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Measurements for the Performance of the Digital Autocorrelation Spectrometer *

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Abstract Injecting phase calibration (PCAL) signals to the feed horn of the observation system and analyzing the output response signals of the spectrometer, we measured the working performance of a 4096-channel digital autocalibration spectrometer. The results demonstrate that the spectrometer has a fine working performance: (1) the channels are distributed uniformly in the spectrometer; (2) line drift produces little effect on the observation results; (3) spectral resolution shows little changes with observation time. The distribution of the frequency resolution in an 80 MHz bandwidth was measured. A trial observation on the two molecular spectral lines of H_2CO and $H110_\alpha$ taken with this spectrometer is described.

Key words: instrumentation: spectrometer — ISM: molecules — radio lines: ISM

1 INTRODUCTION

In spectral line observations it is important to get precise measurements of the line amplitudes, widths and center velocities. The amplitude measurement depends on the line observing system as well as the flux calibration and there are customary rigorous flux calibrations before or after the line observations. The determination of the measuring precision for line widths and center velocities, however, is not made frequently because it takes time. A convenient technique and method of evaluating the line width and velocity measurements need to be developed, especially when the velocities of spectral features are involved.

As a single dish the 25 m radio telescope is advantageous for studying the large-scale distribution of massive star forming regions. The distribution in the Galaxy is hard to determine, especially because the distances of the massive star forming regions are often difficult to measure. For large samples of observation, the tradition way for the distance measurement still employs the kinematic distance, but there is a serious problem of ambiguity in the kinematic distance. It may be resolved when there are both the emitting and absorbing lines, by measuring the radial velocities of both.

The Urumqi Astronomical Observatory (UAO) is a component of the Chinese Very Long Baseline Interferometry (VLBI) project and all its receivers are installed in PCAL systems. The back-end at the 25 m radio telescope is a digital autocorrelation spectrometer with 4096 channels manufactured by SPACEBORNE INC (Operation Manual can be seen at *http://cfa-www.harvard.edu/˜lincoln/ swis/sao1k/ html/ manual.sao1k.pdf)*. The main advantages of this spectrometer are that it has a changeable working bandwidth and resolution. The normal working bandwidth of the spectrometer can be set from 1 MHz to 80 MHz, the minimum working bandwidth can be set at 0.5 MHz, and the integration time can be set from 209 ms to 29.98 s. The spectral resolution can be set in different values with different working bandwidth. The normal frequency resolution is 0.488 kHz at 2 MHz bandwidth and 19.531 kHz at 80 MHz bandwidth.

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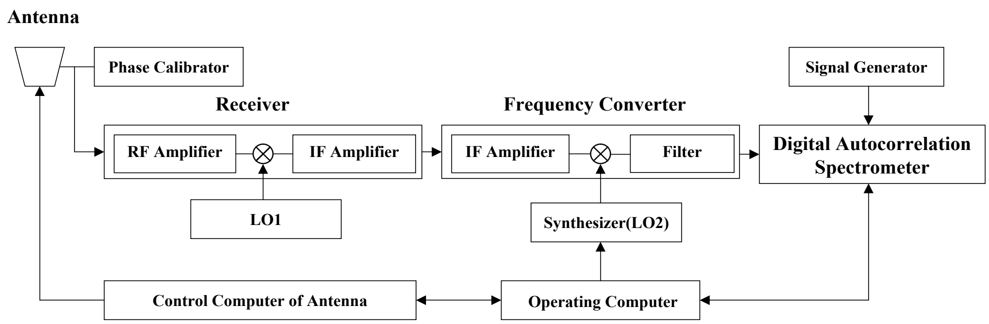

Fig. 1 Block diagram of the experiment system.

The system injects a PCAL signal in a feed horn of the receiver in order to trace changes in the phase of the signal propagated from the feed horn to the frequency convertor. The PCAL signal locked by the frequency standard is a set of narrow-band signals with equal frequency spacing. On another occasion, they are given the name of comb signal. Features in the comb signal spectrum look like spikes 1 MHz apart. PCAL signal is used for frequency phase calibration for VLBI observations and has a very accurate and steady central frequency and frequency spacing. For our observation system the measurements of PCAL signals with an oscilloscope showed that its feature center frequency varies by no more than 24 Hz in one hour and less than 1 Hz change in one minute, and the change of the frequency spacing between two adjacent features in one hour is no more than 5 Hz. The relative change of the frequency spacing is no more than 5×10^{-6}, very small indeed.

The frequency performance of the digital auto-correlator can be evaluated by measuring the drifts, spacing and widths of output response signals. In the experiment we have measured (1) channel spacing distribution over the entire band, (2) line drifts with observing time, and (3) changes of the spectral resolution with observing time. We describe the experimental set-up and the data reduction in detail in the Sections 2 and 3, the results in Section 4. Two spectral lines of H_2CO and $H110_\alpha$ were observed in the experiment. We present the observed spectrum in Section 5.

2 EXPERIMENTAL SETUP

This experiment was carried out on 2005 September 2. Figure 1 shows the block diagram and the signal stream of the line receiving system. It includes a phase calibrator, a 6 cm-band receiver, frequency transform devices, an antenna control computer, an online computer, a frequency synthesizer, a signal generator and a digital autocorrelation spectrometer. The phase calibrator injects a PCAL signal into a feed horn of the 6 cm receiver, which is newly implemented for 6 cm surveying and molecular spectral line observations. The frequency synthesizer and the signal generator are also necessary instruments for molecular spectral line observations. The synthesizer is used as a local oscillator (LO2) in the observation to correct the Doppler shift between the observatory and the Local Standard of Rest (LSR). The signal generator is used to set sampling frequencies for a variety of required bandwidth. A more detailed description of the observing system is given in Zhang et al. (2005).

We conducted the experiment with a center frequency of 4.8519 GHz and a bandwidth of 80 MHz, which covered the $H110_\alpha$ hydrogen recombination line at 4.874 GHz and the formaldehyde absorption line at 4.830 GHz, simultaneously. The central radial velocity in the band was $V_{\rm LSR}$ = 55 km s^{-1}. The LO1 was set at 4620 MHz. The LO2 was calculated by the computer, which changes in step with the observing time. The system temperature on the cold sky was 22 K and the integration time was 1 minute. The instruments were set the same way for observing the H_2CO and $H110_\alpha$ lines. The antenna pointed to the sky background during the experiment. PCAL signals were transformed from the feed horn, the receiver and the frequency converter to the spectrometer. Figure 2 shows an example response signal of the spectrometer.

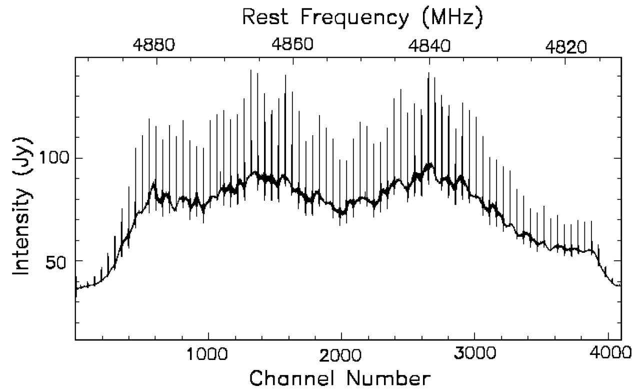

Fig. 2 A sample of the response signal of the spectrometer.

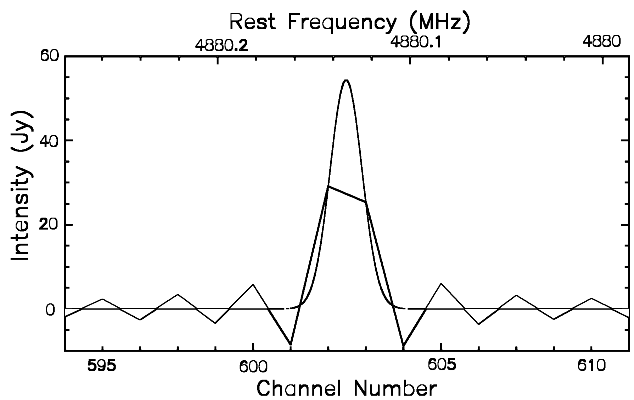

Fig. 3 A sample spectrum of the response signal of the spectrometer. The black line shows the actual spectrum and the gray line the fitted spectrum.

3 DATA REDUCTION

We continuously observed for 131 minutes and recorded 131 groups of data. We use CLASS software package to reduce the observed data. The channel number is used as the units instead of the frequency in the diagram. There are 80 spectrum features in each spectral record and 79 channel spacings between the features. The spectrum features are labelled as 1 to 80 from the first channel to the last, and the channel spacings are labelled as 1 to 79. After the baseline fitting, the features were fitted with Gaussians. Figure 3 shows an example of the spectrum feature so fitted. We output the feature center position, spectrum full width at half-maximum (FWHM), central intensity and the other spectrum parameters, and use SIGMAPLOT 9.0 to draw the figures of the results.

4 DATA ANALYSIS

4.1 Channel Spacing Distribution over the Entire Band

The distribution of the channels in the spectrometer is one of the most important indicators when evaluating the working performance of a spectrometer. Non-uniformity of the distribution of channels can bring more systematic errors to the practical observations. We measured the distribution of the channels in the

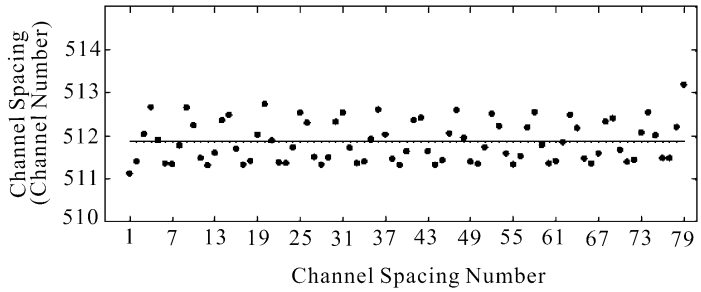

Fig. 4 Average number of channels covered by each channel spacing. The black dots mark the channel numbers that each channel spacing covers and the straight line marks the theoretical value of 51.18988 channels.

spectrometer by measuring the distribution of the channel spacings of the response signals. The frequency spacing between adjacent features is 1 MHz and the channel spacing should be equal. The 79 channel spacings in the experiment cover 4044 channels. So each channel spacing should theoretically cover 51.18988 channels.

We averaged the data of the 131 minutes observation. Figure 4 shows the average channel number that each channel spacing covers. In the figure the straight line marks the theoretical value of 51.18988 channels and the black dots are the channel numbers that each channel spacing covered. The figure shows that the channel spacings are distributed symmetrically about the theoretical value. We compared all the spectral records and found the channel spacing in each spectral record all shows a similar distribution as in the figure. By a statistical analysis of the observation results, we calculated the deviations from the theoretical value. The maximum deviation is 0.06899 channels and the average deviation is 0.04188 channels. The deviation is much smaller than a channel and the average relative deviation is no more than 0.09%. The relative deviation is very small. So we deem that the channels are distributed uniformly in the spectrometer.

4.2 Line Drifts with Observing Time

Though the digital autocorrelation spectrometer has a higher frequency stability than any analog spectrometer, such as the acousto-optical and the filter-bank spectrometer, it is unavoidable that the system response of the correlator shows changes with observation time. This makes the feature center position of a spectrum drift from the center position, which is called the line drift or frequency drift in astronomical observations. This is also an important quantity when evaluating a spectrometer. As examples, Figure 5 displays the feature center position of the 1st, 10th, 20th, 30th, 40th, 50th, 60th, 70th and 80th spectrum changes during the observation time. By analyzing the line drifts of all the observations, we obtained the following results: (1) the line drift changes regularly with observation time, (2) the line drift of every spectrum shows a similar changing curve with observation time, (3) the spectrum in the two outer sides of the band shows more complex drifts than the spectrum in the middle band and (4) the average line drift is 0.0492 channels. The line drift is much smaller than a channel.

Line drift can lead to frequency drift or velocity drift for a measured spectrum and these drifts can bring measuring error into the observational results. For an observation we can estimate the measured frequency drift via $\Delta\nu = (\Delta N/N) \times B$, where N is the total channel number of the spectrometer, ΔN the channel number of the line drift and B the selected bandwidth. The velocity drift can be calculated via Doppler shift function: $\Delta V = (\Delta\nu/\nu_0) \times c$, ν_0 is the center frequency of the band and c the speed of the light. In the experiment the bandwidth is 80 MHz, the center frequency 4851.91 MHz, the line drift 0.0492 channels and the total channel number 4096. So the measured velocity drift is

$$\Delta V = \frac{0.0492}{4096} \times 80\ \mathrm{MHz} \times \frac{1}{4851.91\ \mathrm{MHz}} \times 3.0 \times 10^5\ \mathrm{km\ s^{-1}} = 0.059\ \mathrm{km\ s^{-1}}.$$

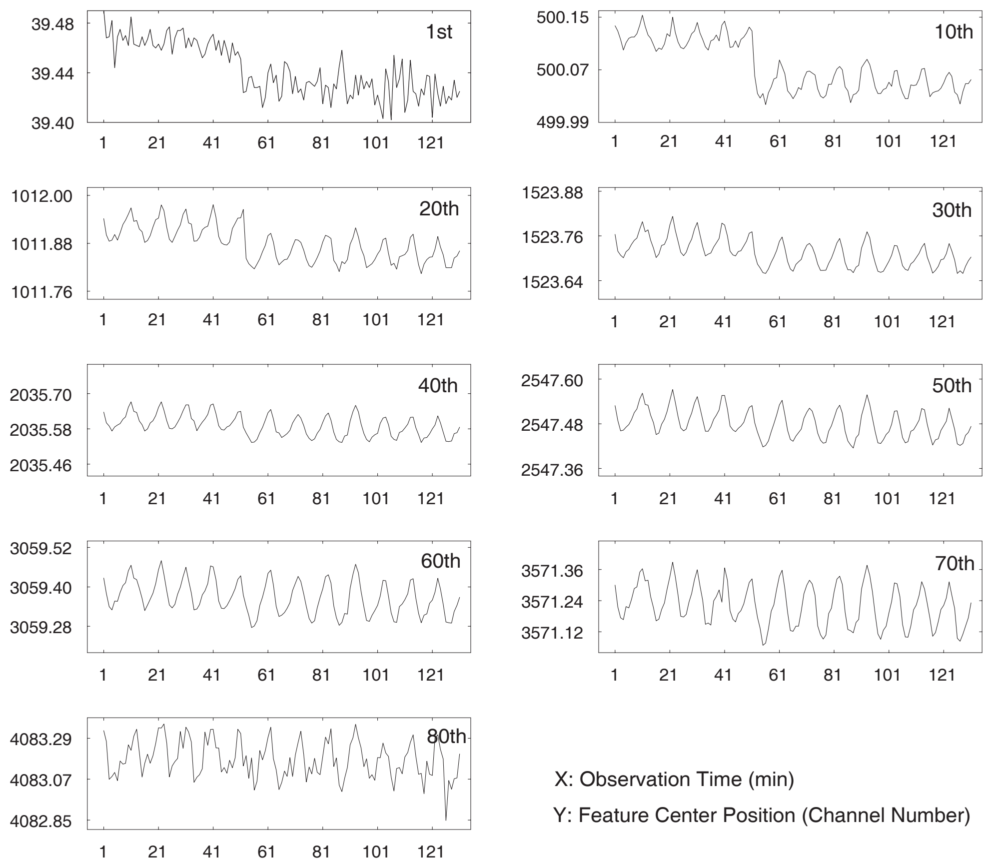

Fig. 5 From top to bottom, the feature center position of the 1st, 10th, 20th, 30th, 40th, 50th, 60th, 70th and 80th spectrum changes with the observation time.

The 22.235 GHz H_2O maser and 1665.402 MHz OH maser are two important molecular spectral lines. If we select the 80 MHz bandwidth and set 22.235 GHz as the center frequency of the band to observe the H_2O maser, the total channel number is 4096 and ΔN is 0.0492, and the maser line will appear in the center of the band and the measured velocity drift will be 0.013 km s^{-1}. As for the 1665.402 MHz OH maser we select 2 MHz bandwidth and set the center frequency 1665.402 MHz, the measured velocity drift will be 0.005 km s^{-1}. In common conditions, the radial velocity of an ordinary molecular cloud is about several kilometers to hundreds of kilometers per second, which is much larger than the measured velocity drift. So the measuring error that line drift brings into the observation results is very small.

4.3 Spectral Resolution Distribution over the Entire Band

In the experiment the measured spectrum profile is a convolution of PCAL signal spectrum profile with the instrumental response of the spectrometer. We derived that the PCAL signal spectrum has a line width of about 19 Hz, and the output response signal spectrum has an average FWHM of 19.531 kHz. So the PCAL signal spectrum line width is much less than the line width of the response signals and the measured spectrum line width is mostly contributed by the instrumental response of the spectrometer. Therfore, the measured spectrum FWHM can show the frequency resolution characteristics of the spectrometer and we can acquire the spectral resolution of the spectrometer by measuring the spectrum FWHM of the output response signals (Zheng et al. 1997). We measured the distribution of the frequency resolution of the spec-

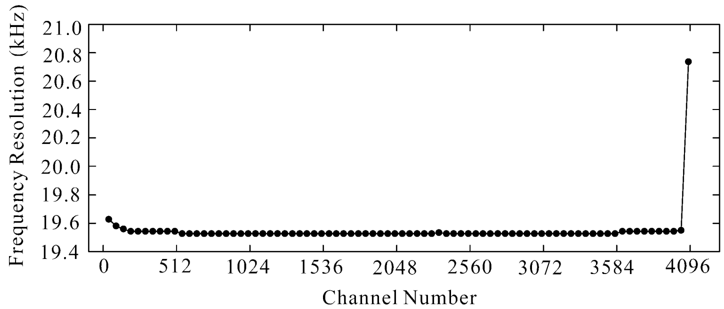

Fig. 6 Frequency resolution distributed in an 80 MHz bandwidth.

trometer in an 80 MHz bandwidth. Figure 6 shows the frequency resolution distribution over the entire band. From the figure we can know that in the middle band of about 500 to 3600 channels the spectral resolution is homogeneous and shows little changes. In the band the frequency resolution is 19.525±0.001 kHz and the velocity resolution is 1.207±0.001 km s^{-1}. The last datum was very much larger than the other data; the corresponding channels may have a worse working state. Ignoring the last datum, the average frequency resolution of the entire band is 19.531±0.014 kHz and velocity resolution is 1.208±0.001 km s^{-1}.

4.4 Spectral Resolution Changes with Observation Time

Because the systematic response of the spectrometer will change with the observation time, the spectral resolution in the entire band may also change with the observation time. We measured the changes of the spectral resolution with the observation time. We found in the middle band from the 4th to 78th spectrum, that is the range from about 150 to 4000 channels, the spectral resolution showed hardly any changes with observation time except that in the 41st and 42nd spectrum the spectral resolution showed changes of about ±0.027 kHz. At the two ends of the band the range from 0 to 150 channels and from 4000 channels to the end, the spectral resolution showed some obvious changes with observation time. Figure 7 displays the changes of the frequency resolution with observation time in the 1st, 2nd, 3rd, 79th and 80th spectrum. As the figure shows, the spectral resolution changes irregularly with observation time at these spectra. Especially at the 80th spectrum the resolution changed violently with the observation time and the maximum deviation to the average value is about 4.375 kHz. Except for the 80th spectrum, the average relative change at the other spectra is about 4%. So the spectral resolution at the two ends of the band is less stable, but the middle band has an excellent working performance and we mostly use the middle band to observe. Then, the stability of spectral resolution is satisfactory.

5 TRIAL OBSERVATION

A trial observation was carried out on 2005 October 24. We tried to observe the two spectral lines of H_2CO and H110$_\alpha$ simultaneously in the region of W51 (α(2000)=19^{h}21^{m}24.401^{s}, δ(2000)=14°24′40.00″) with the same set of the spectrometer as was used in the experiment. We observed the two spectral lines at the 6 cm band. The half-power beam width (HPBW) of the antenna was about 10′. The pointing accuracy was about 15″, the main beam efficiency was about 59%, the system noise temperature was less than 22 K, and the atmospheric attenuation at zenith was about 0.01.

The integration time was 1 minute, and we continuously observed for 16 minutes. Then we used the CLASS software package to reduce the observed data. The result was exciting. Figure 8 shows the result of the summation over 16 minutes. Using the experiment results we estimated the velocity measuring error to be 0.0519 km s^{-1}. So the observed velocities of H_2CO and H110$_\alpha$ spectral lines are 1413.276±0.0519 and −1343.441±0.0519 km s^{-1}, the FWHM of the two spectra of H_2CO and H110$_\alpha$ are 0.237 and 0.559 MHz, respectively. The spectral intensity is calibrated by 3C48, of which the intensity observed with this spectrometer is 8.15 Jy while its real intensity is 5.72 Jy. The central intensity of the emission line is 0.71 Jy and the absorption line is 2.78 Jy. The trial observation is successful and the results indicate that the spectrometer is suitable for observation of the two molecular spectral lines.

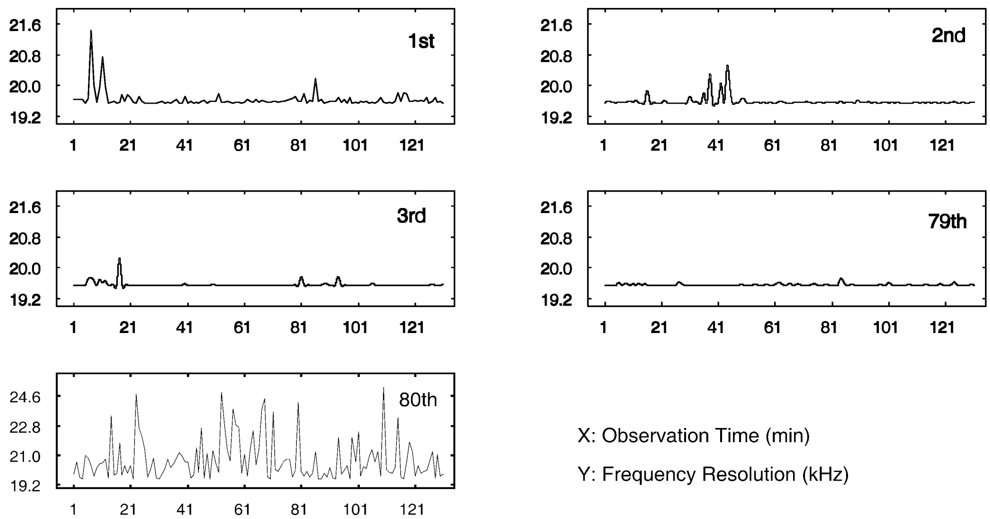

Fig. 7 Changes of frequency resolution at the 1st, 2nd, 3rd, 79th and 80th spectra with observation time.

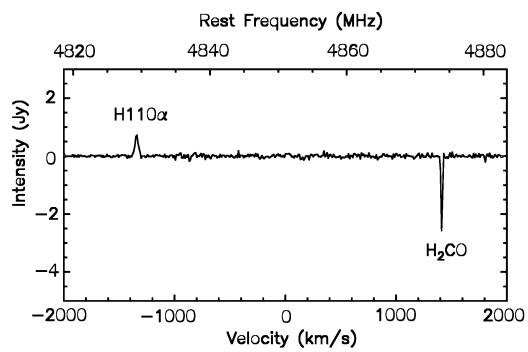

Fig. 8 Result of the trial observation.

6 CONCLUSIONS

The experiment indicates that the spectrometer has a fine working performance. The channels are distributed uniformly in the spectrometer. The line drift shows little effect on the observation results, and the stability of the spectral resolution is satisfactory for our purpose. The average frequency resolution is 19.531 ± 0.014 kHz in the entire band of 80 MHz bandwidth and the middle band has a better frequency resolution of 19.525 ± 0.001 kHz. The spectrometer is suitable for molecular spectral line observations and can be used to serve us for H_2CO and $H110_\alpha$ spectral line observations.

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