Astron. Astrophys. 167, 207–213 (1986)

ASTRONOMY AND ASTROPHYSICS

The University of Cologne 3-m radio telescope

G. Winnewisser, M. Bester, R. Ewald, W. Hilberath, K. Jacobs, W. Krotz-Vogel, M. Miller, M. Olberg, T. Pauls, E. Pofahl, G. Rau, R. Schieder, H. Stubbusch, B. Vowinkel, C. Wieners, and W. Zensen

I. Physikalisches Institut, Universität Köln, D-5000 Köln 41, Federal Republic of Germany

Received February 27, accepted May 19, 1986

Summary. The Cologne 3-m millimeter and submillimeter wave radio telescope has been in operation since early 1984, after a two year construction period. The telescope has recently been moved from the roof of the Department of Physics at the University of Cologne to the Gornergrat Observatory (alt. 3150 m) close to Zermatt in the Swiss Alps, in order to exploit its submillimeter wave capabilities.

The surface accuracy of the telescope is 30 µm (r.m.s.), and current receivers comprise a cooled GaAs Schottky-barrier mixer for the 70–116 GHz band, and an SIS mixer covering 140–150 GHz. Back-ends include a filter bank, three acousto-optical spectrometers with different bandwidths and channel spacings, and a 500 MHz bandwidth continuum system. This paper describes the present technical status, the performance tests and some selected molecular observations made from Cologne.

Key words: radio telescopes – interstellar medium: molecules

1. Introduction

The 3-m radio telescope of the University of Cologne will be used mainly for interstellar molecular spectroscopy, although continuum radiation from H II regions and from cool dust in the submillimeter region should also be observable. Research will be concentrated in three areas: (i) fast mapping of astrophysically important molecular transitions such as CO, CS, HCO^+, etc., and their isotopic species, (ii) frequency surveys in selected molecular clouds to investigate chemical abundance variations and (iii) extension of the observations to the submillimeter wave region.

While the first two objectives could, in principle, be accomplished from low-elevation sites such as Cologne – with considerably reduced efficiencies – measurements in the shorter millimeter and submillimeter wave region can only be done from dry high altitude sites.

With the 3-m radio telescope located on the roof of the Physics building at the University of Cologne we have made measurements of a large number of molecular species with transitions in the 80–90 GHz region, such as HCN, HCO^+, SiO, SO, C_2H, NH_2D (Olberg et al., 1985a) and CH_3C_2H. The first molecular detection (HCN, $J=1\rightarrow 0$) was made in July 1983 (see Winnewisser et al., 1982a, b; Winnewisser and Vowinkel, 1984; Winnewisser, 1985; Bester et al., 1985; Ewald et al., 1985; Olberg et al., 1985b; Pauls and Ewald, 1985), and the telescope was fully operational in Cologne from mid 1984 to September 1985.

Send offprint requests to: G. Winnewisser

2. Telescope design

The two essential design goals achieved in the construction of the 3-m radio telescope were transportability and a high precision primary reflector. Krupp Industrie und Stahlbau served as prime contractor, while the reflector was made by the Dornier company. The telescope was designed in collaboration with Krupp (Vowinkel et al., 1983).

The telescope is an elevation over azimuth mount consisting of two main pieces: (i) the pedestal, which houses the drive motors, encoders, and the necessary electronics and, (ii) the high-precision 3-m reflector which is attached to the pedestal at four points. The essential design features are summarized in Table 1, together with details of the associated electronic equipment employed at present.

The main reflector consists of four panels made of fiber-glass reinforced epoxy. The panel surface is covered with a 100 µm thick aluminum layer which is protected by a 50 µm thick layer of special paint. Each panel can be adjusted with 7 screws fixed to the back-up structure. The final adjustment of the entire mirror was done with a precision 3-D measuring machine (Lamda 4508). The absolute measurement accuracy of any given point is 15 µm, whereas the relative measurement accuracy is close to 5 µm.

The measured total deviation of the main reflector from a best fit paraboloid is 30 µm (r.m.s.) in a horizontal position. A plot of the deviation contours from the best fit paraboloid is shown in Fig. 1. In the vertical position the calculated maximum deformation due to gravity is 7.7 µm. The measured r.m.s. surface roughness of the panels is less than 2 µm. Thus, the quality of the 3-m reflector allows operation well into the submillimeter wave region. The telescope is presently operated in a Cassegrain configuration; however, provisions have been made for a Nasmyth focus by deflecting the beam by means of a mirror system through a portion of the elevation axis.

The subreflector has a diameter of 380 mm, and can be adjusted by three remote controls which change the axial focus, the lateral shift in the elevation plane, and the tilt.

3. Receiving system

The receiver is all solid state and includes a cryogenically cooled GaAs Schottky-barrier mixer. Gunn oscillators with large

Table 1

Total weight	Ca. 3.5 metric tons	
Primary reflector		
Shape	Parabolic	
Diameter	3 m	
f/D	0.4	
Construction technique	Fiber-glass reinforced epoxy	
Surface accuracy	30 micrometers r.m.s.	
Weight including backup structure, secondary mirror and support legs	225 kg	
Secondary reflector		
Shape	Hyperbolic	
Diameter	380 mm	
Construction technique	Machined aluminum	
Focusing	Servo-controlled: axial, shift and tilt	
Pedestal		
Mount	Elevation-azimuth (alt-az)	
Maximum slew rate	1 degree/s	
Maximum tracking rate	0.2 degrees/s	
Maximum wind speed allowed during measurements	18 m/s	
Pointing and tracking accuracy	Better than 5″	
Receiver (Cooled Schottky diode mixer)		
Tuning range	70–116 GHz	
Bandwidth	500 MHz (max)	
Noise temperature	200 K (DSB)	
Backends		
Type	Bandwidth	Channel spacing
Filter bank	256 MHz	1 MHz
High-resolution AOS	64 MHz	32 kHz
Medium-resolution AOS	250 MHz	166 kHz
Low-resolution AOS	500 MHz	370 kHz
Continuum	500 MHz	–

mechanical tuning ranges are used as local oscillator sources. The frequency region between 70 and 116 GHz is covered by two Gunn oscillators (Jacobs et al., 1986) one covering 70–100 GHz, and a second operating between 40 GHz and 58 GHz followed by a frequency doubler, thus covering the frequency band between 80–116 GHz. The required frequency stability of these oscillators is achieved with a frequency-agile heterodyne phaselock system (Bester, 1986). The Gunn oscillators are phaselocked via the bias in an active second-order servo loop. Fast frequency switching with a maximum rate of 10 kHz and a frequency separation up to 80 MHz is possible. The receiver noise temperature is around 160 K DSB with an intermediate frequency of 1.4 GHz. Beam switching is performed with a movable mirror which is the flat aluminum membrane of a commercially available loudspeaker. The receiver is calibrated with a built-in cold and a hot load that can be moved in front of the horn by coupling optics.

A receiver for the 140–150 GHz range is being developed using an SIS mixer. This system has a closed cycle liquid helium refrigerator operating at 3 K, developed in Cologne, and has a bandwidth of 250 MHz and a DSB system temperature in the laboratory of 80 K (Hilberath and Vowinkel, 1986). The mixer chips used in this receiver were provided by the Institut de Radio Astronomie Millimetrique – IRAM – in Grenoble.

Available back-ends include a conventional 256-channel filter spectrometer (FSp) with 1 MHz channel spacing and three compact acousto-optical spectrometers (AOS) with total bandwidths of 64 MHz, 250 MHz, and 500 MHz. More details about the spectrometers have been given by Zensen et al. (1986). The spectrometers are supplemented by a 500 MHz wide continuum back-end. All instruments were developed and built by the Cologne group.

4. Control system

Control and data acquisition are done with a small computer network shown in Fig. 2. The spectrometers, the continuum back-end, the receiver and the telescope servo-control use dedicated microprocessors for communication with the central mini-computer (PDP-11/34a). The microprocessors (Intel 8085), which have been developed at Cologne, perform individual control functions and buffer data for subsequent transfer to the main computer. An additional advantage of this modular system is that each subsystem can be operated on its own for testing purposes during the development and operation phase.

A rubidium frequency standard (Rohde und Schwarz XSRM) serves as the system clock for the central computer and provides a stable frequency reference for all synthesizers used in the telescope system. Its long term stability is better than 10^{-11} per month. The azimuth and elevation enconders have measuring accuracy of 0″.36. The telescope pointing and tracking accuracy is estimated to be better than 5″, with 2″ precision in the astronomical computing programs and about 2″ in the telescope servo system.

Two observing modes are used at present: position switching and beam switching, although frequency switching is also provided. Since position switching involves moving the telescope between a region of blank sky and the desired source at intervals of a few tens of seconds, it is important to establish that the entire system (receiver plus back-end plus atmosphere) is stable over these time-scales. We have developed a simple procedure to analyze the performance of our system based on the Allan-variance, originally applied to study the stability of frequency standards (Allan, 1966). Our method is described in the Appendix. The Allan-variance provides an accurate means of determining the optium integration time beyond which drifts degrade the spectrum. This method shows that the best overall performance is obtained with an integration time of 40 s per position. For beam switching, rates of 200–400 ms are normally used.

5. Observations

All subsystems installed in the telescope were first tested in the laboratory. For example, a laboratory test of the receiver and filterbank combination produced spectra of rotational transitions of various molecules in absorption against a 10,000 K noise source.

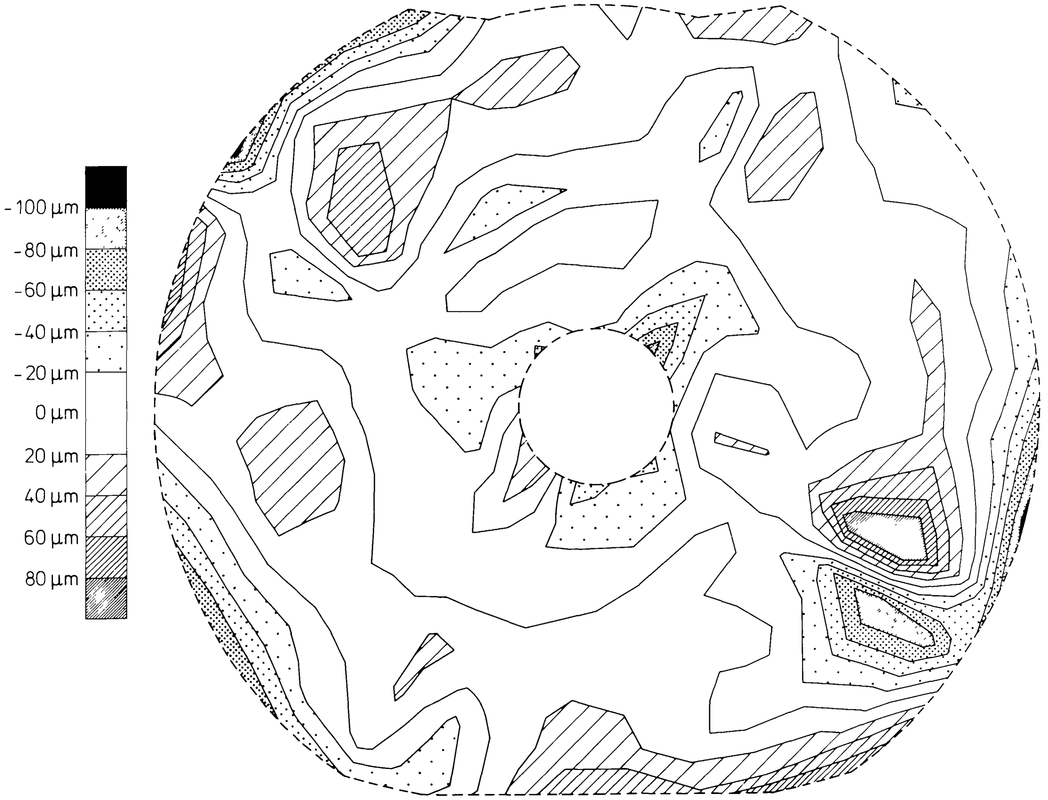

Fig. 1. A plot of the deviation from a best-fit paraboloid of the surface of the 3-m primary mirror. Measurements were taken with a 3-D measuring machine with a relative accuracy of about 5 µm. The root mean square deviation is about 30 µm

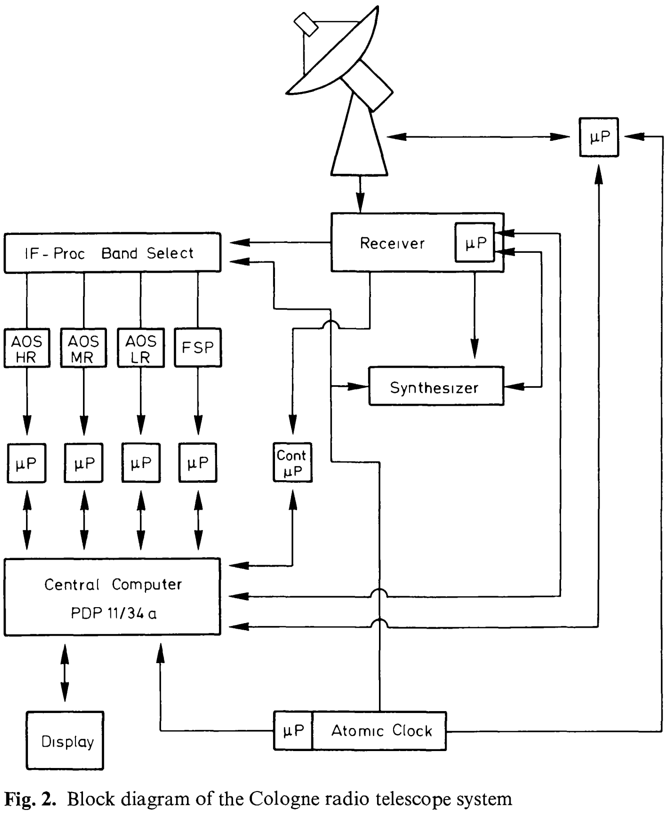

Fig. 2. Block diagram of the Cologne radio telescope system

Reference spectra made with an empty cell were subtracted from spectra taken with the cell filled with a particular molecule (cf. Pauls and Ewald, 1985).

Astronomically, molecular emission has been observed in the band between 80 and 90 GHz from a number of molecules, e.g., emission lines from SO, SiO, HCN, HCO^+, NH_2D, C_2H and CH_3C_2H have been recorded. These transitions are found in all types of molecular sources ranging from giant molecular clouds associated with H II regions, such as Orion, W 51 and S 140 to dark clouds such as TMC 1 and L 183.

Figure 3 presents some sample spectra of $H^{13}CN$ and SiO toward Orion-KL made with three spectral resolutions. The upper panel shows a filterbank spectrum after about 1000 seconds of on-source integration time, the middle and lower panels show medium and high resolution AOS spectra, respectively, with about four times as much integration time as the upper panel. At the highest spectral resolution considerable velocity structure is present in the SiO profile and we plan to monitor the time-dependence of these features.

As an example of a mapping project, we show the brightness temperature distribution of HCO^+ in a $30' \times 30'$ region around W 51 in Fig. 4.

The 3-m radio telescope is also used for continuum measurements with a microprocessor-based digital back-end. The total instantaneous bandpass (500 MHz) is detected and digitized in the receiver box and the resultant signal is sent to the continuum back-end via a lightpipe. The data is stored for subsequent transfer to the PDP-11/34a and simultaneously displayed on an analog chart recorder. Both total power and beam switching operation is

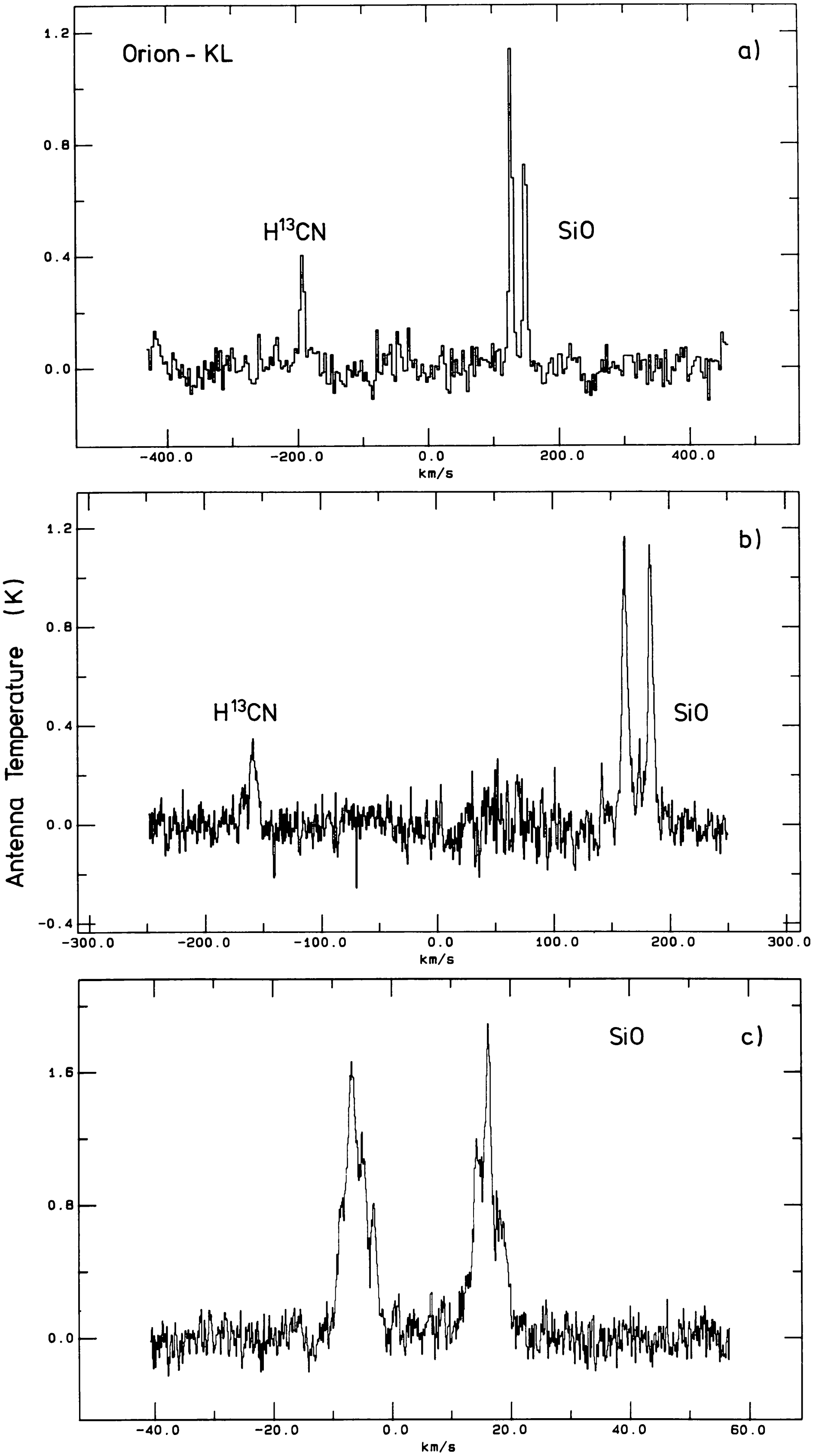

Fig. 3a–c. Spectra near 86.78 GHz showing emission from the SiO maser and from $H^{13}CN$ toward Orion-KL: **a** Filterbank spectrometer, **b** Medium resolution AOS and **c** High resolution AOS

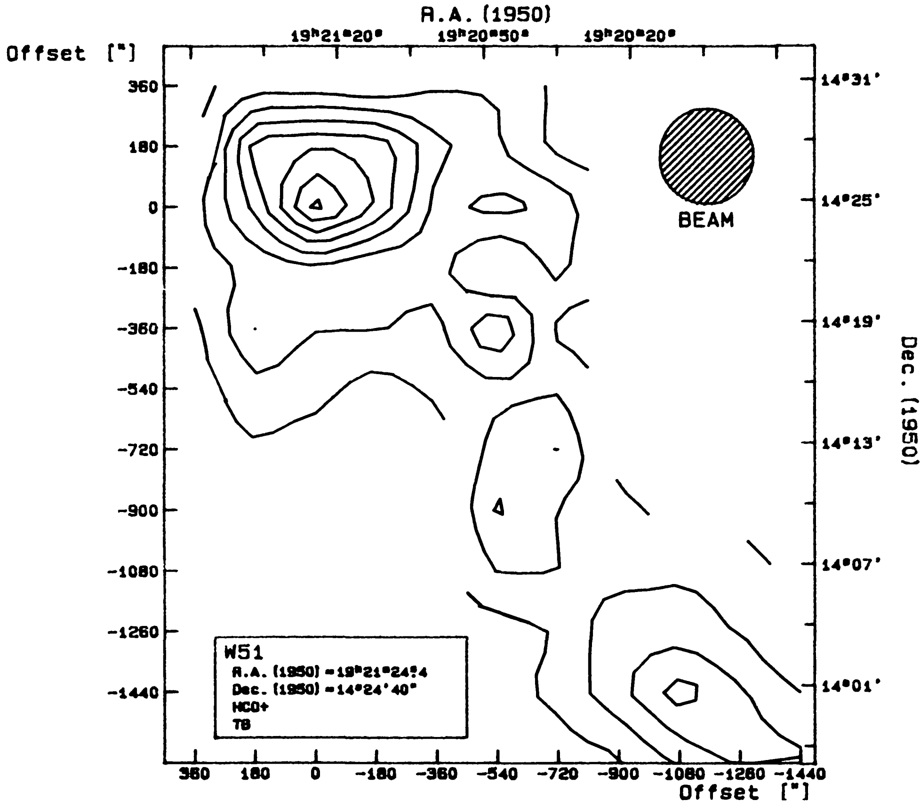

Fig. 4. Contour map of the peak brightness temperature distribution of HCO^+ toward W51 made with the filterbank spectrometer. The contours go from 0.2 to 1.6 K in steps of 0.2 K T_A^*

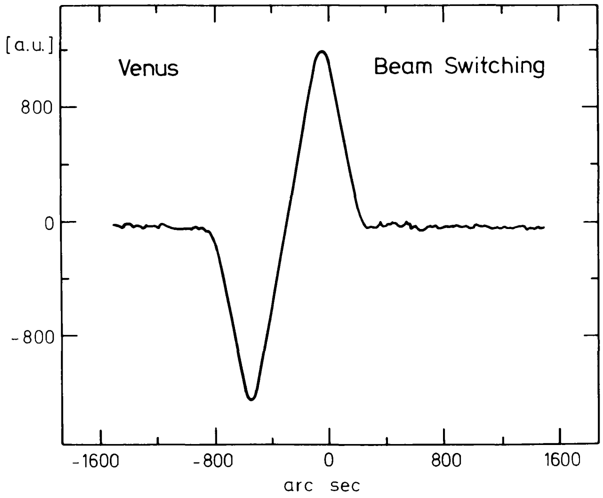

Fig. 5. Azimuth scan through Venus using beam switching

possible. Figure 5 shows an azimuth cross-scan of Venus using beam switching. The 3-m radio telescope has been operational since early 1984. The high surface accuracy of the reflector permits operation in the submillimeter wave region down to a wavelength of about 0.5 mm. For operation at these wavelengths the telescope has been moved from the roof of the Physics Department in Cologne to the Gornergrat Observatory, near Zermatt in the central Swiss Alps.

Acknowledgement. Research in astrophysics and laboratory spectroscopy at the University of Cologne is supported by the Deutsche Forschungsgemeinschaft through special research grants SFB-131 and, since 1985, SFB-301. Additional support through the Ministry of Science of NRW is gratefully acknowledged.

Appendix

We discuss here the use of the Allan-variance to test the stability of a radiometer system. Consider a large number, N, of consecutive samples of the output voltage, X_j, of one channel of a spectrometer, integrated for 1 s. If these samples are stored for further analysis, it is then possible to construct averages for varying integration times by summing over K adjacent samples:

$$R_n(K) = 1/K \sum_{i=1}^{K} x_{nK+i}\,; \quad n = 0, 1, \ldots, M; \quad M = \mathrm{int}(N/K) - 1.$$

The Allan-variance is then defined in terms of these averages as

$$\sigma_A^2(K) = 1/2M \sum_{n=1}^{M} (R_n(K) - R_{n-1}(K))^2.$$

The difference on the right-hand side of this equation can, for example, be the difference between an on-source and an off-source measurement. Now, if the radiometer delivered pure white noise to the output terminals, the Allan-variance would decrease monotonically with increasing integration time (proportional to K), as expected from the radiometer formula. However, noise and drifts in the associated electronic components prevent the variance from continuing to decrease for arbitrarily long integration times. In fact, the Allan-variance normally decreases to a minimum and then

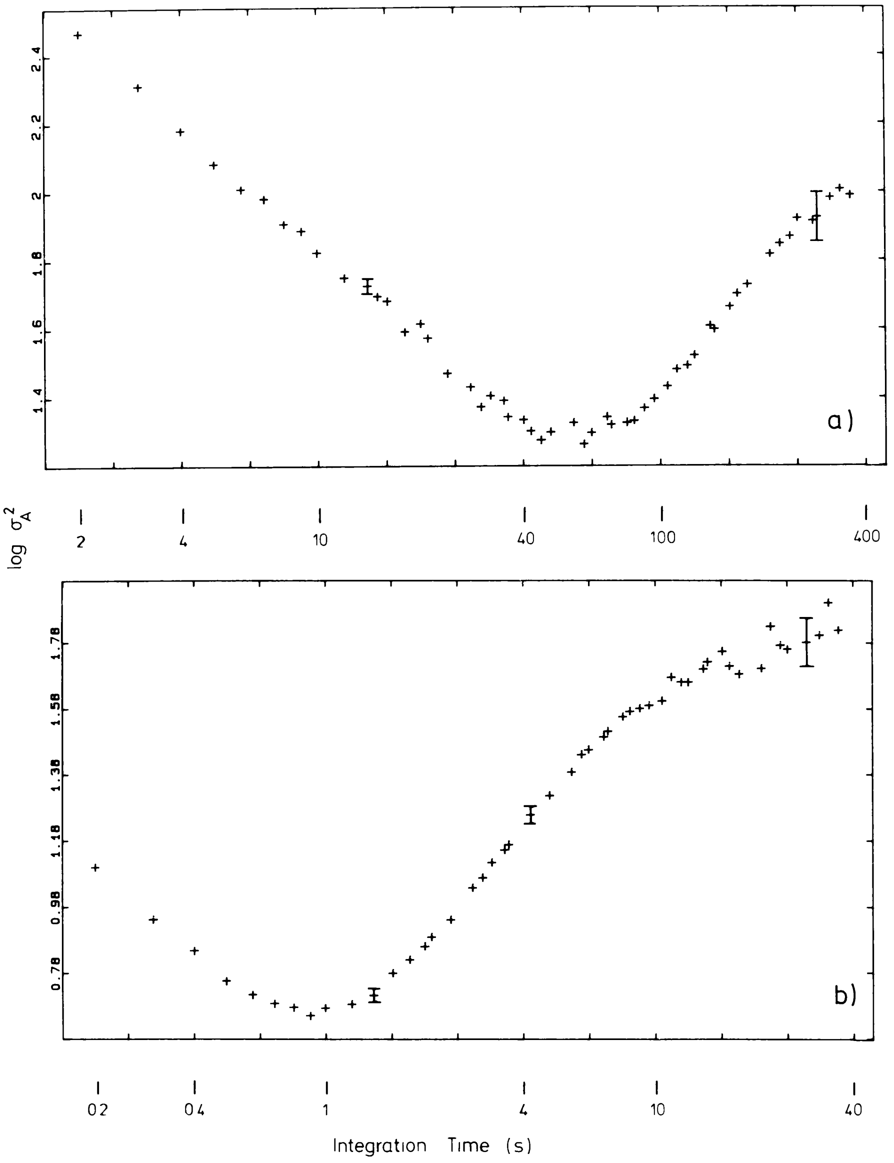

Fig. 6a and b. A plot of the Allan-variance versus integration time for the complete radio telescope system including the earth's atmosphere. The upper plot shows measurements made under clear skies, the lower plot shows the effect of clouds

begins to increase again with increasing integration time. The optimum integration time is, thus, somewhat less than that at the minimum, since this guarantees that we are on the white noise part of the curve (Rau et al., 1984; Schieder et al., 1986).

The behavior described above is shown in the plots in Figure 6, which were made with the telescope, receiver and filter spectrometer. These measurements include a contribution from the earth's atmosphere when the weather was excellent (clear, dry, and cold). The lower plot shows the drastic decrease in the optimum integration time caused by cloudy weather. It may be possible, therefore, to use the Allan-variance to check the atmospheric variability, which is particularly important for submillimeter wave observations.

We note, finally, that increasing the bandwidth, B, of the spectrometer channel reduces the white-noise contribution as the square root of B. Thus, the minimum in the Allan-variance occurs at shorter integration times and can only be improved by increasing the stability of the electronic components. This effect is important if simultaneous measurements are made with several spectrometers with different resolutions or when adjacent channels are added together to improve the signal-to-noise ratio of data taken with a single spectrometer.

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