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A new radio spectral receiving system at $\lambda = 13$ mm in Urumqi Astronomical Station

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Abstract. We describe a new radio spectral receiving system installed on the 25 m radio telescope of the Urumqi Astronomical Station in China. The receiver is conventional cryogenically cooled 22 GHz system, with the front end being a low noise HEMT amplifier. An average noise temperature of the receiver is about 50 K. The back end, however, is less conventional; it is a surface acoustic wave chirp transform spectrometer (SAW CZT), used for the first time in radio astronomy. As the prototype spectrometer, this system has a bandwidth of 40 MHz and 39.06 KHz frequency resolution. The observational results of water vapor masers demonstrate the feasibility of the SAW CZT-based spectrometer as astronomical spectral line observations.

Key words: instrumentation: detectors

1. Introduction

The 25 m radio telescope of the Urumqi Astronomical Station (UAS), Chinese Academy of Sciences, is located at Nan Mountain, which is south 40 km from Urumqi city, Xingjiang province, in the most northwestern part of China (81°10′41″E, 43°28′16″N). It is situated 2080 m above sea level, a very dry site for the short centimeter observations. The telescope was built in 1992 as an element of Chinese VLBI project and has been in operation since 1993. It has been outfitted with receivers for six wavelength bands centered near $\lambda = 92$, 20, 13, 6, 3.6 and 1.3 cm. Table 1 summarizes the relevant information. The table shows the center frequency, bandwidth, antenna efficiency, polarization and system noise temperature.

The antenna as an element of the EVN is important because of its unique location in the middle of the Asia-European land mass and in an area with a very stable geological structure. It has served the VLBI schedule more than 50% of the time per year. As a single dish, the Urumqi telescope has a relatively small aperture for observing cosmic sources. We can take advantage, however, of the good observing conditions of the site such as dry weather and low radio interference and work on special projects in deep integration and wide survey. There are several very important lines in the existing bands, water vapor ($6_{16} \rightarrow 5_{23}$) and ammonia ($J$, $K = 1$, 1) lines in the K band, methanol ($5_1 - 6_0 A^-$) in the C band and hydroxyl lines in the L band. The K band receiver shown in Table 1 covers two lines, water vapor and ammonia without any modification in the receiver system.

Table 1. Receiver information

Band	92	18	13	6	3.6	1.3
Frequency (MHz)	327	1665	2250	4950	8400	22000
Band width (MHz)	20	150	200	400	400	2000
Antenna eff. (%)	40	52	38	55	50	35
Polarization	left	left	right	left	right	right & left
Front end temp.	room	room	room	room	room	cooled (20 K)
System temp.	100	150	150	120	130	115

The 22 GHz H_2O maser lines are most spectacular, displaying many unusual characteristics of astrophysical masers, with their high intensity, point-like structure, great variability and wide velocity range. The masers can be used to trace the youngest star forming regions of the Milky Way, the dynamical properties of outflow in star forming regions, envelope expansion in late-type stars (Moran 1996), as well as gas motions of accretion disks in active galactic nuclei (Miyoshi et al. 1995). The largest surveys to date for H_2O maser emission in the $6_{16} \rightarrow 5_{23}$ transition in the Galactic and extra-galactic sources were carried out by the Arcetri group (Comoretto et al. 1990) and Braatz et al. (1996). About one thousand H_2O maser sources, including perhaps one hundred megamasers, have been found in the north sky. Despite a bounty of information for the Galactic H_2O maser emission, many aspect

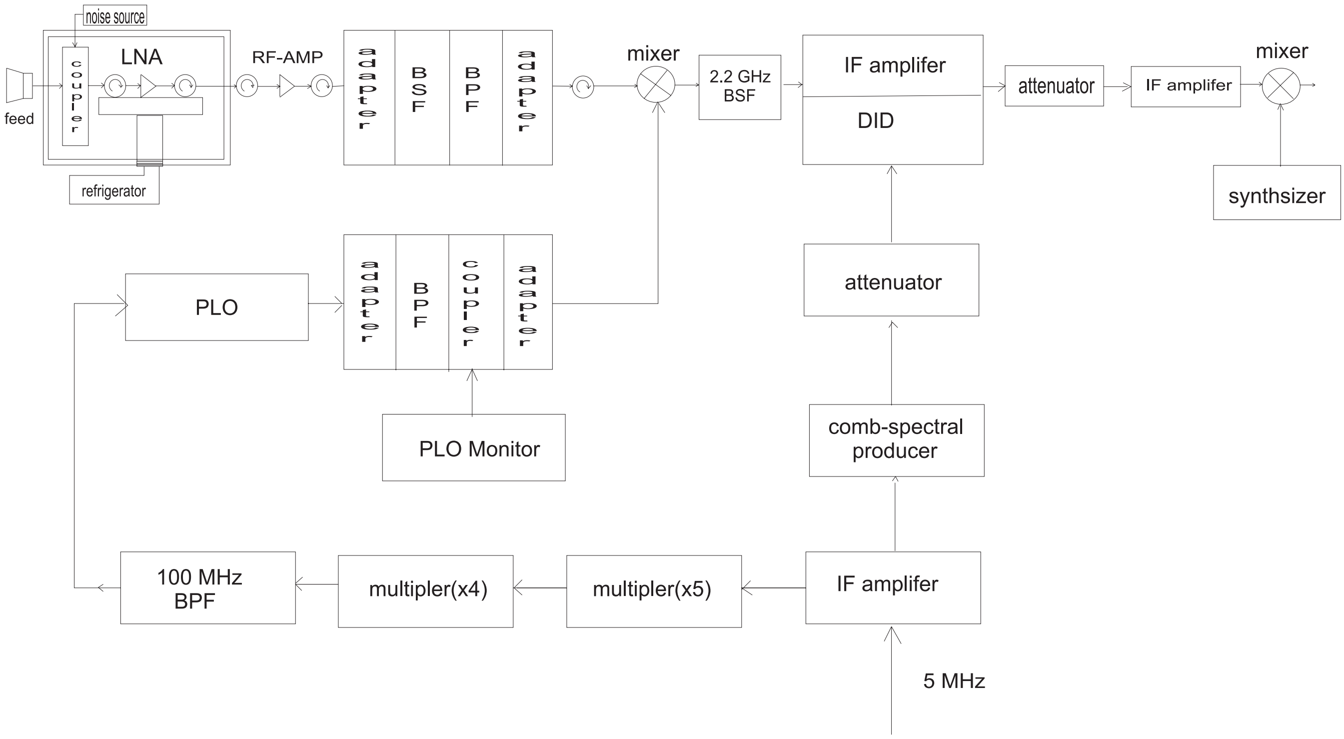

Fig. 1. Diagram of the 22 GHz receiving system in which there are two special features: 1) the IF was made with the 2 GHz wide, in order to suit several different kinds of back ends; and 2) two frequency conversions are used for reducing the cost

still remain unknown. For instance, the large-scale distribution of maser sources in the Milky Way is far from the completely defined (Wang et al. 1992). The variability has been studied in a systematic fashion only for a very limited sample of objects. For H_2O megamaser from distant galaxies, increasing the size of the samples will be quite important for further defining the properties of accretion disks in active galactic nuclei (Greenhill et al. 1997).

At the $(J, K) = (1{,}1)$ NH_3 inversion line at 13 mm wavelength (23.694495 GHz), the HPBW of the Urumqi telescope is about $2'$ which is about 4 times the resolution of the 115 GHz CO survey of the Galaxy by Dame & Thaddeus (1985). Furthermore, The electric quadruple hyperfine structure of NH_3 allows the optical depth and the density of molecular clouds to be derived from the observed relative brightness temperature of the different hyperfine components (Ho & Townes 1983). The structure of the Milky Way would be further elucidated by comparing the maps of NH_3 and CO lines.

Investigating the large-scale structure and properties of the 22 GHz H_2O maser and 23 GHz NH_3 emission in the Milky Way are the main motivations for building a spectral line receiving system for the Urumqi telescope. The receiver is a cryogenically cooled 22 GHz system with the front end being a low noise HEMT amplifier. The back end is a surface acoustic wave (SAW) Chirp-Z-Transform (CZT) spectrum analyzing system.

The aim of this paper is to describe the instrument for the new spectral receiving system. All the calibrations and the first observational data are discussed elsewhere (Zheng et al., in preparation).

2. Receiver

The major parts of the receiver system are designed and developed for the VLBI projects (Ma et al. 1999). We made a slight modification and added a second mixer, which has a reference frequency input from a frequency synthesizer in order to compensate for the Doppler shift due to the motions of source. This generates a fixed output at the 529 MHz central frequency. The diagram of this system is shown in Fig. 1. The HEMT front end is packaged in a dewar, in which a silver plated, oxygen free copper radiation shield was attached to the 70 K stage to reduce the thermal load on the 15 K stage. Cooled dual polarization waveguide transitions will be integrated into the dewar to minimize the added noise due to loss between the feed and HEMT amplifier. The receiver has two filters: One is a special waveguide filter, a combination of band pass filter (BPF) and band stop filter (BSF) to reject the image frequency ahead of the first mixer; the PLO uses a 2.2 GHz phase locked oscillator and two multipliers to provide the final 22 GHz output frequency. Another BSF after the mixer is designed to prevent leakage from the

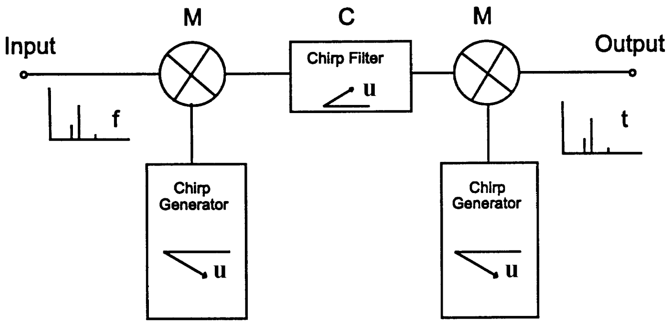

Fig. 2. $M - C - M$ configuration of the CZT. The post-multiplication, used to correct the phase of the output, can be omitted and then reduced to the $M - C$ structure when only power spectrum is interested in

PLO oscillator. For any phase instability mostly in the synthesized band-width of the back end (e.g. MKIII), the phase calibration in the system is inserted at the IF port like most other systems. An average noise temperature of 50 K and a phase stability of 10^{-14} (the overlapping estimate $\sigma \sim \delta\phi/\nu\tau$ of the Allan variance) were measured for the receiver.

3. SAW spectrometer

At present, digital auto-correlation and acoustic-optic spectrometers are in common use as spectrum analyzing systems for radio astronomy. The digital auto-correlation spectrometer provides a flexible selection of bandwidths and resolutions and has convenient digital components. However, its practical application for wide bandwidth and high resolution is limited by the micro-electric technique and the processing speed. The alternative acoustic-optical spectrometer also has its own limitations. As an optical system, its stability is susceptible to influence by the environment. Attempts have been made to develop new type of spectral analyzing system with better stability and reliability in structure and with simplicity of design. The SAW CZT-based spectrometer described below may have the desirable characteristics.

3.1. The CZT algorithm

The CZT algorithm for Fourier transform was developed in 1960's. Since then research on the algorithm from theoretical principle to practical application has flourished. Comprehensive discussions can be found in various review articles (Jack et al. 1978; Jack et al. 1980). To understand the structure of the SAW spectrometer in our spectral receiving system, we summarily depict the CZT algorithm blow.

For a spectral analyzing system, a signal $F(\omega)$ in frequency domain may be expressed in terms of a Fourier integral:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\mathrm{e}^{-j\omega t}\mathrm{d}t. \quad (1)$$

Let us now make a equivalent relation $\omega = 2\pi\mu\tau$ between frequency ω and delay τ, where μ is a chirp slope or a rate of frequency and delay. Using the identity $2t\tau = t^2 + \tau^2 - (t-\tau)^2$, Eq. (1) can be rewritten

$$F(\omega){=}F(2\pi\mu\tau){=}\mathrm{e}^{-j\pi\mu\tau^2} \cdot \int[f(t)\mathrm{e}^{-j\pi\mu t^2}] \cdot \mathrm{e}^{j2\pi\mu(\tau-t)^2}\mathrm{d}t \quad (2)$$

or

$$F(2\pi\mu\tau) = \{[f(\tau) \bullet ch^-(\tau)] \otimes ch^+(\tau)\} \bullet ch^-(\tau) \quad (3)$$

where $ch\pm$ denote Z factors $\mathrm{e}^{\pm j\pi\mu\tau^2}$ and $\bullet$ and $\otimes$ are multiplication and convolution, respectively.

This transform can be realized by a pre-multiplication (M) of input signal $f(t)$ with a down chirp waveform $\mathrm{e}^{-j\pi\mu\tau^2}$, followed by a convolution (C) with a up chirp signal, and finally multiplied by a down chirp signal (as shown in Fig. 2) (Zhang et al. 1996). The signal processing system is named by the $M - C - M$ configuration of CZT or the SAW chirp filter. The post-multiplication, used to correct the phase of the output, can be omitted when only power spectrum is required and reduced to the $M - C$ structure. The CZT algorithm appears to be a frequency axis replaced by a time axis. The spectral components in an input signal are dispersed into a set of pules with different delay and amplitude corresponding to the frequency and the input power, respectively, when they pass the SAW chirp filter.

3.2. The structure of the SAW spectrometer

A diagram of the SAW CZT-based spectrometer consisting of three parts (I, II and III) is shown by Fig. 3 (Chen et al. 1990). Pre-amplifiers and mixers constitutes the first stage with two highly stable L.O. ($f1 = 710$ MHz, $f2 = 690$ MHz). The operating frequency and bandwidth of SAW spectrometer are limited by the technology of SAW devices. So input signals are first split into two bands, A and B, 20 MHz each and then they are down-converted to IF 171 MHz. Part II is the SAW CZT processor containing four parallel CZT subsystem ($A1$, $A2$, $B1$ and $B2$). Each subsystem operates in a bandwidth 20 MHz with 50% working duty cycle and a frequency resolution 39 KHz. The SAW CZT processor, therefore, has a bandwidth of 40 MHz and 100% duty cycle. The equivalent transformation rate is greater 1024 points/66.6 μs. The dynamical range of SAW CZT processor is determined by the sidelobes of impulse response. Hamming weighting is employed to reduce the sidelobe to 35 dB. Part III is a

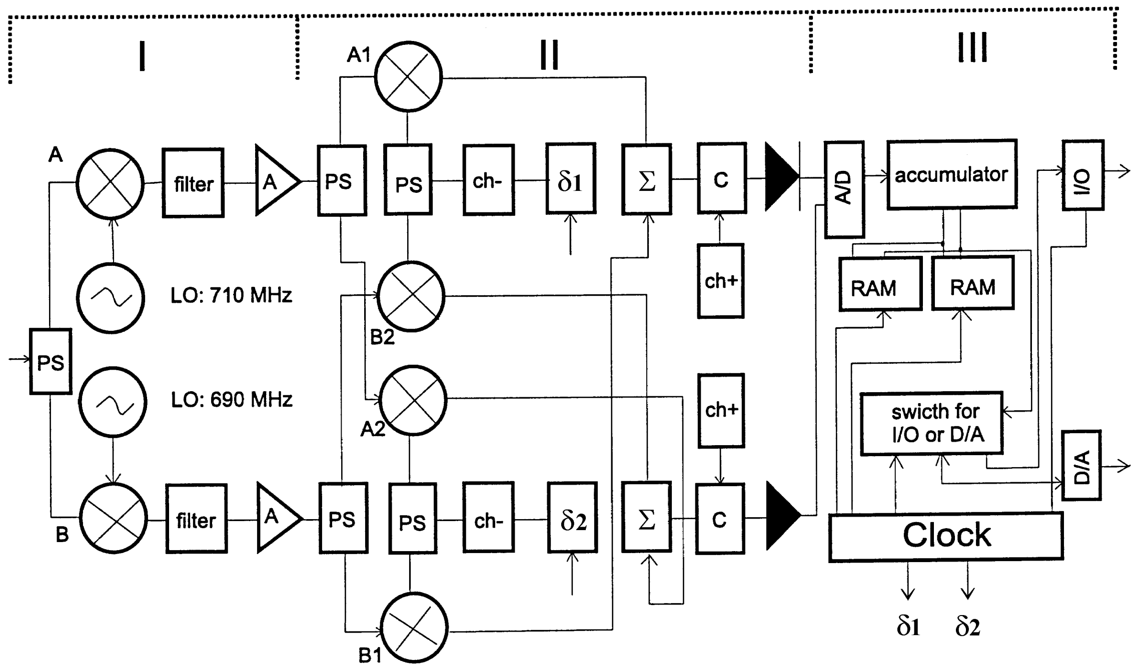

Fig. 3. The structure of the SAW CZT spectrometer consists of three parts: Part I include mixers, pre-amplifiers and filters to split input signals into two bands and down-convert to IF 171 MHz; Part II is the SAW CZT processor. Part III is a digital processor to carry out the A/D conversion and digital integration

Table 2. Properties of the SAW CZT spectrometer

	Bandwidth (MHz)	Delay Time (μs)	C.F. (MHz)	TB	IL (dB)	Sidelobe (dB)
CH^-	40.0	66.6	102.0	2664	42	
CH^+	20.0	33.3	69.0	666	31	30 − 35

digital processor to carry out the A/D conversion and digital integration. The longest integration is about 300 ms. The integration time and the beginning of the integration can be controlled by an I/O interface. Table 2 gives the properties of the SAW CZT processor. Performances of the spectrometer, such as bandwidth, frequency resolution, accuracy of frequency, dynamical range, and temperature behavior were carefully examined and these results have been published in relevant articles.

4. Observational results and conclusions

The SAW CZT-based spectrometer was used for the first time in radio astronomy as a spectral analyzing device. The early experimental observations were carried out at the 13.7 m radio telescope at Qinghai station of the Purple Mountain Astronomical Observatory (Chen et al. 1991). Since then the digital processor in the spectrometer has been improved. The 13 mm spectral receiving system on the 25 m radio telescope at Urumqi was experimentally used to observe H_2O masers in order to continue to testing the feasibility of SAW CZT-based spectrometer for astronomical applications. We observed water vapor maser emission from a number of Galactic sources. To compare with previous observations, the observed lines from some well known sources, such as W49, Orion , W3(OH) and DDG25 are shown in Fig. 4. We estimate that the individual channel sensitivity had typically 7 Jy in the 240 s integrated time. The spectral features for individual sources are consistent with those published in previous paper (e.g. Comoretto et al. 1990). These results demonstrate the feasibility of the SAW CZT-based spectrometer for astronomical spectral line observations. At the same time, the data confirm the excellent meteorological quality of the Urumqi Station for short center-meter astronomical observations.

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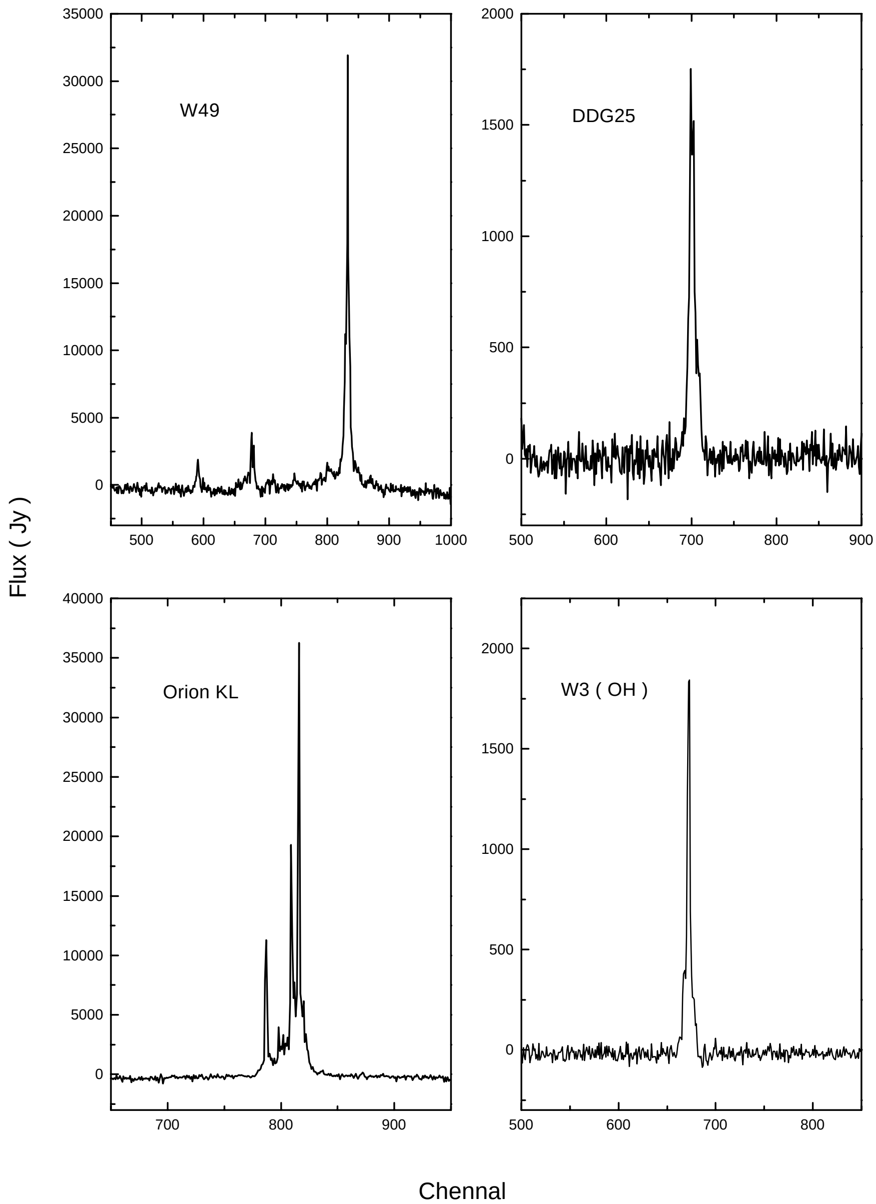

Fig. 4. Observed results of H_2O maser emission from W49, Orion KL, W3 (OH) and DDG25

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