fig. 5.22. The observer can choose the number of pointing and focus iterations and whether only one or both procedures shall be carried out. For the pointing, each iteration consists of five spectra taken at the centre position and at  $\pm$  azimuth and  $\pm$  elevation offsets relative to the centre. If not otherwise specified, the “Velocity Range” (spectral range used in the fitting procedure) is set automatically by MAX CONTROL, based on the pointing-source catalogue entry, and should not be changed. For the focus, the programme observes the source at an initial focus offset, then at “centre  $\pm$  spacings”. These are actual relative positions of the subreflector along the  $z$ -axis in millimetres (the maximum

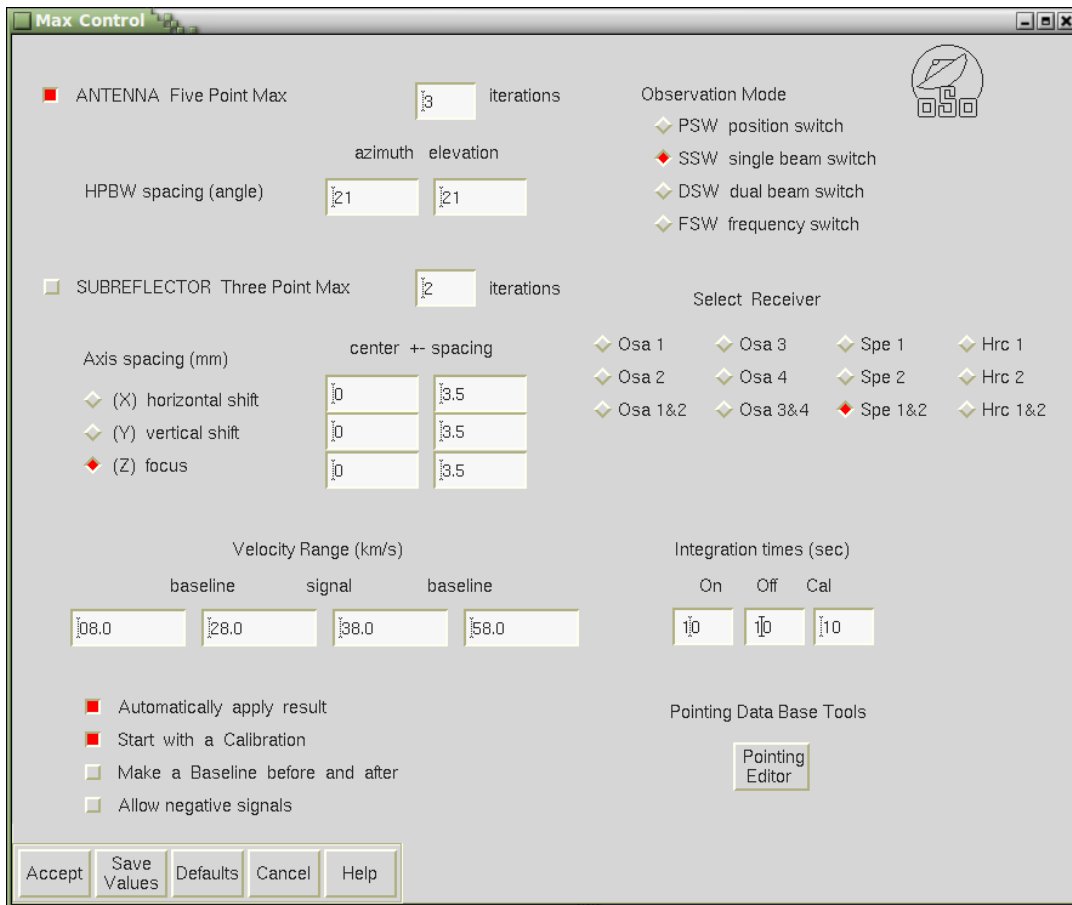


FIGURE 5.22 – The MAX CONTROL window, brought up by MAX in the top menu bar and used to command pointing and/or focus observations.

span is  $\pm 7.5$  mm). We advise the observer to choose zero as the starting value. Note that the spacing is frequency dependent and is approximately equal to the wavelength at which the observations are done.

The SPE backend is used in most cases in a relatively narrow-band configuration. Single beam switch (SSW) mode is typically sufficient when using the 3 mm and 4 mm receivers. Dual beam switch (DSW) can be useful if continuum sources are used. For the broadband receiver, we recommend using PSW.

Selection boxes further allow to choose whether a calibration should be done before the start of an iteration (a calibration is usually only needed for the first pointing), and whether the pointing or focus results should be applied automatically. The latter is to be selected when multiple iterations are requested, since each subsequent loop should be done around the previous fit result to optimise the averaged result. By default, this option is checked.

The observer can also adjust the integration and calibration times. The default is 10 seconds for all of these. In case of bad weather it is advised to adjust the on and off times to 20 seconds, for more stable solutions.

Once all is set, click on  to start the integrations. This will open two new windows in the upper right corner of the workspace: the upper window indicates the number and total time elapsed of the current iteration and shows the current pointing position within this iteration; the lower window shows the time left on the current integration and the name of the FITS file under which the data will be saved. Once the data have been read out from the spectrometer, the spectra obtained will be displayed on the left in the WWW-GRAPHER window (see Sect. 2.2.21). The display may show a calibration, an actual integration, or an average; this will be indicated by the label on the right next to the spectrum. The source name is shown above the spectrum. More information, i.e. what type of spectrum is being obtained, which of the pointing positions is being observed, and at the end of each loop, what pointing corrections will be applied, will be displayed in the feedback window.

The pointing offsets, derived in azimuth and elevation, are calculated from a two-dimensional Gaussian fit to the data and treated as pointing offsets to the applied pointing model. At the end of a sequence, the pointing offsets are sent to POINTING and the subreflector pointing data to SUBREFLECTOR CONTROL.

The spectra obtained during the pointing and focus are saved in the same directory as your other data, and are named NNNNNN $x$ .fits or NNNNNNX.fits – see Sect. 2 in Chapter 4.

### 2.2.19 SINGLE

SINGLE will open the SINGLE POSITION OBSERVE CONTROL which allows the observer to set up and start integrations – Fig. 5.23. The most important settings are the “number of spectra” to be observed, the number of spectra between calibrations (“calibrate before every”), and the “Integration times” for the on-source and off-source positions and for the calibration. The off-source time is only used in case of PSW observations, where it is the time spent on the reference position. Note that for PSW and FSW observations, a reference position for the calibration measurement is taken from CATS. For PSW observations, the reference spectra are

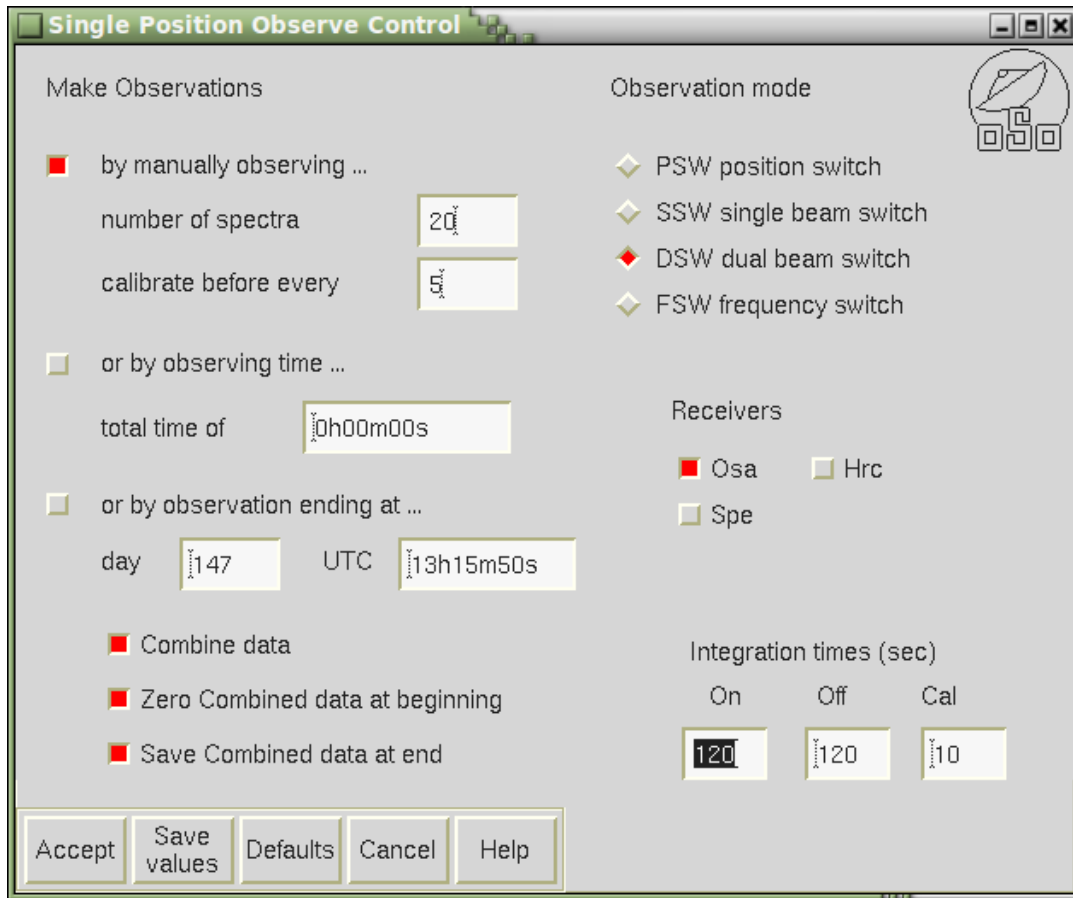


FIGURE 5.23 – The SINGLE POSITION OBSERVE CONTROL window, brought up by clicking SINGLE in the top menu bar. This window lets you control the basic settings for observations of a single sky position at a given frequency.

taken *before* each on-source spectrum. If no reference position is supplied by the observer, a relative throw of  $6'$  in azimuth is used by default. The same is true for the calibration measurements in PSW and FSW modes.

Clicking on  will move the telescope to the currently commanded position and collect the requested number of spectra along with the specified number of calibrations. As soon as the integration begins, two windows will open on the right indicating the current integration status. Once a spectrum has been obtained it will be displayed on the left in the WWW-GRAPHER window (see Sect. 2.2.21). The selection boxes in the SINGLE POSITION OBSERVE CONTROL also allow to “Combine data” to be shown in the WWW-GRAPHER window and to “Save Combined data at end” of a loop. If, after a first loop, more spectra are obtained in a second loop, and these are to be added to the previous average to obtain a new total average, the “Zero Combined data at beginning” option should be off. Individual spectra have unique, incremental scan numbers and are saved in files following the convention NNNNNNs.fits, whereas averages are saved with the extension S.fits. Calibration scans are saved with the extension c.fits. In PSW mode, the raw reference spectra are saved with the extension r.fits. See Sect. 2 in Chapter 4 for a summary of the file naming conventions.

### How to stop an integration

In order to stop an ongoing integration, you need to use the buttons in the window showing the current integration status. The observer can either use **Abort** to make an immediate abort without saving the current integration, or use **Break** to make a smooth stop, waiting until the current integration has finished and then saving this integration and an average, if selected, to disk. In DSW mode, the second spectrum will always be collected before stopping.

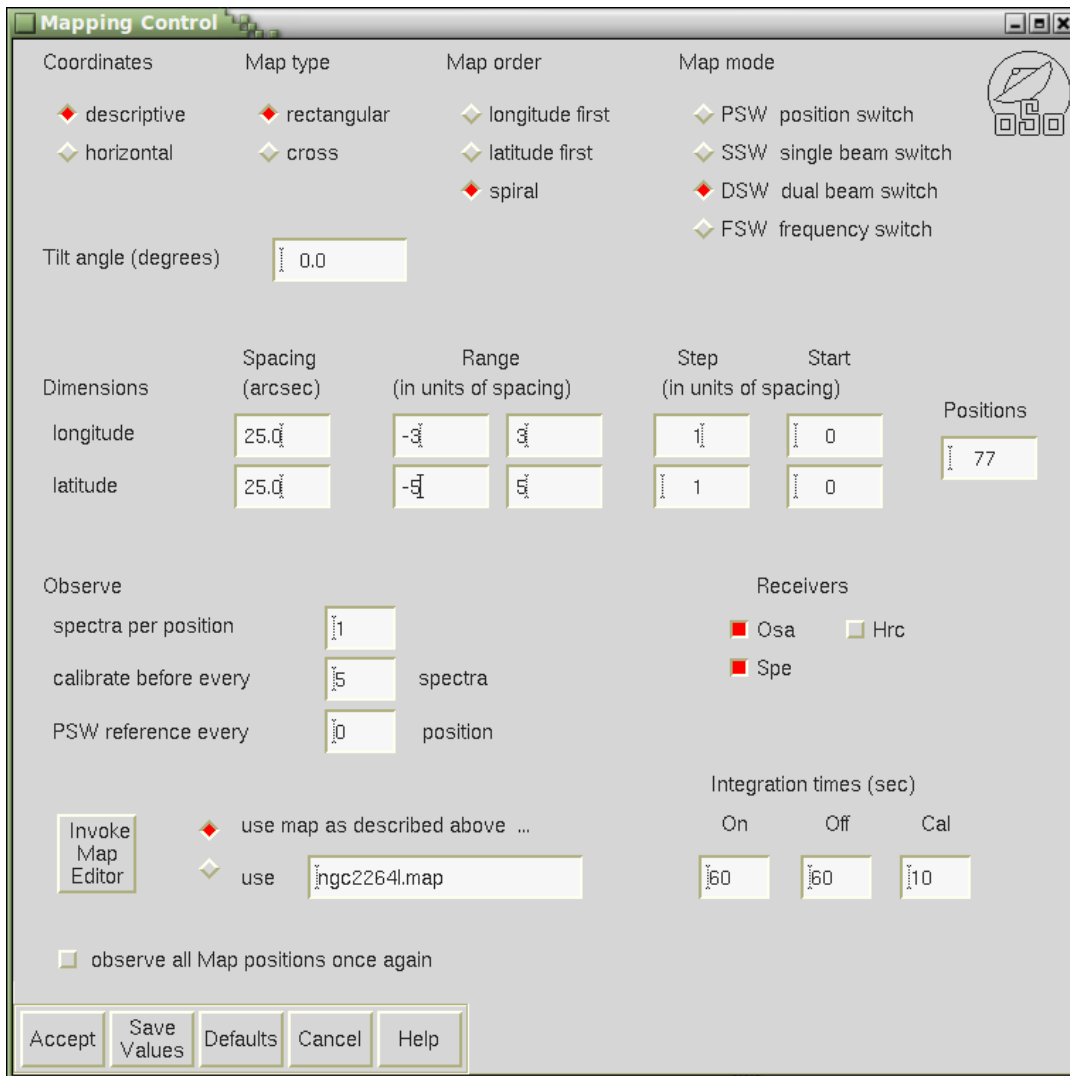


FIGURE 5.24 – The MAPPING CONTROL window, brought up by clicking MAP in the top menu bar. This window allows the observer to set up the basic properties of mapping observations.

#### 2.2.20 MAP

MAP will open the MAPPING CONTROL shown in Fig. 5.24. It offers basic mapping routines that allow one to map an extended source in “descriptive” or “horizontal” coordinates. For standard mapping a “rectangular” or “cross” map can be selected, which will then simply take the map, defined by “Spacing” in arcseconds and

“Range”, “Step” size and “Start” position in units of map spacing. The total number of map “Positions” will automatically be calculated and shown on the right in the box under “Positions”.

The grid coordinates (“longitude” and “latitude”) of the map are defined with respect to the current source position defined in `SOURCE`. A selection box allows to choose if the map should be done “longitude first” or “latitude first” or in “spiral” mode. The map can also be tilted w.r.t. the coordinate system. For mapping galaxies the normal convention is to define the “Tilt angle” or position angle (P.A.) of the major axis as increasing from north towards east. Thus in order to have the major axis of a galaxy defined along the Y-axis the tilt angle should be set to P.A..

After setting the desired selection boxes in `MAP`, make sure that the selection box “use map as described above” is activated if the map is supposed to be created based on this description. However, any type of *special* map (e.g. O-, S-, T-, V-shaped) may be defined with `Invoke Map Editor`. This graphical editor (see Fig. 5.25) allows to define arbitrary grids with positions offset in any way from the source central position. The map is then saved in a file and referred to by indicating the name of this map in the selection box in the bottom left corner of the `MAPPING CONTROL` window. Observers can of course also specify the file name of a correctly formatted descriptive file set up without the use of the map editor. Click `Accept` to start the mapping procedure.

The observing mode is selected in the top right corner, in the same way as done for single pointing observations. The “number of spectra on each map position” to be obtained can be specified, along with how often calibrations and reference position spectra should be taken. If several spectra per position are requested, averaged as well as individual spectra will be saved. Individual map spectra are saved in increasing numbers with the `m.fits` extension, whereas averages get the extension `M.fits`.

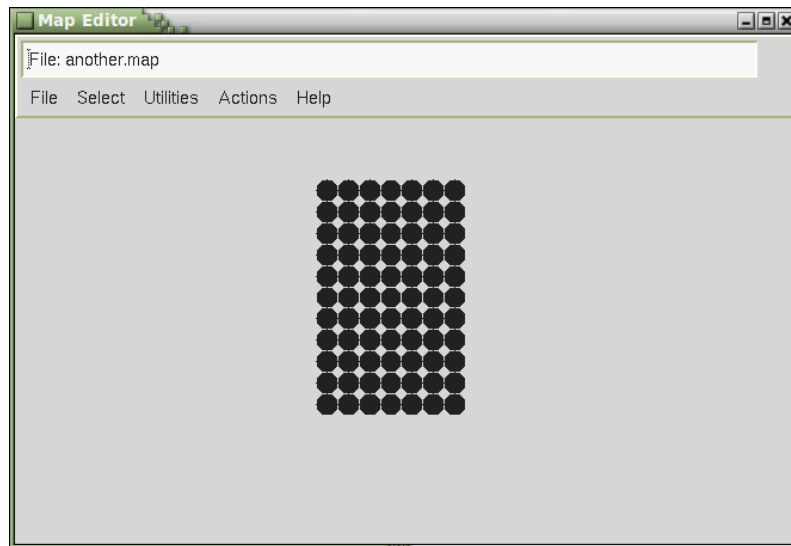
If the observer chooses to “observe all Map positions once again”, averages will automatically be created for each map position. These averages will continue to accumulate any following map spectra for the corresponding positions, until the map is initialised again in the map editor.

### 2.2.21 SHOW and WWW-GRAPHER

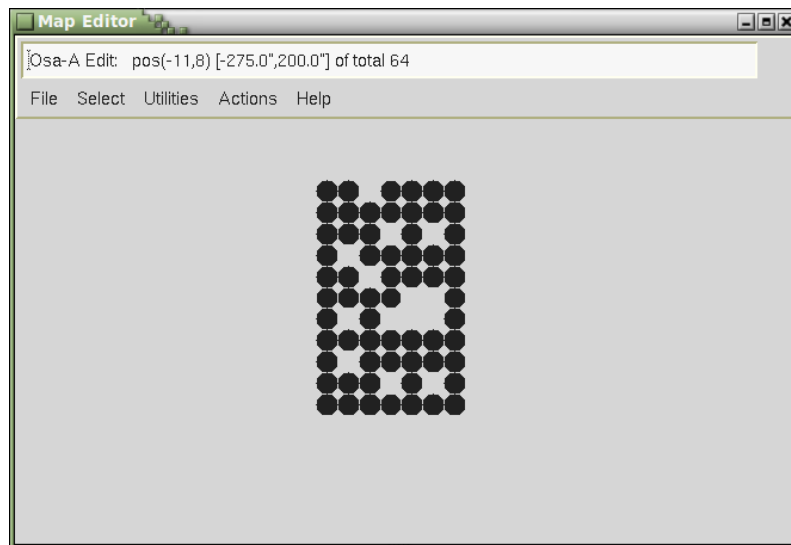
`SHOW` opens a menu where the observer can specify how spectra are displayed in the `WWW-GRAPHER` window – see Fig. 5.26. This is the default manner in `PEGASUS` to display the results of the ongoing observations. The `WWW-GRAPHER` window should always appear when the first integration of any observation is ready. Fig. 5.26 shows both windows in an example configuration.

Different spectra can be visualised on request. For example, if you only want to see the current (latest) spectrum read from the OSA backend, click `Show` in the top menu bar, then click “Zero all”, “Show 1”, “OSA 1” (under “Receiver”), “current” (under “File type”), and `Accept`. Up to 4 spectra can be displayed simultaneously. A standard choice is to show the current spectra obtained along with continuously updated average(s) called “combine”. However, the latter only exist if that option was selected in `Single` or `Map` when the observation was started.

Of course, any type of spectra chosen from the selection boxes may be displayed



(a) Standard rectangular map.



(b) Standard rectangular map with holes.

FIGURE 5.25 – The MAP EDITOR window. Observers can interactively set up arbitrary maps using this graphical editor.

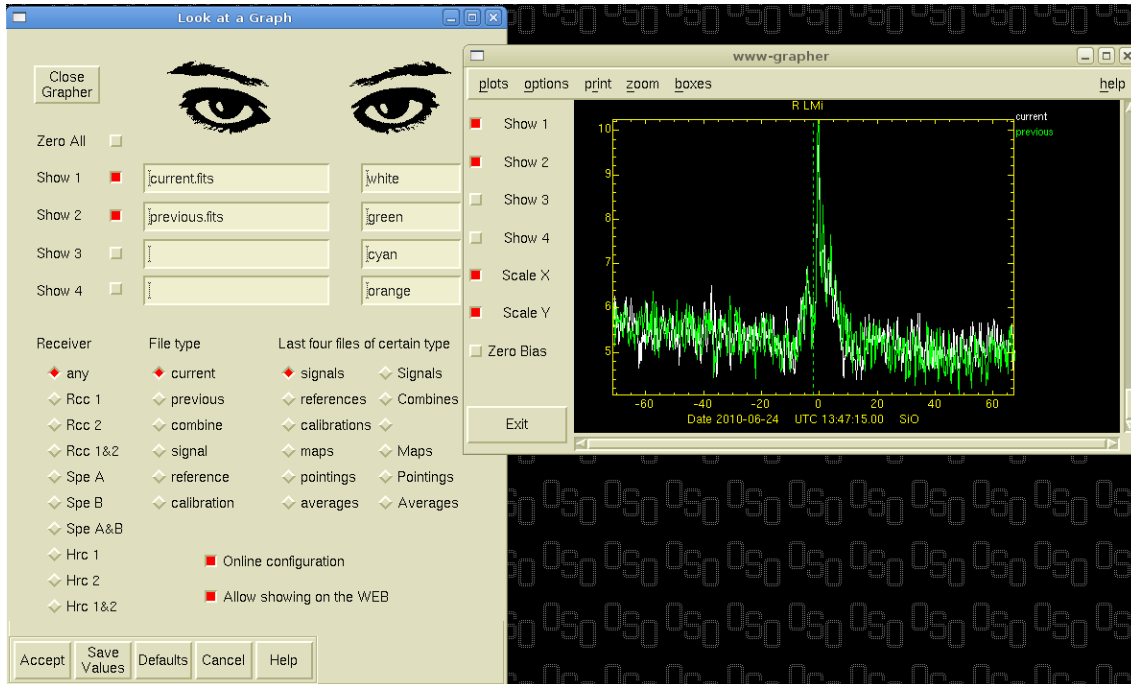


FIGURE 5.26 – The SHOW and WWW-GRAPHER windows.

in this way, e.g. “reference”, “calibration”, etc. Alternatively, you can display the “Last four Files of certain type”, e.g. “pointings” after a pointing, “maps”, or “averages” to see the last four averaged spectra saved to disk.

Older/other spectra may also be displayed without changing the on-line configuration. In this case, without selecting “on-line Configuration”, just type the name of the spectra you would like to see (e.g. 12345s.fits or 67890M.fits) in the “Show 1-4” boxes. You may also use the selection boxes to select the “previous” spectrum or a “reference spectrum”, for example, and again up to four spectra may be displayed simultaneously. As soon as a new spectrum is written to disk, however, the displayed spectrum will be replaced according to what has been selected for the “on-line Configuration”.

To distinguish between plotted spectra, different colours are being used *and* you may toggle spectra on and off by clicking on the corresponding selection boxes labelled “Show 1”, “Show 2”, etc, in the WWW-GRAPHER window. To enlarge a section of a spectrum shown in the display, use the left mouse button to click left and right of the section you would like to see, then click the right mouse button to zoom in onto that section. Clicking the “Scale X” or “Scale Y” buttons resets the spectrum to its full width and height, respectively.

### 2.2.22 COMET

*At the moment, we do not recommend this function to be used as its functionality has not been verified recently and parts of the algorithms may need updating. Instead use ephemerides generated by JPL Horizons through the JPL top menu button, see Sect. 2.2.23.*

At OSO a tracking routine is provided in PEGASUS for the observations of comets or asteroids. COMET will open the TWO BODY EPHEMERIS GENERATOR



PROGRAM shown in Fig. 5.27. Here, “Comet” or “Asteroid” can be selected and the “Orbital Elements” have to be given by the observer according to the Epoch chosen for these “Input Elements”. The “Output Ephemeris” can be set to B1950.0 or J2000.0 to produce a printout of the precessed coordinates (movement of the object in R.A. and Dec. in respect to UT), extrapolated between the given “Begin Date” and “End Date” in time units given in “Step Size”. For “Program Options and Setups” the “Option 2 variables” should be selected. The Doppler Correction should be set automatically, once the tracking is started with `Accept`, and you can check this in CATS or FREQUENCY CONTROL.

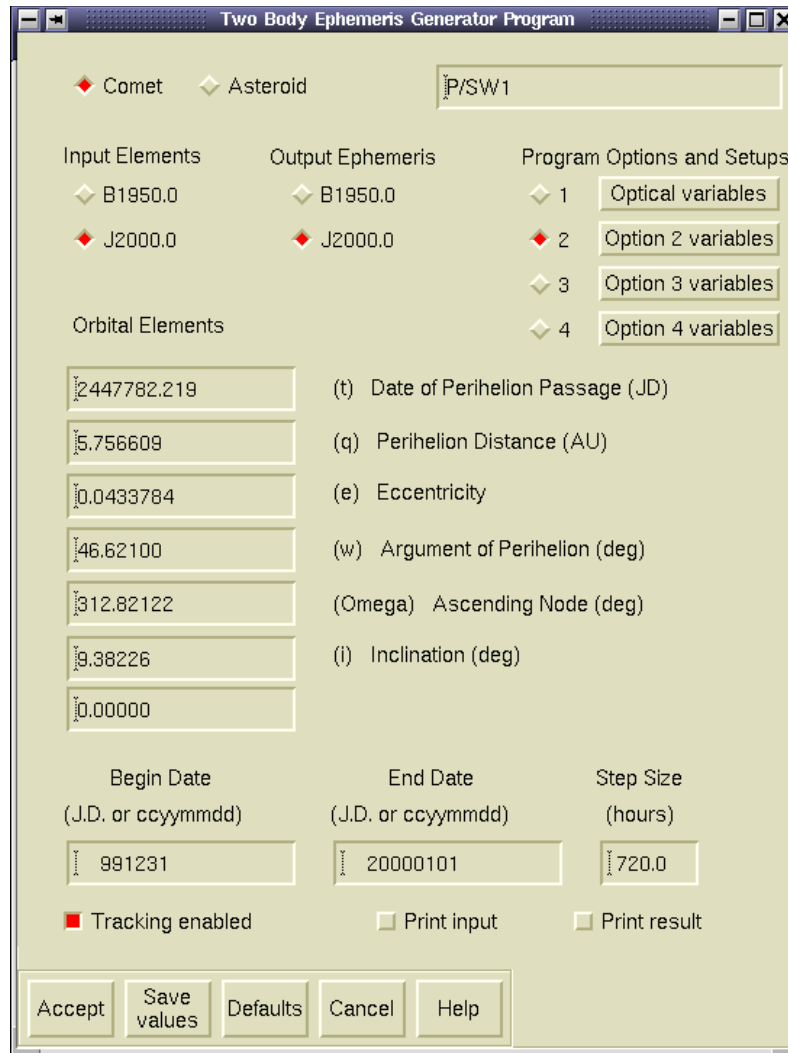


FIGURE 5.27 – The TWO BODY EPHEMERIS GENERATOR PROGRAM window.

### 2.2.23 JPL HORIZONS

Via the `JPL` button, PEGASUS offers a tracking routine for observations of objects described in a JPL Horizons Ephemeris file. Any user supplied file can be used but it needs to follow strict format conventions; consult staff. However, the easiest option is to let PEGASUS download the ephemeris file using the `ephemwin`

programme. This programme can either be started from a `Shell` window or by clicking “Download ephemeris” in the JPL HORIZONS window. When the `Accept` button is pressed, it produces a new ephemeris file named `horizons.out`, in a format specific to the ACAPS antenna control programme. The file is automatically and immediately sent to the `jupiter` machine (on which ACAPS is running) and the telescope will start to track the object. Note that this file is only valid for 24 hours and must hence be regenerated every new observation day.

### 2.2.24 FILES

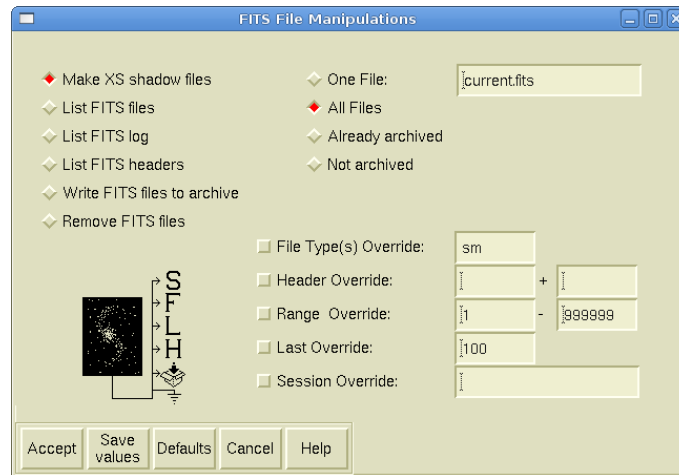


FIGURE 5.28 – The FITS FILE MANIPULATIONS window, brought up with FILES from the top menu bar.

FILES opens the FITS FILE MANIPULATIONS window shown in Fig. 5.28. It is used to list, check or backup data files, which have been written to disk. It is possible to simply just check the numbers and types of the FITS files to see which spectra have been taken so far (“List FITS files”), to list some short information like the frequency and map position (“List FITS log”), or to view the entire FITS header of each file (“List FITS headers”). “Make XS Shadow files” is used to create a subset of the observed FITS files that is reachable by the workstation `brune` for data reduction in the `shadow/` directory. This can be useful when one wants to work on only a subset of data files without being slowed down by e.g. the increasing data volumes caused by newly obtained data. The menu also includes “Remove FITS files”. This function deletes scans from the user’s account and consequently a great deal of care should be taken to configure the scan selection filters correctly before using it.

The selection boxes can be used to choose “One File” or “All Files”, in which case a “File Type(s) Override”, i.e. `s` for single, `S` for averaged, `m` for single map, `M` for averaged map, `x` for pointing, `X` for central position pointing spectra, etc. and/or a “Range Override” can be set to restrict the FITS files handled by the FITS FILE MANIPULATION. These boxes should be checked carefully, before clicking on `Accept`. All FITS FILE MANIPULATIONS commands may be done on-line without any interference with the observation.

#### Data backup

All obtained spectra are saved as FITS files and they are written to two separate

directories in real-time. On top of that, daily backups are made to a separate computer. User backups of project data as gzipped tar files can be made by choosing the option “Write FITS files to archive”. The name of the created file will be displayed in the feedback window. This file can now be copied to a USB memory stick or burned on a DVD.

After each project is finished, the observer should make a full archive backup of *all* their data in FITS format and make sure to take it on departure, or download it promptly through the UbuntuOne cloud service if that is the arrangement agreed upon. The observatory *can* provide backups of older data from our own archive in case the original user backup was lost by an observer but this service is not guaranteed. It is in principle the observer’s responsibility to retain a copy of the data after a project is completed.

Note that other file types such as `.cat`, `.map`, and `.job` files, used to configure the observations, *may not be archived at all*. We advise observers to make their own copies of them before leaving (for book-keeping purposes or later reuse).

There is no on-line observing log. The observers are responsible to set this up themselves. Paper log sheets are available in the control room.

### 2.2.25 EDIT

EDIT opens a menu from which different editors can be chosen to edit files (e.g. source lists) on the observer’s guest directory.

### 2.2.26 JOB

JOB is a simple tool to programme a series of observations as a batch job, saved as an ASCII file. It has limited functionality and it is not explained further here, but a few sample files can be seen in Appendix A. Ask the staff if you need help to configure a job file for your project.

### 2.2.27 SHELL

This command opens a terminal window with an operating *bash* shell in the observer’s home directory. Here, one can perform any common operation, like listing, editing, copying, deleting, or transferring files.

### 2.2.28 EXIT

Click EXIT to end an observing run and log out of the account. Before doing this, the telescope must be stopped in ANTENNA CONTROL and *CtrlC* pressed in the ACAPS CONSOLE window. This can be followed by typing *shutdown* if you were instructed by staff to do so. Additionally, staff might request you to shut down the receiver you were using. Only do this after explicit instructions. The ALARM STATUS should also be aborted if active.

If you want to make a daily or final backup of your data (see FILES), it should be done before you press Exit. Make sure you have a few minutes left before the end of your run and do not rely on the next observer to give up any time to allow you to make backups.

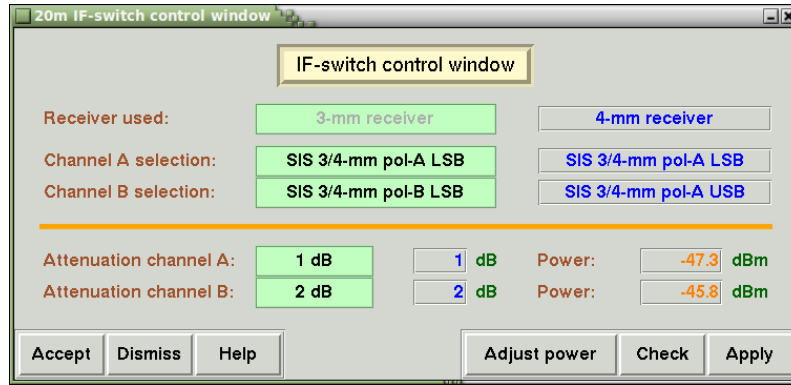


FIGURE 5.29 – The 20M IF-SWITCH CONTROL WINDOW shows which receiver is in use and what part of the observed spectrum the different spectrometer channels will record. In this example only the LSB will be recorded for the chosen tuning, and the two backend channels will record the two different polarisations, here called pol-A and pol-B.

### 2.2.29 IF-SWITCH

The IF-SWITCH button in the top menu bar calls forward the 20M IF-SWITCH CONTROL WINDOW – see Fig. 5.29. This window shows which receiver is in use and lets the observer choose which part of the spectrum will be recorded by the backend. Note that the active receiver cannot be changed from this window. The observer can freely select to e.g. monitor only one sideband (LSB or USB) in two polarisations (pol-A and pol-B), or both sidebands (LSB and USB) in only one polarisation (pol-A or pol-B). An upgrade to the backend will allow the recording of both polarisations in both sidebands, i.e. making full use of the sideband-separating and polarising capabilities of the new receivers, at 2.5 GHz bandwidth in each sideband.

Click  after selecting the appropriate backend channels. Throughout the observations, these different channels will be recorded in separate fits files, with the according information on sidebands and polarisation written in the header (see Sect. 3 in Chapter 4).

### 2.2.30 WEATHER

WEATHER opens the WEATHER STATION window shown in Fig. 5.30. It displays relevant weather information obtained from the OSO weather station. For the humidity, only the relative value is obtained, while the absolute humidity is calculated in the subsequent programs. These data are used to calculate the atmospheric refraction and are essential for a correct pointing of the telescope. If the communication with the weather station fails, indicated by a value larger than 10 minutes in the lower right corner, the weather data have to be typed in. If you cannot get the ones for the 20 m telescope from the OSO weather display (Fig 5.5), then enter those reported in that window for the 25 m telescope. When doing so, turn off the three buttons labelled “Temperature”, “Pressure” and “Humidity” for the system to accept these manually added values.

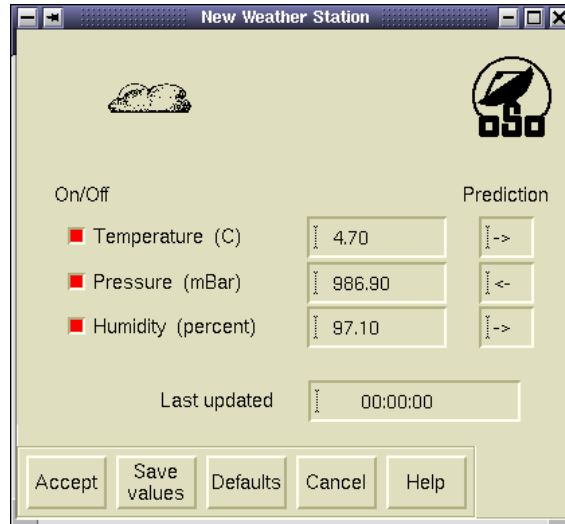


FIGURE 5.30 – The WEATHER STATION display.

### 3 Summary of a typical observing session

#### 3.1 Starting a session

- Log onto a session on the `munin` workstation.
- Enter project details in the pop-up window.
- Follow the start-up action list. Each step is described in this chapter. Usually a pointing source is selected when tracking is started with `Cats`.

At this stage you are tracking a source and have configured the spectrometer(s). The most common ensuing sequence is then:

- Select and tune to an SiO maser in order to perform a pointing measurement by clicking `LINES`. The receiver tuning procedure is described in Sect. 2.2.13 of this chapter.
- Click on `Backend` and click the `Adjust` button for each spectrometer that is being used. It is convenient to leave the `BACKEND RECEIVER AND PATH LENGTH CONTROL` window open as you need to do adjusts after every source change or retuning. Reconfiguration of the spectrometers is also done from here through the `Setup` buttons.
- Start a pointing measurement using `Max`. It can be a good idea to first verify that you are using a sufficiently strong SiO source by doing a short integration with `Single`. `Max` and `Single` are described earlier in this chapter.
- If the pointing and/or sub offsets found by `Max` are not deemed realistic (can happen if the weather is unstable or the source is too weak) the values can be manipulated manually with `Pointing` and `Sub`. The best option is however to try again using another pointing source.

- Now the astronomical observation can begin by tracking the science source (`Cats`), setting the observation mode (`Obsmode`), tuning to the desired line/frequency (`Lines` or `Doppler`), configuring the spectrometers and doing adjusts (`Backend`), and starting integrations (`Single` or `Map`).
- Don't forget to start the `Alarm` once the observations are running as intended.

### 3.2 Ending a session

- Stop the tracking of the antenna in `ANTENNA` by pressing “Stop” and `Accept`.
- Click on `Abort` in the `ALARM STATUS` window if the alarm programme was started earlier.
- Press `Ctrl+C` after activating the `ACAPS CONSOLE` window. Type `shutdown` in the same window *only* if you were instructed to do so.
- Press `Exit` in the top bar menu.

## 4 Troubleshooting

### 4.1 Telescope runaway

One of the following measures will stop the telescope:

- Click on `ANTENNA`, select “Stop” and then `Accept`.

If this doesn't help,

- push one of the two red 20 m emergency buttons in the control room. These are located towards the upper left on the wall of racks opposite to the `munin` control computer display.

Naturally, staff should be alerted as soon as possible after such an event has taken place.

### 4.2 Errors reported in the `FEEDBACK` window

If an error is reported in the `FEEDBACK` window, it may aid the troubleshooting to investigate if it has happened previously and to note the times, scan numbers involved, etc. By pressing `Error` in the top menu bar, a list will show up in which only error messages are selected from the sometimes crowded `FEEDBACK` window. Press `Error` again to make it disappear.

### 4.3 Clock failure

The internal clock in `jupiter` was known to jump by integer seconds on rare occasions. The problem should now be completely eliminated but the clock is still monitored by `ALARM STATUS` (if selected) and on-screen in a small window showing the current deviation. In the unlikely event this problem occurs again, the clock must be reset. A tool exists for that purpose, a shell command called `netime`, but it is not updated for the current system configuration. Thus, *staff should be alerted* before any action is taken.

#### 4.4 FEEDBACK window disappears

- Click on `Shell` from the top menu bar to get a terminal.
- Command `start_show_feedback`, followed by an `exit` from the terminal window.

#### 4.5 Other trouble

If ACAPS would need to be rebooted or in the case of PLC failures, please contact observatory staff to recover from these events. In case of any unidentifiable observing trouble or insecurity about what procedures to follow, please also contact staff before improvising a solution.

# APPENDIX A

## SAMPLE JOB FILES

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This appendix contains several sample job files. Observers have to remember that they cannot mix the `MAX`, `SINGLE`, and `MAP` modes of observation within one such job. Although most users will not want to run a job for pointing/focus, one of the sample job files included here shows how a typical pointing run could be carried out.

Since the tuning cannot always be optimised from within a job file, it is possible that the phase lock loop deteriorates when changing tuning frequency considerably throughout the job execution. This might be the case when sources in the list have large differences in systemic velocity, causing rather large shifts between consecutive sky frequencies. In this case, the error voltages in the status monitor window (see Sect. 2.2.16 in Chapter 5) could indicate such issues.

When observing many sources of which some of them are up for only a short time, one might want to spend as much time as possible on these latter sources in the time they are up. One way to do this is to define a relatively short integration, e.g. in a `SINGLE` with 5 scans, and to then command the telescope to these sources many times in the job list. As long as the sources are not up, the job will skip them. Once they are up, they will indeed be observed more often than the other sources, according to the number of entries in your job file.



```
#####
# Below are the available variables that can be used to control a JOB.
# Values are taken from here and updating the corresponding windows
# unless the line is commented out with a '#' sign.
#
# Some modifications have been made to this automatically generated
# header for clarity.
#####
#
{ OBSERVER someone }
{ COMMENT This is a demo job file }
{ CATALOG user somecatalogue.cat }
#
# Either uncomment:
#
# ...the three lines below for pointing runs
# { MAX antenna=3 spacing=21,21 }
# { MAX subreflector=2 focus=-0.2,3.5 }
# { MAX ssw rcc int=10,20,10 calibrate !baseline apply }
#
# ...or the line below for single position observations
{ SINGLE fsw observe=20,5 speA !speB rcc int 60,60,10 average !zero save }
#
# ...or these three lines for mapping
# { MAP psw observe=1,26,5 !speA !speB rcc int 10,22,10 !force }
# { MAP horizontal rectangular spiral tilt=0.000 }
# { MAP spacing=20.0,20.0 range=-6,6, -6,6 step=1,1 start=0,0 }
#
# Optional commands executed prior to each SOURCE:
# { UTC hh:mm 30m }
# { ANTENNA stop }
# { MOLECULE Sio }
# { ADJUST }
{ ADJUST spe,rcc }
# { EXECUTE antenna -mode position -azim ' -90 ' -elev 10 }
#
-----
S140
NGC2024
W51N
Mon R2
B335
```

```
#####
#
{ OBSERVER someone }
{ COMMENT   }
{ CATALOG user somecatalogue.cat }
{ SINGLE psw observe=30,5 spe osa int 60,60,10 average zero save }
#
-----
#
SOURCE_1
SOURCE_1
SOURCE_2
{ ADJUST spe,osa }
SOURCE_2
SOURCE_2
SOURCE_2
SOURCE_2
SOURCE_2
SOURCE_1
{ ADJUST spe,osa }
SOURCE_1
SOURCE_1
SOURCE_1
```

---

```
#####
#
{ OBSERVER someone }
{ COMMENT   }
{ CATALOG user somecatalogue.cat }
{ MAP psw observe=1,10,5 spe osa int 60,60,10 force }
{ MAP file=mymap.map }
-----
{ ADJUST spe,osa }
SOURCE_1
```

```
#####
#
{ OBSERVER someone }
{ COMMENT   }
{ CATALOG user somecatalogue.cat }
{ SINGLE psw observe=5,5 spe int 30,30,10 average zero save  }
#-----
#
{ COMMENT v1 }
{ EXECUTE dop -rest 43122.080 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_1
SOURCE_2
{ COMMENT v1 }
{ EXECUTE dop -rest 43122.080 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_2
{ COMMENT v2 }
{ EXECUTE dop -rest 42820.587 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_2
{ COMMENT v3 }
{ EXECUTE dop -rest 42519.379 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_2
#
{ COMMENT v1 }
{ EXECUTE dop -rest 43122.080 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_3
{ COMMENT v2 }
{ EXECUTE dop -rest 42820.587 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_3
{ COMMENT v3 }
{ EXECUTE dop -rest 42519.379 }
{ EXECUTE spes -R }
{ SINGLE psw observe=10,10 spe int 30,30,10 average zero save  }
SOURCE_3
#
```

```
#####
#           POINTING RUN AT 86GHz
#####
{ OBSERVER observer }
{ COMMENT   }
{ CATALOG  pointing 86 }
{ MAX antenna=3 spacing=21,21 }
{ MAX subreflector=0 focus=0.0,3.5 }
{ MAX ssw osa5 int=10,10,10 calibrate !baseline apply }
#
-----
{ ADJUST osa }
{ MAX ssw osa5 int=20,20,10 calibrate !baseline apply }
IK Tau
{ MAX ssw osa5 int=15,15,10 calibrate !baseline apply }
Ori IRC2
{ MAX ssw osa5 int=40,40,10 calibrate !baseline apply }
V Cam
{ MAX ssw osa5 int=30,30,10 calibrate !baseline apply }
TX Cam
{ MAX ssw osa5 int=20,20,10 calibrate !baseline apply }
R Leo
{ MAX ssw osa5 int=30,30,10 calibrate !baseline apply }
S CrB
{ MAX ssw osa5 int=60,60,10 calibrate !baseline apply }
S UMi
{ MAX ssw osa5 int=15,15,10 calibrate !baseline apply }
Ori IRC2
{ MAX ssw osa5 int=20,20,10 calibrate !baseline apply }
chi Cyg
{ MAX ssw osa5 int=30,30,10 calibrate !baseline apply }
T Cep
{ MAX ssw osa5 int=20,20,10 calibrate !baseline apply }
R Cas
```

# APPENDIX B

## ENCODERS

---

In case there is a problem with one of the two antenna elevation absolute encoders, it is possible to carry out the makeshift solution described below in order to continue observing.

- Identify which encoder gives anomalous reading by studying the logs located under `/usr/local/20m/cfht/Logs`.
- Use only the healthy encoder by issuing `useleftenc` or `userightenc` in a Linux shell on `munin`.

This will allow observations to continue until the encoder is repaired or replaced but one penalty is a worse performance from the pointing model manifested by higher offsets measured when doing pointing observations with `Max`.

- To restore normal operation with both encoders, use the command `usebothenc`.

# APPENDIX C

## MAINTENANCE & TELESCOPE DOWN-TIME

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If an interruption for maintenance purposes is required mid-observation the following procedure must be followed:

- If requested, first park the telescope at a predetermined (and most often predefined) position using `Antenna`. This can, for example, be the “Skylift” position.
- After the telescope has reached the commanded position, click “Stop” and `Accept` in the `ANTENNA CONTROL` window.
- Press `Ctrl+C` in the `ACAPS CONSOLE` window, followed by `shutdown` if instructed to do so.
- Upon instruction, turn the key labelled “20-M” to OFF. This key is located on a rack marked “20-M Antenna” towards the upper left behind a transparent sliding door across the aisle from the `munin` control computer. A green light in the centre of the rack should go out when the key is turned.
- Turn the paper sign mounted in the upper right of the windows between the control room and the radome so that the red surface faces the control room.
- Also make sure that as many people as possible are aware that the antenna is being ‘worked on’ (may also include cabin visiting, skylift operations, etc.).

When maintenance is finished, simply follow the procedure in reverse, i.e., turn the sign with the green surface towards the control room, turn the key to ON, command `cycle` and `display` in the `ACAPS CONSOLE` window, and set the antenna in “Run” again in the `ANTENNA CONTROL` window. If it was still in “Run”, then first put it into “Stop” and then into “Run” again. The STATUS flag in the `ACAPS` display will show the text “POWER OFF” until all motors are ready.

In case the antenna was not in use before a session is started, it is possible that the key described above has been left in the OFF position. If so, simply turn it to ON after you have logged in to the system but before any item in the startup

procedure is performed. However, first *always make sure* that the cardboard sign in the window is showing the green surface towards the control room. If it is red, any antenna operation is forbidden (and dangerous!) until staff inform you otherwise.

Normally, the 20-M key should not be operated by non-members of observatory staff/students/operators. Visiting observers should always consult staff if the key is in the OFF position when observations are supposed to commence.

# APPENDIX D

## REMOTE OBSERVATIONS

---

### 1 Conditions

Observations can be conducted remotely using an SSL-encrypted VNC connection. The observer will then see and interact with the desktop of the control computer, as shown inside a window of her/his local computer. Experience shows that the connection speed is typically sufficient for remote observations from within Europe and sometimes from the Americas.

To be allowed to observe in this manner, we require that the user has at least two days of previous on-site experience with 20 m telescope observations.

### 2 Software

One VNC client software that seems to work well on Mac, PC, and Linux, is called TigerVNC. Links to the latest versions can be found at

<https://github.com/TigerVNC/tigervnc/releases>.

However, under Linux/Ubuntu this client may be difficult to find using the package handling software (TightVNC will not work). In this case, “ssvnc” can be used instead which should be searchable under Ubuntu Software Center.

### 3 Servers

The server to log on to for observations is `munin.oso.chalmer.se`. Remote data reduction can be carried out by logging on to `brune.oso.chalmer.se`. Note that we use non-standard ports for our connections as a safety measure against open port sniffers and attacks. Please ask staff for the port number and VNC password to use before doing remote observations and/or data reduction.



# APPENDIX E

## FREQUENCIES AND FITS FILES

---

### 1 How the system is tuned

The control system looks for the user-selected reference frequency which is given in the source's rest frame. Note that this is not necessarily the centre frequency, since the user may have requested an offset. The system calculates the corresponding Doppler-shifted frequency in the topocentric frame based on the total radial velocity difference between the observatory and the source. If any offset is needed or requested, it is added as the last step. The LO is then set to a value that will make this sky frequency the centre of the bandpass.

### 2 What appears in the FITS file

The reference frequency will appear in the RESTFREQ keyword, and the CRPIX1 keyword defines to which channel this frequency refers. The OBSFREQ gives the sky frequency at this channel. These are all unambiguous and strictly correct quantities. The CDELTA1 keyword however – that defines the channel spacing – is only truly valid in the topocentric rest frame. Out in the source's rest frame the channel separation is slightly different depending on the total red- or blueshift (they are only the same if the source is perfectly at rest w.r.t. the observer). We do not correct for this effect but are leaving the topocentric CDELTA1 as is. This means that a frequency axis built up using the CRPIX1, RESTFREQ, and CDELTA1 values will have a slight error in it which will increase with the distance from the CRPIX1 channel (at CRPIX1 itself it is correct). *An example:* consider the rather extreme case of observing a source with a net Doppler velocity of  $+100 \text{ km s}^{-1}$  in a 2.5 GHz spectrometer bandwidth configuration centred at 91 GHz but with a reference frequency far to the side, at 90.0 GHz. The error in the frequency axis near 92.0 GHz will then be about 667 kHz. Note, however, that a sky frequency axis, built up of CRPIX1, OBSFREQ, and CDELTA1 will always be correct at every channel. The simplest way to correct for the effect is to simply recalculate the CDELTA1 value according to

$$\text{CDELTA1}' = \frac{\text{CDELTA1}}{1 - V_{\text{Dop}}/c}$$

The reason the system does not do this automatically is that every spectrum would then have a (very slightly) different frequency axis since the Doppler correction

is continuously updated due to the Earth's rotation and orbital motion as can be seen in the variation in the OBSFREQ value. *Therefore, it is up to the observer to consider this effect in the data reduction and analysis.* In most cases, a satisfactory solution would be to apply the correction according to the expression above, using a  $V_{\text{Dop}}$  average over the whole observational campaign. However, if the campaign is drawn out over different parts of the year and the source is near the ecliptic plane, this may not be feasible since the difference in contribution from the Earth's orbital motion may be up to  $\pm 30 \text{ km s}^{-1}$ . In such cases, frequency corrected spectra from each part of the campaign may need to be resampled to have a common axis before averaging them together.

But, again, this is never a problem if the lines to be analysed are at or close to the reference frequency. And it is never a problem anywhere in the spectra if the total Doppler correction for the source is small.

### 3 Image band frequency

The IMAGFREQ keyword should reflect the image band sky frequency of the reference channel. Strong lines from the image band can leak into the signal band even when the sideband suppression is quite good and it is always a good idea to check if any unidentified lines could come from the image band. Lines will be mapped in mirror image style between the sidebands. Example: if an LSB signalband is centred at 91 GHz and the frequency we are interested in is 90.5 GHz, it means that possible leakage to that channel could come from a USB frequency of  $90.5 + 0.5 + 2 \times \text{IFFREQ} + 0.5 = 103.5 \text{ GHz}$  for an IF frequency of 6 GHz. If we are interested in 91.5 GHz instead, the USB frequency would be  $91.5 - 0.5 + 2 \times \text{IFFREQ} - 0.5 = 102.5 \text{ GHz}$ . A more convenient way to write it would be using a band centre frequency,  $f_c^{\text{sig}}$ .

$$f^{\text{im}} = 2f_c^{\text{sig}} - f^{\text{sig}} \pm 2 \times \text{IFFREQ}$$

Now please note the following:

- The quantities in the expression above are in the sky frequency domain. The  $f^{\text{im}}$  should then be calculated back to the source rest frame by accounting for the Doppler shift at that frequency. Note that the difference between the upper and lower sideband centres are only identically equal to  $2 \times \text{IFFREQ}$  in the sky frequency domain. In the source rest frame, the difference will vary since the Doppler corrections, in terms of frequency shift, are slightly different for the two sidebands.
- Note that  $f_c^{\text{sky}}$  is not necessarily the middle of the spectrum range, it is rather the middle of the receiver bandpass of the signal band which is in turn determined by the LO setting. When the 4 GHz spectrometer mode is used, for instance, the bandpass is covered by two offset but partly overlapping spectrometer halves and  $f_c^{\text{sky}}$  would correspond to a position half a gigahertz inside the upper or lower edge of each 2.5 GHz spectrum.
- Up until March 2016, the IMAGFREQ keyword did not provide a correct value for offset tunings; it simply added or subtracted  $2 \times \text{IFFREQ}$  from the OBSFREQ value.

- The XS reduction software does not properly display the image frequency for data taken with offset tunings and/or using the 4 GHz mode.

# APPENDIX F

## ABBREVIATIONS

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<b>Abbreviation</b>	<b>Meaning</b>
2SB	dual sideband, or equivalently, sideband-separated
ACAPS	antenna control and positioning software
AoD	astronomer-on-duty
BSW	beam switching
DSB	double sideband
FFTS	fast Fourier transform spectrometer
FITS	flexible image transport system
FSW	frequency switching
FWHM	full width at half maximum
GUI	graphical user interface
HEMT	high electron mobility transistor
HPBW	half power beamwidth
IF	intermediate frequency
LO	local oscillator
LSB	lower sideband
LSR	local standard of rest
OSA	Omnisys A
OSO	Onsala Space Observatory
PSW	position switching
RFI	radio-frequency interference
SIS	superconductor-insulator-superconductor
SPE	spectrometer
SSB	single sideband
USB	upper sideband
VLBI	very-long-baseline interferometry