Chapter 6

The Plateau de Bure Interferometer

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6.1 History

The design of the millimeter wave interferometer started in June 1979, in the year of the foundation of IRAM, the Institut de Radioastronomie Millimétrique. The construction of the first antenna was completed in June 1987, and three years later an interferometer consisting of three antennas was opened to guest observers. First fringes at 230 GHz were obtained in April 1995, and the current configuration of the interferometer was attained one year later. Work is currently in progress to extend the north-south track and for the construction of the sixth antenna. Starting with the commissioning period in 1990 up to the end of 1998, the Plateau de Bure interferometer was able to carry out more than 450 different projects which involved more than 200 investigators from all around the world.

6.2 Description

The Plateau de Bure interferometer is located in the South of the French Alpes, near St-Etienne en Dévoluy in the Départment of Haute Alpes. The interferometer's altitude is 2552 m (2560 m at the intersection of the azimuth and elevation axes of the telescopes) and its longitude and latitude at the array phase center are 05:54:28.5 E and 44:38:02.0 N. A cable car provides access to Plateau de Bure. A hangar in which the sixth antenna is currently under construction, is used for antenna maintenance, overhaul periods and, in general, for antenna repair work which needs to be carried out in between times but under safety conditions. The hangar houses a few workshops for cryogenics, mechanics, electronics, a power station which provides electric autonomy in case of interruptions in the external power supply and finally, the correlator room and the control room for remote array operation. Almost adjacent to the hall are the living quarters for the staff who supports the uninterrupted round the clock operation of the interferometer.

Currently, the interferometer consists of five antennas arranged in a T–shaped pattern extending over a maximum of 408 meters east-west and 232 meters north-south. A sixth antenna is expected to be ready mid 2000, and further baseline extension of the north track is under way.

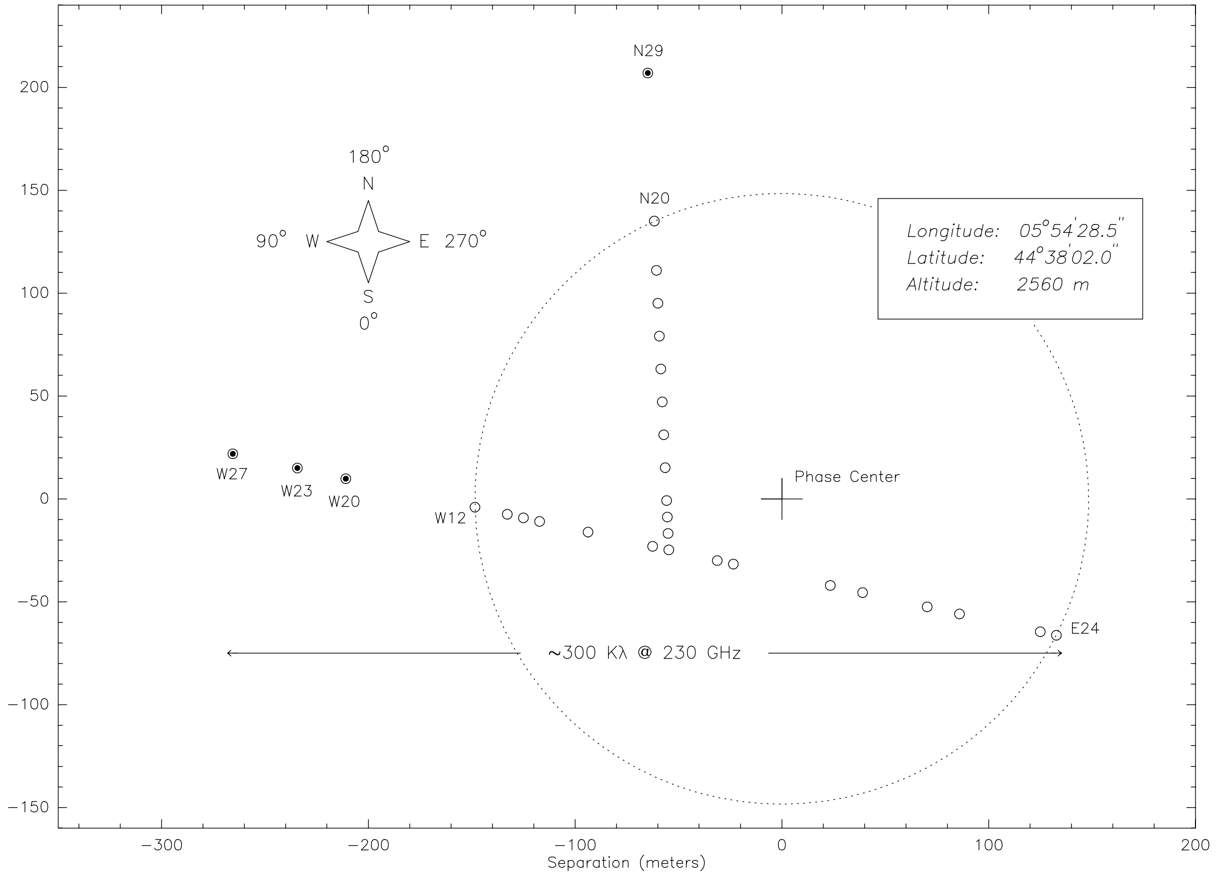

Figure 6.1: PdB interferometer station layout as of September 1998. The interferometer origin is defined as the center of the circle which goes through the stations N20, E24 and W12, the so-called IRAM phase center, and thus gives a unique vector definition to each station.

The antennas are conceptually identical: they all have a fully steerable alt-az mount which incorporates a self-propelled transporter for moving the antennas (130 tons) along the tracks between stations. Each antenna is a 15 m diameter Cassegrain telescope with the backstructure and quadrupod legs largely made of carbon fiber for high thermal stability. The high precision of the reflecting antenna surface (40-60μm) guarantees best performance: all antennas have essentially the same sensitivity (22 Jy.K^{-1} at 3 mm, 35 Jy.K^{-1} at 1 mm – see lecture by A.Dutrey), and very similar pointing and focusing characteristics.

All the antennas are equipped with dual-frequency SIS receivers operating simultaneously in the 82 GHz$-$115 GHz and 205 GHz$-$245 GHz range. Typical double sideband receiver noise temperatures are between 25 K and 50 K at 3 mm and between 40 K and 60 K at 1 mm. The receivers upper and lower sidebands are separated by the correlators with a rejection better than 26 dB. The lower to upper sideband gain ratio depends on the receiver and varies typically between 0.2 and 4.0 under standard operating conditions in the 3 mm band, and yields essentially a double-side band tuning in the 1 mm band. Pure single sideband tuning (with rejection 15 to 25 dB) is also possible in the 3 mm band, with receiver temperatures around 60 to 80 K.

Six totally independent correlators units are available that provide an 87% correlation efficiency (for more details see H.Wiesemeyer's lecture). Each correlator unit provides 4 choices of bandwidth/channel configurations, a single unit provides an additional configuration with a nominal velocity resolution of 50 m.s^{-1} at 230 GHz. The correlators can independently be connected either to the 3 mm (100-600 MHz IF1) or to the 1 mm receivers (100-600 MHz IF2).

A central control computer coordinates the entire interferometer (antennas, receivers and correlators and quite some other equipment) and makes the data acquisition. Raw data corresponding to the individual dumps of the correlator buffers will not be available as real-time jobs apply automatic calibrations (clipping correction, apodization, FFT, sideband separation, small delay correction, bandpass correction and other corrections) and make automatic data quality assessments (marking bad data, shadowing, phase lock, just to cite a few flags) before data is written to disk. A second workstation provides the software resources for offline data analysis and for data archiving before transfer to the Grenoble headquarters.

6.3 Array operation

6.3.1 Array calibration

The astronomical setup of the interferometer involves a number of steps that are done under the joint responsibility of the array operator and of the astronomer on duty (AoD). The goal of the setup is to maximize the interferometer performance in view of sensitivity and positional precision.

Change of array configuration

A change of configuration is the responsibility of the operators and of the technical staff. Since most projects, as mapping, mosaicing and snapshot observations, require more *uv*–coverage than a single configuration can provide, the antennas are moved typically every three weeks or so, to a new configuration. Every additional configuration increases the mapping sensitivity and the uniformity of the *uv*–coverage by adding $N(N-1)/2$ baselines to the sampling function (these are 10 baselines during the winter period, 6 baselines during the summer period when the array is operated with only 4 antennas). Configurations are usually selected among six types according to several criteria: antenna availability, project type, atmospheric seeing, *uv*–coverage, pressure in local sidereal time, sun avoidance and other factors.

Six primary configurations are needed to cover the desired range of angular resolution at the two operating frequencies with 5 antennas:

Configuration	Stations
D	W05 W00 E03 N05 N09
C1	W05 W01 E10 N07 N13
C2	W12 W09 E10 N05 N15
B1	W12 E18 E23 N13 N20
B2	W23 W12 E12 N17 N29
A	W27 W23 E16 E24 N29

The configurations can be combined to produce five sets of configurations for different angular resolution:

Set	Configurations	Purpose
D	D	detection / lowest resolution
CD	D, C2 or C1	$3.5''$ at 100 GHz
CC	C1, C2	higher resolution than CD
BC	B1, C2	$2.0''$ at 100 GHz
BB	B1, B2, C2	higher resolution and sensitivity
AB	A, B1, B2	$1.0''$ at 100 GHz

Special configurations and sets of configurations are used during the annual antenna maintenance period which is usually between May and October. During this period observations at 1 mm are for most of the time not feasible, specially in the two extended B configurations. Observations in the A configuration whether at 3 mm or 1 mm will in general only be scheduled during the winter period. Requested non-standard configurations are considered only in exceptional cases.

Antenna focus

Sensitivity is one of the most important concerns. As a rule of thumb, an axial displacement of the secondary by $\sim \lambda/3$ results in a 20% loss of sensitivity. To avoid losses larger than 3%, the position of the secondary needs to be measured to much better than $\lambda/10$ on regular time intervals. The positional precision, however, depends on the source strength, the operating wavelength, the sampling of secondary positions and, finally, on atmosphere stability. In general, the focus is measured at 3 mm on a strong quasar by displacing the secondary in steps of 1 mm (in steps of 0.45 mm if done at 1 mm). This is systematically done by the operators at the beginning of every project and is automatically verified by the system every hour during project execution.

Antenna pointing

A high pointing accuracy is demanded in view of sensitivity and mapping quality. Antenna pointing errors affect the global sensitivity of the interferometer and may lead to severe errors in the image restoration process. As a rule, a pointing precision of $\Delta\theta \sim \theta_{\mathrm{FHWP}}/20$ is desirable at the highest frequency. The good pointing accuracy results from an optimized structural design: a good knowledge of the gravitational load, a good positional stability of the receivers (a good alignment is needed for dual-frequency observations), a precise control of the secondary, high precision bearings and position encoders, a good servo system, ... and a good software control for repeatable antenna pointing errors. The quality of a pointing model is generally limited by wind and thermal load effects. The absolute pointing accuracy achievable with the IRAM antennas is in general below the 2-3$''$ rms at each axis with a slightly higher uncertainty in elevation. Such a pointing accuracy leads to very small intensity variations, most of the time with negligible effects on the image reconstruction. Higher accuracy is obtained by regular relative pointing measurements every hour.

Each antenna is characterized by a fixed set of pointing parameters. These are measured only in certain circumstances: when an antenna is going to see first light, when modifications are made which may affect the pointing of an antenna, or more generally in cases of suspected pointing problems. In these cases a precise interferometric pointing session, eventually with a preceding less sensitive full-sky single-dish session, is required to derive the full set of antenna pointing parameters. Such pointing sessions are reduced with a dedicated non-linear fitting program in use at Plateau de Bure.

The pointing model is actually based on 5 parameters only, all others being negligibly small. These parameters are: IAZ and IEL (the azimuth and elevation encoder zero point correction), COH (the antenna horizontal collimation), and IVE and IVN (the antenna East-West and North-South inclination). IAZ, IEL, IVE and IVN are in station dependent, while COH is in principle an antenna constant. IAZ, IEL and COH are measured in interferometric mode by pointing on a few low elevation and high elevation sources. In general, three strong quasars at 3 mm are fully sufficient. The remaining two parameters, IVE and IVN are measured on every project start with an inclinometer by making an antenna turn through 360°.

Delay measurements

Delay measurements aim at the correction of cable length (electric path) differences between two antennas after compensation of the geometrical path length. An improper knowledge of the difference in cable length is visible as a frequency dependent phase slope in the intermediate frequency bands (IF1 and IF2), and, depending on the amplitude of the slope, may result in a more or less important loss of sensitivity. The delay is measured by a cross-correlation on a strong radio source at the beginning of every project.

Baseline lengths measurements

The goal is to measure the position of each antenna i relative to a common reference point (distances X_{ij}, Y_{ij}, Z_{ij} between antennas i and j or distances dX_i, dY_i, dZ_i with respect to the theoretical station position) in order to subtract the phase term $2\pi w$ (see lecture 2 by S.Guilloteau) at any hour angle and declination from the observed phase. The absence of a good baseline solution is equivalent to having large uncertainties in the baseline separation between different antennas. As a consequence, the geometrical delay might improperly be compensated and large time-variable phase errors might affect observations.

Though the quality of a baseline solution is easily found out – the calibrator's visibility phase shouldn't vary with reference to the phase tracking center as function of hour angle and declination – a good baseline solution is truly indispensable for the purpose of phase calibration. Phase errors can often be more deleterious on compact configurations where source visibilities are stronger than on extended configurations. As a reference, winter conditions allow baselines in the D configuration to be measured at 3 mm with a $5° - 8°$ phase accuracy and with $5° - 20°$ in the A configuration. In summer conditions the accuracy is often $2 - 3$ times lower.

Though no high accuracy is needed for antenna positioning (offset position from the target location is routinely within a wavelength), the actual antenna position has to be known with high precision: within a small fraction of a wavelength (70-300μm). The precision is limited essentially by the atmosphere and by thermal effects.

The baseline parameters can be obtained to high accuracy from observations of a number k of relatively strong point sources, well-distributed in hour-angle and declination, for which accurate positions are available. The analysis of these observations is usually carried out with CLIC, the calibration program, using a least-square-fit analysis on the geometric phase difference for antenna pairs (i,j):

$$\phi^g_{ij} = \phi^s_{ij} + \phi^a_{ij} = 2\pi\, w =$$

$$= \frac{2\pi}{\lambda}\, \underbrace{(X_{ij}, Y_{ij}, Z_{ij})}_{b} \cdot \underbrace{\begin{pmatrix} cosH cos\delta \\ -sinH cos\delta \\ sin\delta \end{pmatrix}}_{s} + \phi^a_{ij}$$

$$\longrightarrow \quad \Delta\phi^g_{ijk} = \frac{2\pi}{\lambda}\,(\Delta b_{ij}\cdot s_k + \underbrace{b_{ij}\cdot\Delta s_k}_{\simeq 0}) + \Delta\phi^a_{ijk}$$

where ϕ^s_{ij} is the assumed geometrical phase between the two stations, H and δ the hour angle and declination of the source, and where $\Delta\phi^a_{ijk} = O_{ij}\cos \mathrm{El}_k$ are elevation dependent correction terms for the non-intersection of the elevation and azimuth axes in the nodal point of the antennas. These terms are well-known and stand for non-negligible elevation dependent variations of the visibility phase which need to be removed as accurately as possible before solving for the baselines.

In theory, three sources are sufficient to measure the actual baseline lengths, in practice 10-12 sources are necessary to obtain an accurate measurement. Since a displacement by $1''$ at 100 GHz on a baseline of 100 m translates already to a phase offset of $\sim 58.2°$ (~ 1 rad), the positions of the radio sources used for baseline measurements need to be known with an accuracy Δs_k better than $0.02''$.

The baseline equation implies that positional errors are equivalent to phase errors. Since baseline length errors scale with the angular separation between calibrator and source, the aim is to have calibrators as close as possible to minimize the phase errors.

Sometimes, accurate baselines are not required as in the case of self-calibration projects. Sometimes, however, even if good baselines are required, they simply cannot be determined precisely enough after a change of configuration. Projects observed in the meantime will then need to wait for a better baseline model. Such projects will in general not be phase-calibrated by the astronomer on duty, but phase-calibration has to be done later on by the proposers of the observations.

Gain measurements

Gain measurements (GAIN scans) are cross-correlations on strong radio sources which are essentially used to measure the image to signal sideband ratios for both the 3 mm and 1.3 mm receivers. The required sideband ratio depends on the project, the achievable sideband ratio depends on the receiver and the frequency. An accurate measurement of the receiver gain is necessary for a good estimate of the atmospheric opacity and of the associated thermal noise with which the atmosphere contributes during the observations. Therefore, results of a gain measurement are followed by an atmospheric calibration (scan `CALI`).

Receiver stability

As a rule, a high receiver stability $\leq 3.10^{-4}$ is never required. Sometimes, however, depending on atmospheric conditions, array configuration and observing frequency, a higher stability may be desirable in view of a very promising radiometric phase correction. Though such a high stability is not always achievable on all the receivers, it makes possible an improvement in data quality when the atmospheric phase correction technique becomes practical (see lecture 9 by M.Bremer). Experience at Bure from the last three years shows that the radiometric phase correction is quite efficient under clear sky conditions: from spring to autumn essentially during the evening and morning hours, in winter almost always when the weather allows to observe.

Since observations on more compact baselines suffer less from the effects of the atmospheric phase noise – for reference, an rms of less than $10°$ rms at 3 mm is routinely obtained on the shortest baselines – a high receiver stability in compact configurations is only exceptionally required. Typically, under average observing conditions with a receiver stability of 3.10^{-4} we may already correct atmospheric phase fluctuations with a precision of $10°$ at 115 GHz.

6.3.2 Array observations

Setting up a project

Since projects are spread over typically a few months, it is impractical that astronomers actually come to the interferometer for their observations. In some exceptional case, however, when observations require rapid decisions, the presence of a visiting astronomer may become necessary. Up to now and after almost ten years of operation, only a handful of projects required the presence of a visiting astronomer. Only non-standard observations like mapping of fast moving objects, coordinated observations may require a member of the project team to be present on the site. All observations are carried out "in absentee", and a *local contact* is assigned to each project.

The observer has to specify all aspects of his/her program in an observing procedure. For routine observations, this is usually done with the help of the local contact by parameterizing the general observational procedure. Once the procedure is written, a copy is made available to the operation center at Plateau de Bure. Before start, further verifications will be made by the scientific coordinator and, to finalize the procedure, by the astronomer on-duty who makes a last check by looking at the technical details in the proposal, at the technical report and at the recommendations made by the programme committee.

Quite some time, however, may pass between the preparation of an observational procedure and the actual observations. Depending on the requirements, between a few hours and a few months may go for the decision to start the observations. On average 90% of the projects are completed within 6 months from their acceptance.

Observations

For the observations, the array is operated by an operator with the assistance of an astronomer and under the supervision of the scientific coordinator. The operator has the full responsibility for conducting all observations following pre-established observing procedures or with the help of the astronomer in case of unpredicted events.

The operator will execute the observing procedure according to a pre-established planning which allows for some flexibility in the scheduling, and to a few criteria (as the maximum amount of precipitable water in the atmosphere, the required atmospheric phase stability, the requested observing frequencies, the declination of the targets, the sun avoidance limit and a few other aspects) which will help both the operator and the astronomer in their final decision-making on which project to carry out as next. As a rule, excellent atmospheric conditions will be used for high grade projects requesting sensitivity at high frequencies while the remaining time will in general be devoted to projects which require less stringent atmospheric conditions.

Once a project is selected, the operator will start the observing procedure which sets up the needed equipment configuration (essentially sky frequencies, correlator settings and target coordinates according with the observer's wishes) and will start preparing the interferometer for the observations: the receivers are

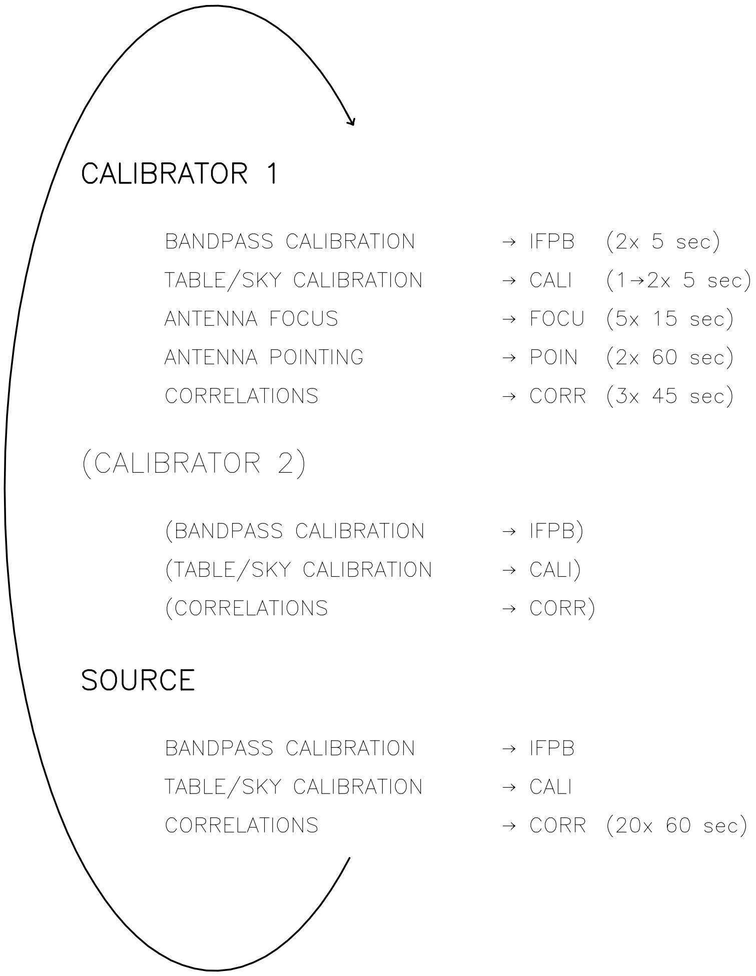

Figure 6.2: Standard observations: a cyclic sequence of measurements. `IFPB` scans aim at calibrating the IF passband, `CALI` are auto-correlations on a hot load (290 K) and on the sky (on a 15 K load only at the beginning of every project) to adjust the temperature response of the array, `FOCU` and `POIN` scans measure focusing and pointing offsets (done only every 45 minutes) and `CORR` scans are cross-correlations (complex visibilities). In projects requesting two calibrators every other calibration is made on the second calibrator.

tuned, the gains and the zero-delay of the receiving antenna is adjusted and verified, the antenna pointed and focused, the RF passband is measured and the temperature scale of the interferometer calibrated. The flux of the primary calibrators are then verified, eventually replaced if their flux density has dropped too much, and the observations started.

As soon a project is started, the astronomer on-duty will monitor the execution of the project and the data quality by examining the visibility amplitude and phase of the calibration sources, the antenna tracking in presence of wind, the antenna pointing corrections, and all time-dependent instrumental and atmospheric parameters which could have some implications on the observations. Furthermore, to avoid further observing on a target with wrong coordinates, the astronomer will verify the presence or absence of line and/or continuum emission according to the expected values quoted in the proposal. Finally, the astronomer on-duty will provide pre-calibrated data on a best effort basis. Depending on project complexity and needs, further data analysis is sometimes required on the site to decide on follow-up observations.

When the observations are running, commands are regularly issued to the antennas and to the peripheral equipment (phase rotators, correlators and others) following a well-defined, cyclic sequence as shown in Figure 6.2. This sequence may slightly change depending on the number of calibrators and on the number of phase centers (i.e. the fields of view requested for different sources or for mosaic-type observations) the observer wishes to track in a single run. Typical observations at Plateau de Bure fall in one of the following categories:

- Detection: deep integrations aiming at measuring the flux densities of faint targets (continuum emission and/or line emission/absorption) with the interferometer mostly in compact configurations.
- Snapshot: observations in one or more configurations, aiming at measuring apparent sizes in a small sample of targets, in some cases even allowing for mapping. The observational procedure sets up short integrations on individual objects in a cyclic manner.
- Mapping: observations generally in two or more configurations aiming at mapping a single object.
- Mosaic: similar to snapshot observations, except that the array switches between adjacent, half-beam spaced phase centers to map field of views which are more extended than the primary beam of the antennas.

Monitoring project execution

Under normal circumstances only a few parameters of interest are regularly verified and corrected (mostly automatically) during the observations, but instantaneous (every second) and much more detailed information can be obtained at any time by connecting to the equipment (receivers, antenna control parameters, digital correlator units and others). During the operation the array status is continuously monitored so that the operator can provide fast feedback in response, at any time when necessary. An automatic data quality assessments (flagging bad data, antenna shadowing, receiver phase lock and others) before writing data to disk. The astronomer on-duty has the responsibility of periodically monitoring the data acquisition and to write a few notes assessing the data quality during and after the observations. Monitoring the progress of a project by making intermediate data reductions, however, is the responsibility of the observer. This is not the responsibility neither of the astronomer on-duty nor of his/her local contact.

6.4 Proposal submission and contact people

Quite some people are required to run such a complex instrument as an interferometer. Sooner or later you will meet some of these people, but for most of the projects only a few will play an essential role.

At proposal submission time, you will first get in touch with the scientific secretary who will address you a confirmation of the proposal reception shortly after the deadline. Once a proposal is registered it is sent to the members of the Programme Committee (eight members: two from each country of the IRAM partner organizations plus two external) and, at the same time, its feasibility assessed by the scientific coordinator. Technical considerations as observing strategy, observational risk factors and other issues are communicated to the Programme Committee, only if necessary and only at the time of the meeting to avoid any technical remark to influence the scientific evaluation. Shortly after the meeting, during which the Programme Committee expresses its recommendations, a global proposal evaluation is made by the IRAM director who takes the final decision. Thereupon, a notification is addressed to you which contains the recommendations of the Programme Committee and a technical report. If the proposal is not rejected from the beginning, a local contact (a staff astronomer) will be appointed to the project and his name communicated to you.

In the course of the observations, only four persons will play a role for the principal investigator who proposed the observations: the local contact, the scientific coordinator, the astronomer on-duty and the array operator. The local contact, who is the direct interlocutor of the observer, is a staff astronomer whose role is to help the observer in a concerted effort to prepare his/her observations and, later on, in the Grenoble headquarters to help (if needed) the observer in calibrating the data.

Finally, once the observations are completed and before coming to Grenoble, the principal investigator or one of his team members will need to get in touch with two persons: the local contact and the coordinator for the data reduction activities who will finalize the stay of the visiting astronomer at the Grenoble headquarters.

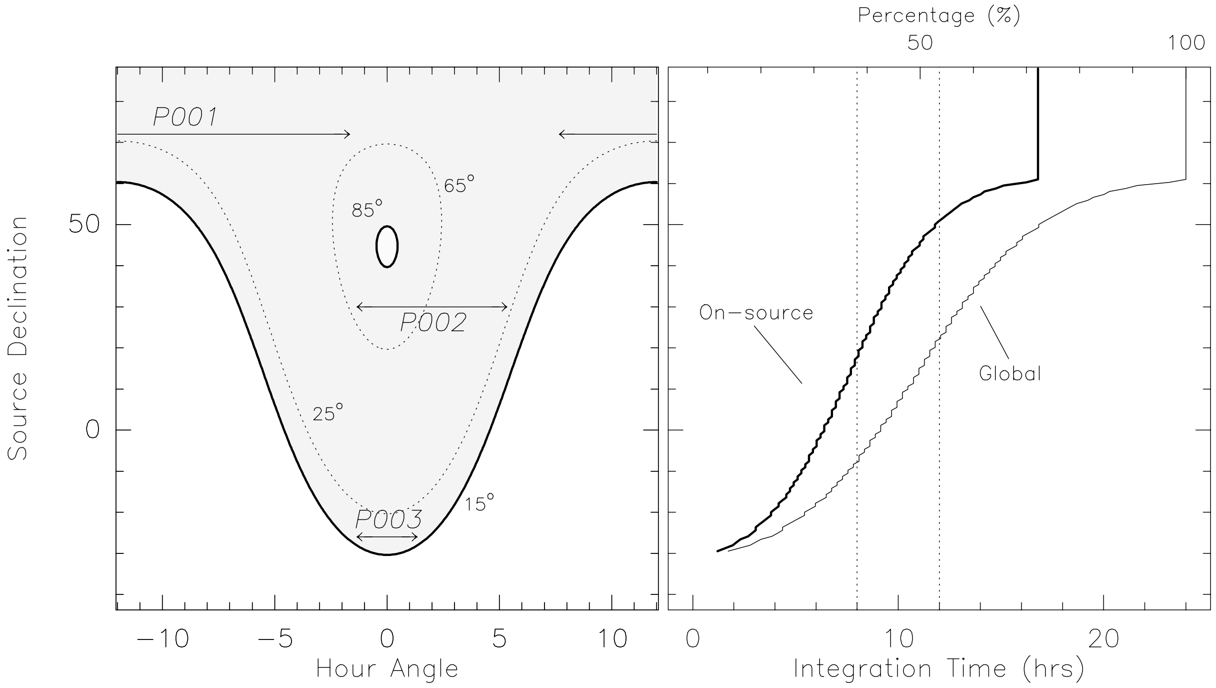

Figure 6.3: Source visibility and effective observing time. The scheduling priority is in general inversely proportional to the declination (observations of low declination sources tend to be more difficult, as they cannot be carried out at any time – the shaded region is the sky above 15° elevation). The total observing time per track for depends on the declination of the source and is usually limited to 8-12 hrs for sources of the northern hemisphere. For standard mapping projects, observational overhead counts in by 28% of the time. This is equivalent to an effective on-source integration time of about 6-9 hrs.

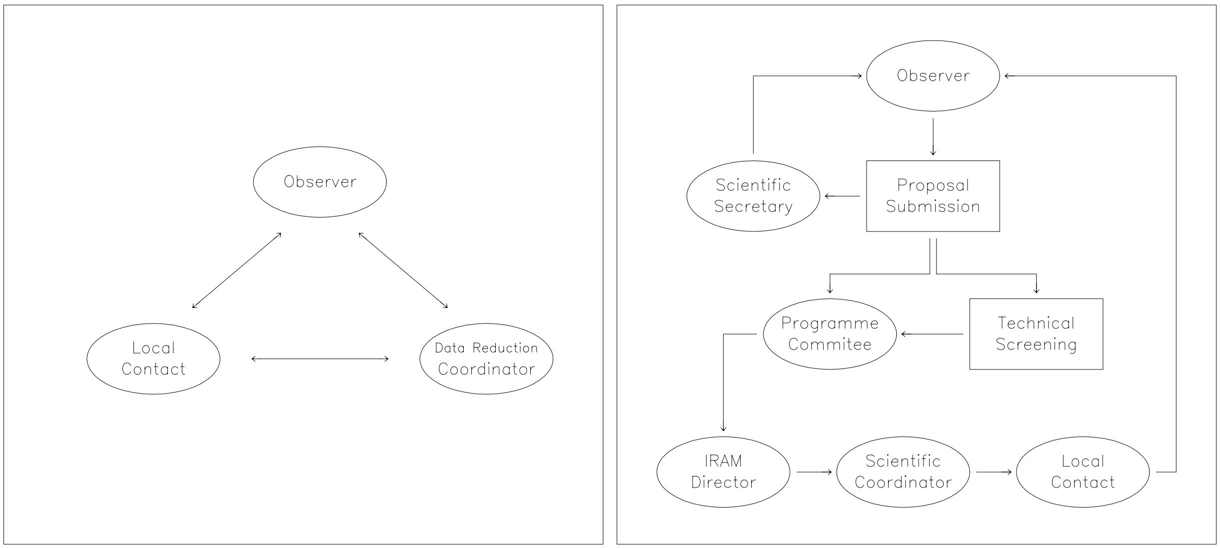

Figure 6.4: Proposal submission and contact persons at IRAM