Publ. Astron. Soc. Japan **35**, 323–335 (1983)

A 1.5-m Millimeter-Wave Telescope with Acousto-Optical Spectrometers at Nagoya University

Toshiaki TAKANO, Hideo OGAWA, Tatsuji KATO,* Mitsuaki FUJIMOTO,
Yasuhiro FUJIMOTO, Yasuo FUKUI, Yoshikazu HAYASHI,
Kin-aki KAWABATA, Ryohei KAWABE,
and Yoshiaki SOFUE†

Department of Physics and Astrophysics, Nagoya University,
Chikusa-ku, Nagoya 464

(Received 1982 July 7; accepted 1983 January 18)

Abstract

A new 1.5-m millimeter-wave telescope has been in operation at Nagoya University for CO-line observations at 115 GHz since 1981. The Nasmyth optics has been introduced for the first time to radio astronomical antennas, which makes room for the receiver system larger and the front-end system not to tilt with the elevation angle, and consequently the access to the receiver system has become easier. The back-end consists of two acousto-optical spectrometers; one is a high-resolution spectrometer whose bandwidth and frequency resolution are 44 MHz and 40 kHz respectively and the other a wide-band spectrometer of 280-MHz bandwidth and 240-kHz resolution. The two spectrometers allow us to observe the 115-GHz CO line with a velocity resolution of 0.1 km s^{-1} and in an instantaneous velocity range as wide as 730 km s^{-1}. The large-scale structure and kinematics of dark clouds, giant molecular clouds, and the galactic center region are being investigated by this facility.

Key words: Instruments; Millimeter-wave observations; Molecular lines; Radio-frequency lines; Radio telescopes.

1. Introduction

Carbon monoxide is used as a tracer in investigating the distribution, structure, and kinematics of interstellar molecular clouds on account of its ubiquity in the Galaxy. Observations with small-aperture telescopes have an advantage in investigating the large-scale structure of extended molecular clouds, because the large beam of the telescope makes it possible to get fully-sampled maps of extended regions rapidly. The surveys of large extended region of molecular clouds with small-aperture telescopes, such as the Columbia 1.2-m telescope and the Kisarazu Technical College 1.5-m telescope, have revealed important results up to the present (e.g., Kutner et al. 1977; Cohen et al. 1980; Blitz and Thaddeus 1980; Kodaira et al. 1977). But these telescopes have some limitations in back-ends, the frequency resolutions are insufficient to investigate the fine velocity structures of dark clouds and the total frequency bandwidths are not wide enough for observations of the galactic

* Present address: Faculty of Education, Utsunomiya University, Mine 350, Utsunomiya 320.
† Present address: Nobeyama Radio Observatory, Nobeyama, Minamimaki-mura, Minami-saku-gun, Nagano 384–13.

center region.

We have constructed a 1.5-m Nasmyth telescope (figure 1) at Nagoya University for the studies of large-scale structure and dynamics of molecular clouds at the 115-GHz ^{12}CO line. The telescope is equipped with high-resolution and wide-band acousto-optical spectrometers which allow us to observe celestial objects with a velocity resolution of 0.1 km s^{-1} and in an instantaneous velocity range of 730 km s^{-1} at the 115-GHz CO line. We constructed acousto-optical spectrometers stable enough to operate with a long switching interval of the order of 1 min using commercially available acousto-optical light deflectors without special technical effort. The present paper describes this new facility.

2. Equipments

The main characteristics of the antenna are summarized in table 1. The antenna is

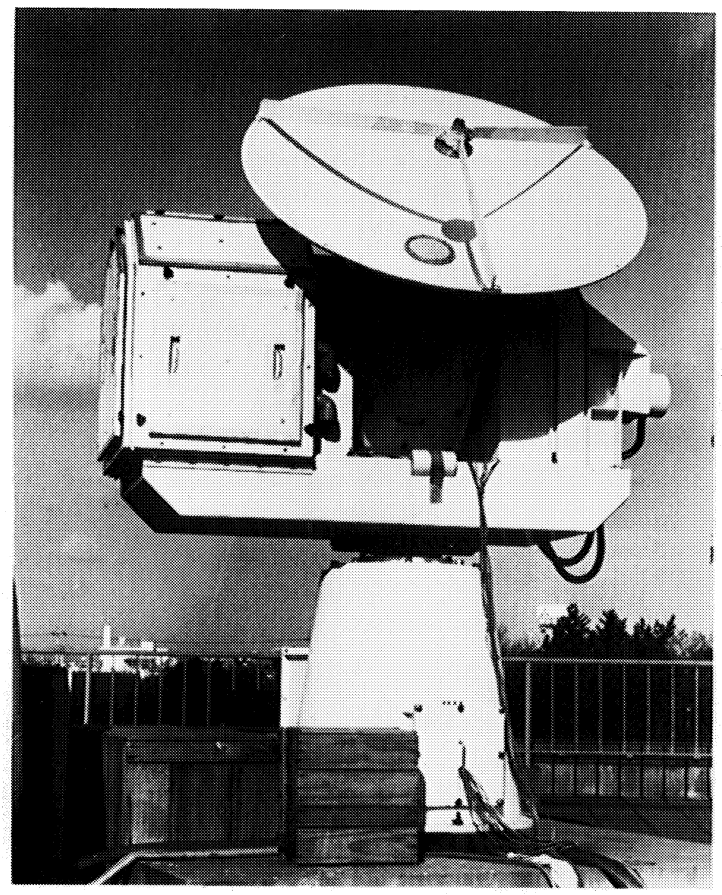


Fig. 1. 1.5-m telescope at Nagoya University.

Table 1. Main characteristics of the antenna optics.

Antenna diameter	1.51 m
f/D ratio	0.3
Surface accuracy (rms)	50 μm
Half-power beamwidth	8′
Pointing accuracy (rms)	15″

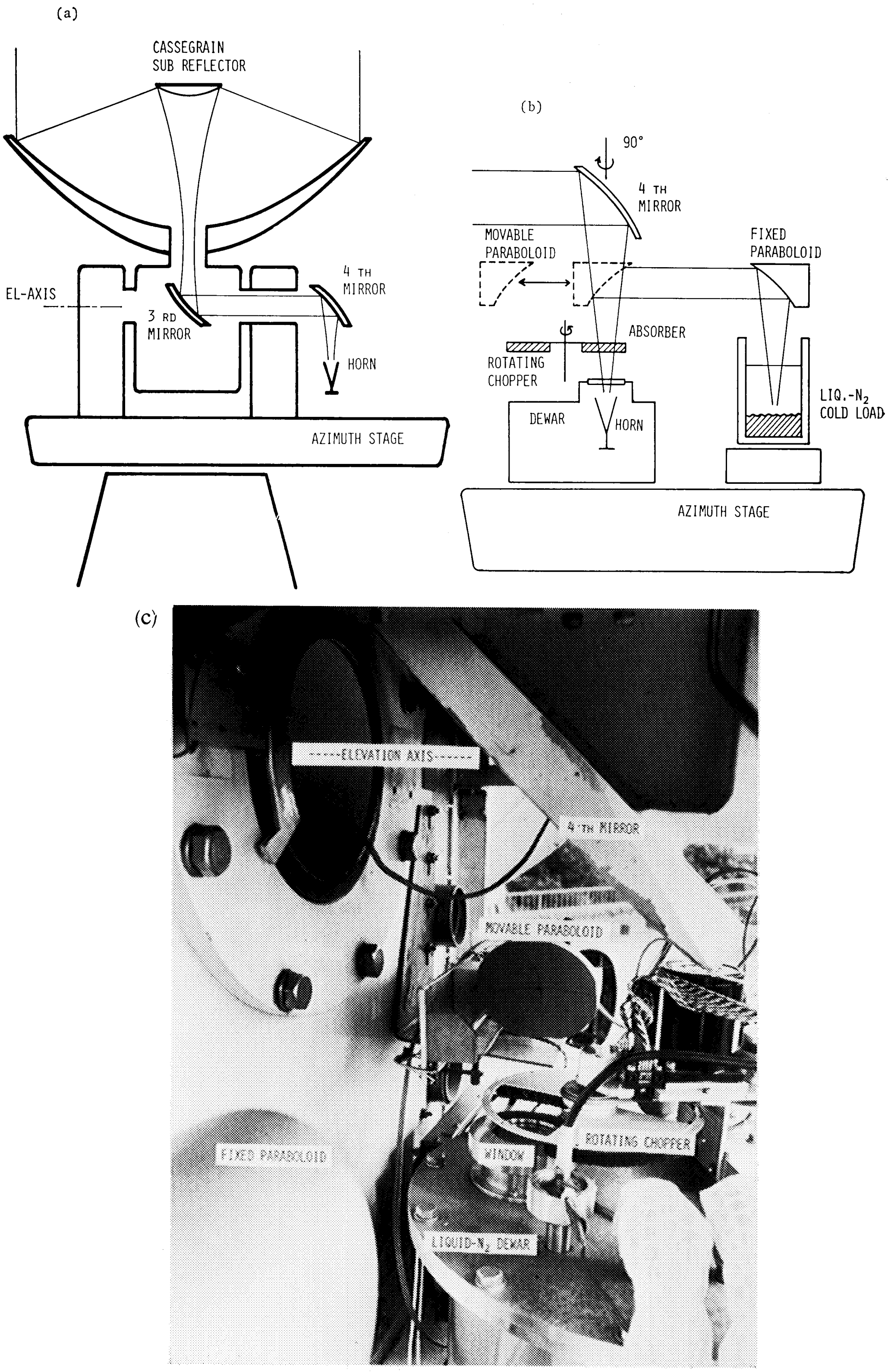


Fig. 2. (a) Schematic diagram of optics. The radio-wave reflected by the Cassegrain sub-reflector is again reflected along the elevation axis by the third mirror, focused by the fourth mirror and introduced into the feed horn placed on the flat stage which does not tilt with the elevation angle. (b) The temperature calibration system. The room temperature absorber and the liquid-N_2 cold load are monitored alternately. (c) Photograph of the calibration system.

on the roof of a building of the Faculty of Science, Nagoya University, at 35°10′N in latitude and 136°58′E in longitude. The site is about 60 m above the sea level. Typical atmospheric optical depths in the clear sky are about 0.2 in winter and 0.5 in summer at the zenith at 115 GHz. The telescope mount is of azimuth-elevation design.

2.1. Antenna Optics

In order to make room for the receiver system larger than the usual Cassegrain antennas and not to tilt the front-end system with the elevation angle, we introduced the Nasmyth optics for the first time to astronomical antennas for millimeter-wave spectral line observations. Consequently the access to the receiver system for tuning and for maintenance work has become much easier. Figure 2 illustrates the Nasmyth optics schematically. Radio waves reflected by the Cassegrain sub-reflector are transmitted through the elevation axis by the third mirror and focused by the fourth mirror into the feed horn seated on the flat stage, which does not tilt with the elevation angle. The latter two mirrors are identical off-axis paraboloids and the parallel beam travels between them. We measured that the transmission loss of these two mirrors, including the spillover loss, was negligibly small, i.e., less than 3%. Therefore we believe that the Nasmyth optics is very useful with negligible degradation in the antenna performance compared with the existing Cassegrain optics.

The calibration system is shown in figure 2b and a photograph is provided in figure 2c. The temperature calibration is made by watching the power difference between the room temperature and liquid-N_2 cold loads. A movable paraboloid is put between the fourth mirror and the horn. The Nasmyth optics enables us to adapt the system to such a small-aperture telescope.

The half-power beam width and the beam efficiency have been estimated from obser-

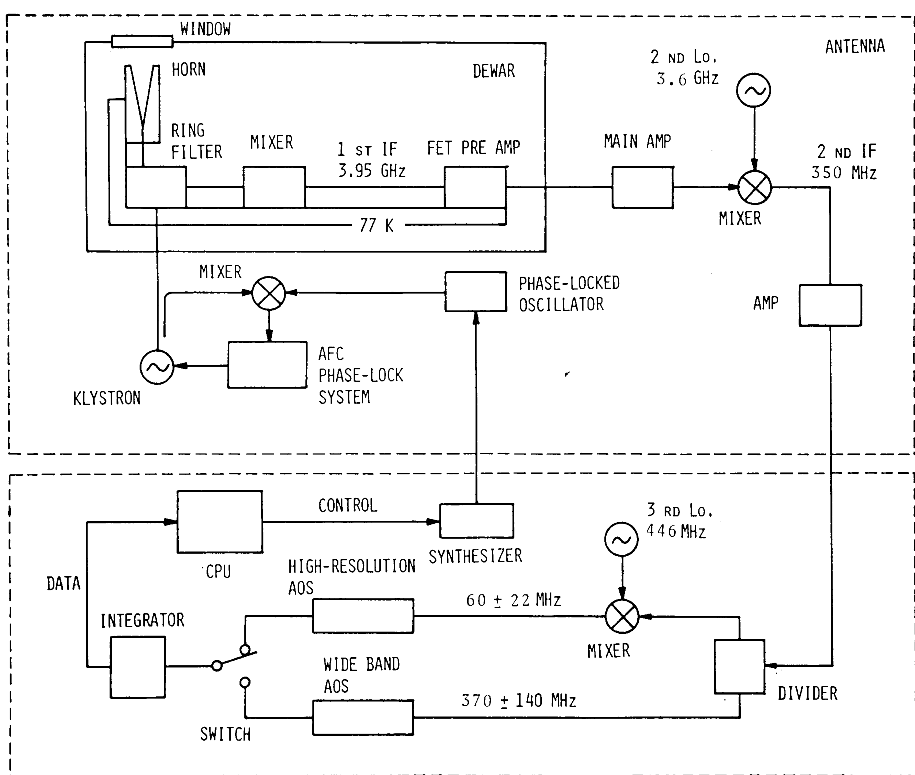


Fig. 3. Block diagram of the receiver system.

vations of the Sun, to be 8′ and 0.6 respectively.

2.2. *Receiver System*

Figure 3 shows a block diagram of the receiver system. A Ga-As Schottky-barrier diode mixer cooled by liquid-N_2 to 77 K is followed by a cryogenic FET pre-amplifier at the same cold stage. The first intermediate frequency (IF) is centered at 3.95 GHz with an instantaneous bandwidth of 400 MHz. The system noise temperature exclusive of the antenna noise temperature was measured to be about 1000 K SSB. The local oscillator is a klystron (Oki 120V10) phase-locked to a reference signal which is supplied via a multiplier from a frequency synthesizer (Fluke 6160B). The frequency synthesizer is controlled by a mini-computer so as to compensate for the Doppler shift of molecular clouds.

Two acousto-optical spectrometers (AOS) have been set up and combined to the front-end. One is a high-resolution (HR) spectrometer whose bandwidth and resolution are 44 MHz and 40 kHz, respectively, and the other a wide-band (WB) spectrometer of 280-MHz bandwidth and 240-kHz resolution. The AOS's are essentially of the same design as described by Kaifu et al. (1977) for the HR and Kai et al. (1980) for the WB spectrometer. The main characteristics of the spectrometers are summarized in table 2.

Table 2. Main characteristics of spectrometers.

Characteristic	High-resolution type	Wide-band type
Frequency range	38–82 MHz	230–510 MHz
Bandwidth	44 MHz (104 km s^{-1})	280 MHz (728 km s^{-1})
Resolution	40 kHz (0.1 km s^{-1})	240 kHz (0.6 km s^{-1})

The light-deflector elements are TeO_2 crystals (Matsushita Electronic Components) and He-Ne gas lasers at 6328 Å are used as coherent light sources. The first-order deflected light is received by a 1728-channel photo-diode array. The results of the measurements about the frequency resolution, stability, and signal-to-noise ratio degradation of the AOS's are described in the Appendix. A more detailed description about the structure, resolution, stability, and so on of the AOS's is given by Takano (1983; copies are available on request to the author).

2.3. *Drive and Control Systems*

This facility is controlled by a mini-computer (Nova/3). The telescope mount is driven by DC servo motors at angular velocities of $0^\circ.005$–$0^\circ.7$ s^{-1} by 12-bit parallel commands from the CPU. The azimuth and elevation angles are read by optical rotary encoders whose angular resolution is $0^\circ.001$. The rms pointing error was measured to be less than 15″ by observing the Sun.

We can carry out two observing modes: position-switching mode and frequency-switching mode. In the position-switching mode one or two reference points are taken a few degrees apart from an observed point. The switching interval from 20 to 40 s is chosen depending on the atmospheric condition and the elevation angle of the observed points. The receiver system including the spectrometer is stable enough to permit such a long switching interval. It takes about 10 s to move the antenna for the position switching. In the frequency-switching mode we can take an arbitrary value less than about 40 MHz as the frequency separation which is mainly limited by an electrical tuning range of the klystron. The frequency switching is done at the rate of a few hertz.

2.4. Data Acquisition

The CPU and its periphery are shown schematically in figure 4. The data from the AOS's are integrated in external memories and read by the CPU about every 240 s. The data read in are written on a magnetic disk and displayed on a graphic display unit and/or an X–Y plotter.

3. Preliminary Observations

Figures 5, 6 and 7 show some results of astronomical observations of the Orion

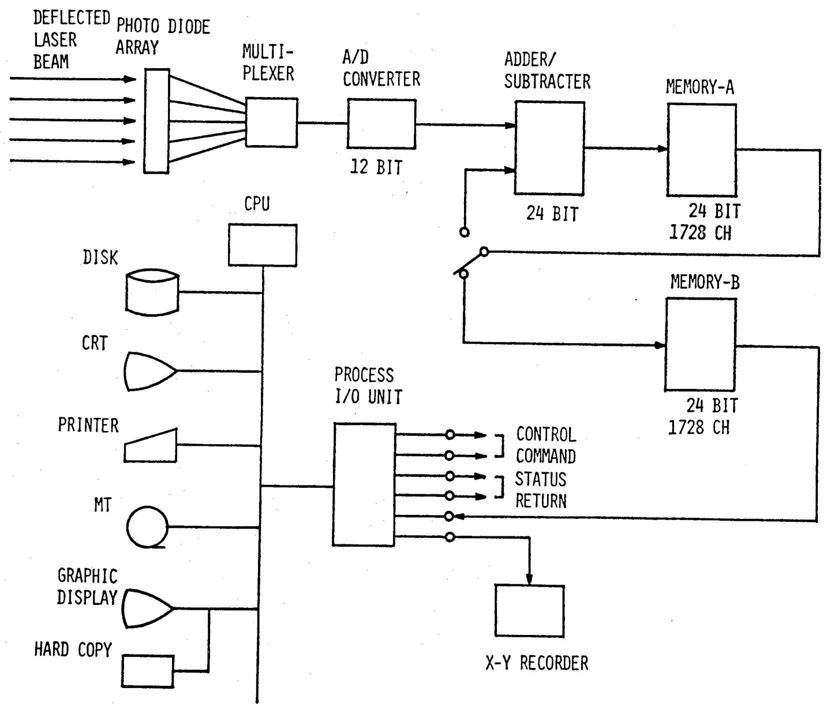


Fig. 4. Flow of the data around the CPU and its periphery. The adder/subtracter, memory etc. are controlled by the CPU via the process I/O unit.

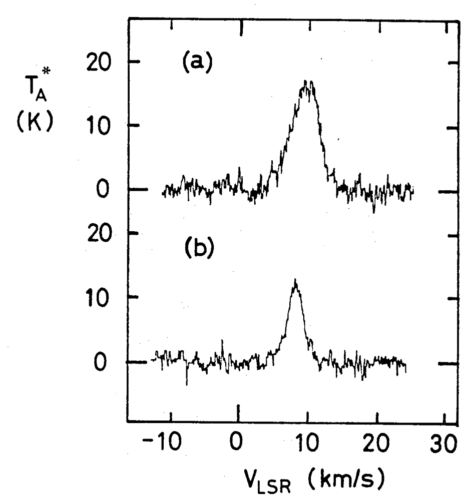


Fig. 5. Results of observations using the high-resolution AOS in the Orion region. The upper, (a), is the CO profile toward the KL nebula ($\alpha=5^h32^m47^s$, $\delta=-5°24'18''$, 1950) and the lower, (b), at a point near NGC 1999 ($\alpha=5^h33^m12^s$, $\delta=-6°42'00''$, 1950).

Molecular Cloud 1 (OMC 1), the Taurus Molecular Cloud 1 (TMC 1), and the galactic center region respectively.

High frequency resolution is necessary for investigating fine velocity structures of small velocity-dispersion clouds such as dark clouds. Figure 5 shows CO profiles in the Orion southern complex. The upper profile (a) was taken toward the KL nebula and the lower one (b) at a point near NGC 1999. Owing to the high velocity resolution the fine velocity structures are clearly resolved. For example, in the profile (b) two components can be distinguished: a narrow and intense component which has a peak antenna temperature of 13 K and a half-power velocity width of 2.5 km s^{-1} and a wide and weak wing of more than 8-km s^{-1} extent. These fine velocity structures could not be resolved by the Columbia telescope, because the velocity resolution was 2.6 km s^{-1} (Kutner et al. 1977). A $1° \times 3°$ fully-sampled map of the Orion region has been already taken by our facility, which will be described in a separate paper (Fujimoto et al. 1983).

Figure 6 shows another example of profiles using the high-resolution AOS. The

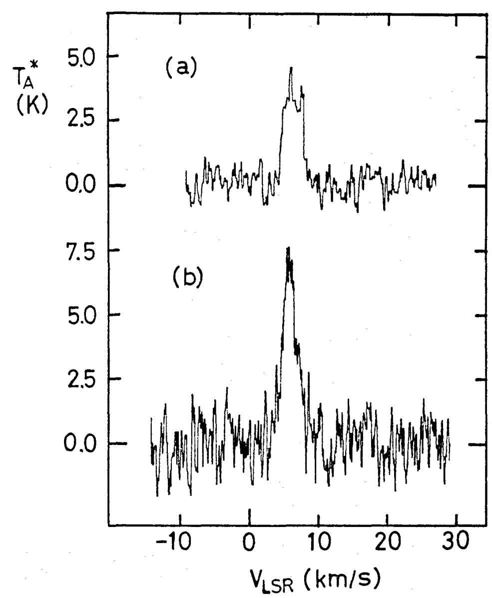


Fig. 6. CO profiles (a) at the central point of the Taurus Molecular Cloud 1 ($\alpha=4^h38^m35^s$, $\delta=25°37'30''$, 1950) and (b) at its south-east edge ($\alpha=4^h39^m15^s$, $\delta=25°27'30''$, 1950) using the high-resolution AOS.

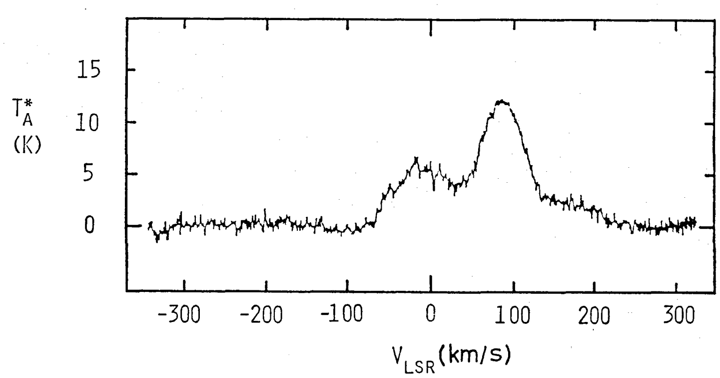


Fig. 7. CO spectrum toward the galactic center region ($l=1.°35$, $b=+0.°15$) using the wide-band AOS. A flat base line is obtained over 700 km s^{-1}. A narrow dip, which is an absorption feature by the local cold gas, is resolved in the vicinity of the zero velocity.

upper profile (a) was taken at the point of strong HC_3N emission in TMC 1 (Tölle et al. 1981) and the profile (b) at its south-east edge. The profile (a) shows steep shoulders and a flat top, while the profile (b) has a sharp tip and seems to be a single component which has a velocity width of as narrow as 2.4 km s^{-1}. These fine velocity structures are detectable by the 0.1-km s^{-1} resolution.

In order to determine base lines for broad velocity-dispersion profiles it is necessary to have a sufficient bandwidth. The CO emission in the galactic center region extends more than 300 km s^{-1}. By the wide-band AOS we can get enough bandwidth to determine the base line as shown in figure 7 (Kawabe et al. 1983). Another remarkable merit of the wide-band AOS is its many resolved points in frequency. In spite of its wide bandwidth the velocity resolution is as high as 0.6 km s^{-1}. In figure 7 a narrow dip which is an absorption feature by the local cold gas is resolved near 0 km s^{-1}. This high resolution should be compared with a 2.6-km s^{-1} resolution of conventional 256-channel 1-MHz filter bank spectrometers. These results certainly demonstrate that this facility is suitable for investigations of both fine velocity structures and extremely violent motions of the extended molecular clouds.

4. Summary

This paper describes a new 1.5-m millimeter-wave telescope at Nagoya University. We have introduced the Nasmyth optics for the first time into astronomical millimeter-wave antennas for molecular line observations. We conclude that the Nasmyth optics is suited for millimeter-wave line observations and has the following merits:

a) The room for the receiver system can be made large enough, for example, to construct quasi-optical devices such as the calibration system, the local oscillator coupler and so on without restricting of the antenna-mount structure. This point is especially important for such a small-aperture telescope which has usually a rather tight space for receivers.

b) The Nasmyth optics prevents the front-end system from tilting with the elevation angle. For a millimeter-wave receiver a cryogenic system is necessary for decreasing the mixer noise temperature, and it is desirable that the cooled receiver system is kept horizontal for adjustment and stable operation.

This facility has realized a combination of a small-aperture antenna and spectrometers with extremely high frequency resolution and broad frequency coverage. We can study dynamics in giant molecular clouds by the high-resolution AOS with 0.1-km s^{-1} velocity resolution and by the wide-band AOS with a instantaneous veolcity coverage of 730 km s^{-1}. First observational results presented in this paper demonstrate the power of such a combination.

The authors would like to acknowledge useful advice of Professor S. Kodaira of Kisarazu Technical College and Dr. J. Inatani of Tokyo Astronomical Observatory in constructing the receiver. The 1.5-m paraboloidal dish was transferred to Department of Physics and Astrophysics, Nagoya University from the Research Institute of Atmospherics, Nagoya University, where it was used as a part of the 4000-MHz solar interferometer. Norizuki Machinery Works, Ltd. machined the dish within the accuracy of 50 μm rms. The authors thank the staff of the machine shop of Department of Physics and that of Faculty of Science, Nagoya University for their help in constructing the facility.

This work was in part supported by the Grants-in-Aid for Scientific Research of the Ministry of Education, Science, and Culture (Nos. 542003 and 5784003).

Appendix. High-Resolution and Wide-Band Acousto-Optical Spectrometers

We make use of TeO_2 AO deflectors of Matsushita Electronic Components EFL-D1000 for HR and EFL-D800S1 for WB spectrometer. The characteristics of TeO_2 (paratellurite) crystals as an AO deflector were investigated by Warner et al. (1972) and Uchida and Niizeki (1973). The parameters for the both types of the deflectors are given in table A1. Because the TeO_2 crystal is an anisotropic medium, the velocity of the acoustic wave depends on the traveling direction (see table A1).

Table A1. Main parameters of the high-resolution and the wide-band acousto-optical spectrometers.

Parameter	High-resolution type	Wide-band type
Deflector	EFL-D1000	EFL-D800S1
Direction of the acoustic-wave propagation	off-[110]	[001]
Acoustic-wave velocity (v) (10^5 cm s^{-1})	0.625	4.20
Central frequency (f_0) (MHz)	60.0	370
Frequency range (MHz)	38–82	230–510
Frequency width (Δf) (MHz)	44	280
Aperture of the crystal (D) (mm)	16	18
Typical input power (mW)	50	400
Deflection angle (θ) (degree)	2.2–4.7	2.0–4.4
Resolved points (N)	1100	1200
Calculated frequency resolution ($\Delta f/N$) (kHz)	39	233
Measured frequency resolution (kHz)	40	240

The EFL-D1000 deflector utilizes the abnormal Bragg diffraction of light and then the following equations, the Bragg condition, can be applied (Dixon 1967):

$$\sin\theta_i = n_i \sin\theta_i' = \frac{\lambda f}{2v}\left[1 + \frac{v^2}{\lambda^2 f^2}(n_i^2 - n_d^2)\right], \quad \text{(A1a)}$$

$$\sin\theta_d = n_d \sin\theta_d' = \frac{\lambda f}{2v}\left[1 - \frac{v^2}{\lambda^2 f^2}(n_i^2 - n_d^2)\right], \quad \text{(A1b)}$$

where θ_i' and θ_d' are the angles of the incident and deflected light measured from acoustic-wave plane in the crystal and θ_i and θ_d are those at the outside of the crystal, n_i and n_d are refractive indices, λ is the wavelength for the light and f and v are the radio-wave frequency and the velocity of the acoustic wave. On the other hand, the EFL-D800S1 deflector utilizes the normal Bragg diffraction and then the Bragg condition is reduced to the first terms of equation (A1) because n_i is equal to n_d.

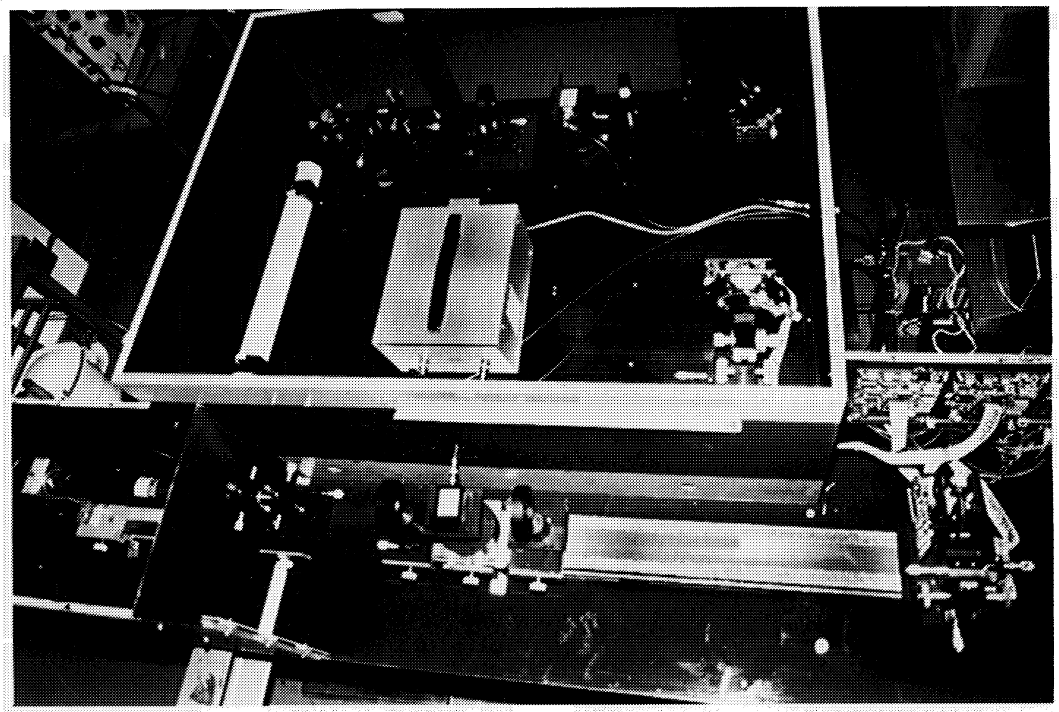
For the WB deflector $\partial\theta_i/\partial f = \partial\theta_d/\partial f = \lambda f/2v$ and the deflection angle between the incident light and the deflected light, $\theta_i + \theta_d$, is equal to $\lambda f/v$. On the other hand, for the HR deflector in the vicinity of f_0, which satisfies $\partial\theta_i/\partial f = 0$ for equation (A1), $\partial\theta_d/\partial f$ is equal to $\lambda f/v$ and the deflection angle is the same as in the case of the WB deflector (Warner et al. 1972).

The number of resolved points is defined as the ratio of $\Delta\theta_d$ to $\Delta\theta_b$, where $\Delta\theta_d$ is the span of the deflected angle for the frequency width and $\Delta\theta_b$ is equal to λ/D, the diffraction limit of the incident light beam:

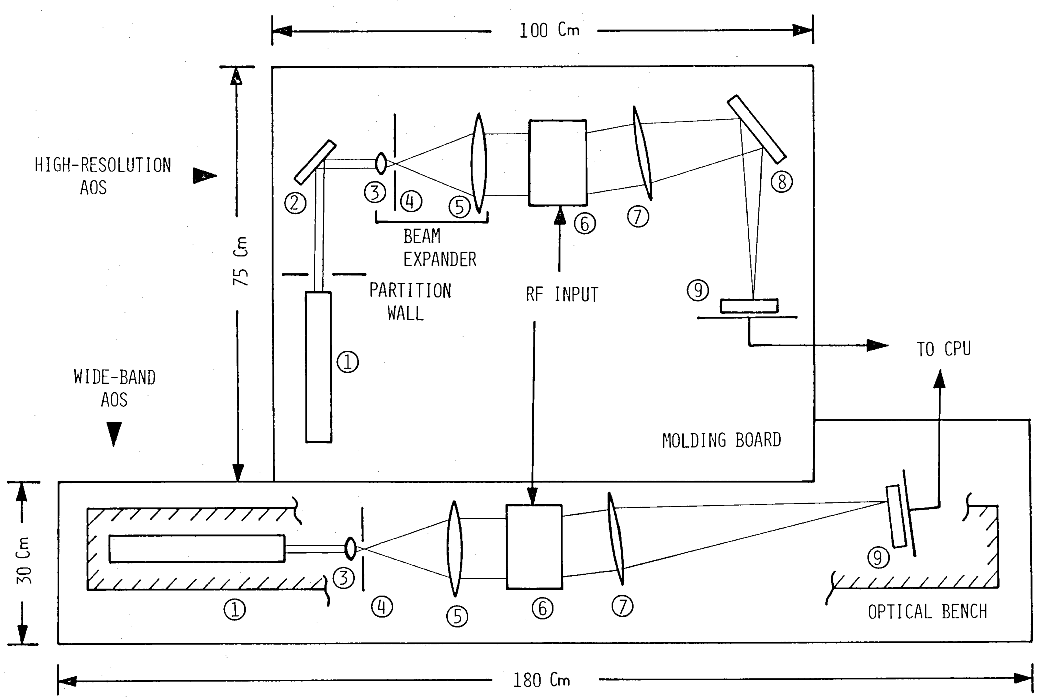
$$N \equiv \frac{1}{\gamma}\frac{\Delta\theta_d}{\Delta\theta_b} = \frac{1}{\gamma}\frac{D}{v}\Delta f, \quad \text{(A2)}$$

where γ is the coefficient determined by the beam shape of the light; $\gamma=1$ is for the uniform beam and $\gamma=1.27$ for the Gaussian beam. N is the number of independent information and corresponds to the number of channels for filter-bank spectrometers.

The deflected angles, the number of resolved points, and the frequency resolution of



(a)



(b)

Fig. A1. (a) Photograph of the acousto-optical spectrometers at Nagoya University. (b) Sketch of the high-resolution and the wide-band acousto-optical spectrometers.

Table A2. Characteristics of components of acousto-optical spectrometers.

Component	High-resolution AOS	Wide-band AOS
1. . . . . He-Ne laser polarization	Linear	Linear
Polarization direction	Horizontal	Vertical
Output power	5 mW	5 mW
2. . . . . Mirror	D=25 mm	—
3. . . . . Microscope objective lens	×40	×40
4. . . . . Pinhole	D=10 μm	D=25 μm
5. . . . . Collimator lens	D= 50 mm	D= 50 mm
	f =200 mm	f =200 mm
6. . . . . AO deflector	HR type	WB type
7. . . . . Lens	D= 50 mm	D= 50 mm
	f =600 mm	f =500 mm
8. . . . . Mirror	D= 50 mm	—
9. . . . . Photo-diode array	1728 channels	1728 channels

deflectors at $\gamma=1$ are also shown in table A1.

A photograph and a schematic diagram of AOS's at Nagoya University are shown in figure A1 and the parameters of the components are summarized in table A2. The HR-type AOS is constructed on a 100 cm×80 cm, 350 kg weight molding board and two mirrors are used to bend the ray path. We use the mloding board in order to prevent vibration of the system. On the other hand, the WB AOS is placed on an optical bench, 150 cm in length and 8 cm in width, to simplify the optics and to reduce the weight of the system. The molding board and the optical bench are placed on rubber sheets to absorb vibration coming from the floor.

Linearly polarized 5-mW He-Ne lasers are used for the coherent light sources. In order to prevent the turbulence of the air by heat rising from the lasers, they are separated from the other parts by a partition wall.

Because the diameter of the laser beam is small the beam should be expanded enough to cover the aperture of the deflector [see equation (A2)]. For the WB AOS we use a ×40 microscope objective lens, a 10-μm diameter pinhole, and a single lens of D=50 mm, f=200 mm, and the beam is expanded from 0.8 to 26 mm in diameter.

The deflected beam in each type of deflector is focused by a single lens onto a 1728-channel photo-diode array (Reticon RL-1728H). The focal length of the lens is $f=A/\Delta\theta_{\rm d}=vA/\lambda\Delta f$, where A is the linear dimension of the used part of the array. The length of the array is 26 mm and we use a 500-mm focal length lens for the WB AOS. Each of these components is placed on an X–Y stage and, for the deflector, a rotating stage which can be finely adjusted.

Figure A2 shows the response of several channels to the frequency of the CW input. We get the system frequency resolutions (3 dB width) of 40±1 kHz for the HR AOS and of 240±5 kHz for the WB AOS with the Gaussian fitting and these correspond to N of 1100 and 1170, respectively. As shown in table A1 these measured values of the frequency resolution correspond well to their theoretical values. We have realized the theoretical frequency performance of AO deflectors in practical systems.

Figure A3 shows the several channels of output from each photo-diode array around the peak channel under a CW input. The frequency of input signal is 60 MHz for the HR type and 350 MHz for the WB-type AOS.

The stability of the AOS system could be degraded by the fluctuation of the laser emission power and frequency, the mechanical distortion and/or displacement in the system,

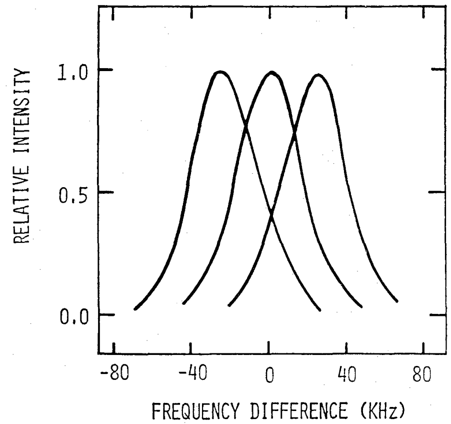


Fig. A2. Response of several channels in the high-resolution spectrometer to the frequency of the CW input.

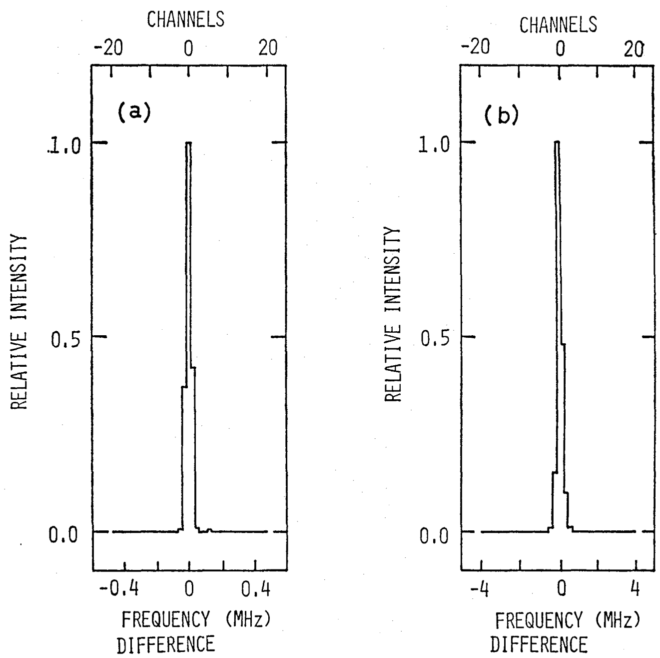


Fig. A3. Output of the photo-diode arrays around the peak channels for (a) the high-resolution type and (b) the wide-band type spectrometers. The frequency of each CW input is 60 MHz for the HR type and 350 MHz for the WB type AOS. The abscissa is the difference of the frequency (bottom) and channels (top) from the center.

and the fluctuation of the air mass (Masson 1982). To test the stability of the system, we monitored the central channel (figure A3) for half a day from midnight to noon under the CW input signals whose frequencies were well stabilized during these measurements. The fluctuations of the peak intensities were less than 3 %, and the movements of the central channel of AOS's were less than 2 % of the measured frequency resolutions of the both spectrometers. Therefore the stability of the AOS's is good enough for astronomical observations.

Some degradation of the S/N ratio could be caused by the AOS's (Chikada 1978, private communication). The degradation of the S/N ratio through the AOS's is not detectable by comparing spectra of hot and cold loads (Takano 1983).

The performance of our AOS's described above enables us to operate the facility with a long switching interval of the order of 1 min.

References

Blitz, L., and Thaddeus, *IEEE J.* P. 1980, *Astrophys. J.*, **241**, 676.
Cohen, R. S., Cong, H., Dame, T. M., and Thaddeus, P. 1980, *Astrophys. J. Letters*, **239**, L53.
Dixon, R. W. 1967, *IEEE J. Quantum Electron.*, **QE-3,** No. 2, 85.
Fujimoto, Y., Fukui, Y., Ogawa, H., Takano, T., and Fujimoto, M. 1983, submitted to *Astrophys. J. Letters.*
Kai, K., Sawa, M., Shiomi, Y., Aiba, S., Sekiguchi, T., Shibuya, N., Kosugi, T., and Nakajima, H. 1980, *Publ. Astron. Soc. Japan*, **32**, 371.
Kaifu, N., Ukita, N., Chikada, Y., and Miyaji, T. 1977, *Publ. Astron. Soc. Japan*, **29**, 429.
Kawabe, R., Fukui, Y., Ogawa, H., Takano, T., and Fujimoto, M. 1983, submitted to *Astrophys. J.*
Kodaira, S., Ishii, K., Nakamura, T., Inatani, J., Nagane, K., Tojo, A., and Sato, F. 1977, *Publ. Astron. Soc. Japan*, **29**, 53.
Kutner, M. L., Tucker, K. D., Chin, G., and Thaddeus, P. 1977, *Astrophys. J.*, **215**, 521.
Masson, C. R. 1982, *Astron. Astrophys.*, **114**, 270.
Takano, T. 1983, Ph. D. Thesis, Nagoya University.
Tölle, F., Ungerechts, H., Walmsley, C. M., Winnewisser, G., and Churchwell, E. 1981, *Astron. Astrophys.*, **95**, 143.
Uchida, N., and Niizeki, N. 1973, *Proc. Inst. Elec. Electron. Engrs.*, **61**, 1073.
Warner, A. W., White, D. L., and Bonner, W. A. 1972, *J. Appl. Phys.*, **43**, 4489.