On-The-Fly Observing System of the Nobeyama 45-m and ASTE 10-m Telescopes

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Abstract

We have developed a spectral line On-The-Fly (OTF) observing mode for the Nobeyama Radio Observatory 45-m and the Atacama Submillimeter Telescope Experiment 10-m telescopes. Sets of digital autocorrelation spectrometers are available for OTF with heterodyne receivers mounted on the telescopes, including the focal-plane 5 × 5 array receiver, BEARS, on the 45-m. During OTF observations, the antenna is continuously driven to cover the mapped region rapidly, resulting in a high observing efficiency and accuracy. Pointing of the antenna and readouts from the spectrometer are recorded as fast as 0.1 s. In this paper we report on improvements made to the software and instruments, requirements and optimization of observing parameters, the data-reduction process, and verification of the system. It is confirmed that, using optimal parameters, the OTF is about twice as efficient as the conventional position-switch observing method.

Key words: radio lines; ISM — techniques: image processing — telescopes

1. Introduction

On-The-Fly (OTF) is a technique to perform mapping observations efficiently with single-dish radio telescopes. In OTF, the antenna is driven continuously in a region to be mapped, and the data are taken in a short interval, instead of integrating at discrete positions on the sky [such as a conventional “step-and-integrate” method is hereafter referred to as position-switch (PSW) observation]. OTF observations have advantages over PSW modes as follows: (1) The observing efficiency is improved, since the dead time of the telescope is reduced, and a large number (≥ 10⁵) of on-source integrations are made per an emission-free reference integration; (2) The system variation (e.g., atmospheric conditions, receiver gain, pointing of the telescope) affects the map less since the entire map can be covered in a short period; and (3) Since the data are acquired more frequently than the Nyquist sampling rate, the spatial information is not lost. A comprehensive review and discussion of the OTF technique have been made by Mangum, Emerson, and Greisen (2007).

The OTF technique has been commonly and widely used in radio continuum observations. Technical limitations, such as fast readout from the spectrometer and dealing with huge data, had prevented OTF from being applied to spectral line observations. In the last decade, spectral line OTF has been made practicable at some observatories (e.g., Mangum et al. 2000; Muders et al. 2000; Ungerechts et al. 2000), and has been established as an efficient method. Likewise, with the Nobeyama Radio Observatory (NRO) 45-m and Atacama Submillimeter Telescope Experiment (ASTE): Ezawa et al. 2004; Kohno 2005) 10-m telescopes, continuum OTF observations have already been available. We enabled the telescopes to be also operated in the spectral line OTF observing mode, as reported in this paper. Hereafter, we designate “spectral line OTF” simply as “OTF”. The OTF observing system of the telescopes now works with an array of digital autocorrelation spectrometers (MAC: Sorai et al. 2000). Heterodyne receivers equipped with the telescopes, including the 25-beam focal plane array receiver (BEARS: Sunada et al. 2000; Yamaguchi et al. 2000) on the 45-m telescope, can be connected to the MAC and be available for OTF observations.

The capability of OTF to obtain a high-quality map efficiently is important in various scientific fields. For example, investigating how the initial mass function (IMF) of stars is...
determined is one of the most important issues in astronomy. Recent studies have suggested that the stellar IMF is well related to the mass function (MF) of dense molecular cloud cores (e.g., Ikeda et al. 2007), which are sites of star formation. Therefore, detecting a number of cores in various star-forming regions is needed in order to study the relation between the star-forming activity and the MF or physical/dynamical conditions of the cores. In this case, sensitive unbiased mapping observations of wide fields are required. In addition, OTF data are ideal to be combined with interferometric data, since they preserve spatial information in the (spatially) low-frequency regime, which is lost via interferometric observations. Thus, the fidelity to be combined with interferometric data, since they preserve high-resolution images of, e.g., molecular cloud cores or external galaxies, taken with interferometers are significantly improved by being combined with OTF data. The fidelity (preserving the total flux) is essential to various kinds of studies. For instance, in order to investigate the evolution of the interstellar medium (formation and destruction of giant molecular cloud associations (GMAs)] across spiral arms in external galaxies, it is required to detect not only GMAs, which are spatially confined to spiral arms, but also diffuse emission in interarm regions.

In order to make spectral line OTF observations available with the NRO 45-m and the ASTE 10-m telescopes, various improvements have been applied to the control software system, COSMOS-3 (Morita et al. 2003; Kamazaki et al. 2005), and related instruments. In particular, fast and synchronized control of instruments and the handling of a huge amount of data are difficulties, as discussed later. The way to determine the optimal observing parameters is also complicated.

In this paper we report practical information and implementation of the OTF observing mode for the telescopes. Basic concepts and parameters of OTF observations are introduced in section 2, followed by a brief description on controls of related instruments in section 3. Requirements on the observing parameters, procedures to estimate sensitivity, and how to maximize the observing efficiency are explained in section 4. We describe the data-reduction process in section 5. The desired characteristics of convolution functions to regrid the data onto a map are discussed, and some appropriate functions are shown. In section 6 we describe measurements of the driving performance of the antennas, a comparison with a PSW map, and a verification of the frequency-switch observing mode.

2. Basic Observing Process and Parameters

An OTF scan pattern is schematically illustrated in figure 1. A constant-speed raster scan with a single-beam receiver is assumed. Like the usual PSW observations, the standard “chopper-wheel” technique (Penzias & Burrus 1973; Ulich & Haas 1976) is employed to calibrate the antenna temperature, $T_A$, in which the atmospheric and antenna losses are corrected. For the chopper-wheel calibration, a hot load (R) at the ambient temperature and blank sky (SKY) are observed during an observation at an appropriate interval. Data at an emission-free reference position (OFF) are taken before every on-source scan (ON, hereafter simply “scan”) or set of several scans. The OFF is usually taken by pointing the antenna outside the source. However, it can also be taken by shifting the observing frequency (see subsection 3.4.2). During a scan, the antenna is driven at a constant speed ($v_{scan}$) on the sky, and the data are “dumped” from the spectrometer at an interval of $t_{dump}$. The “approach-run” at a speed $v_{scan}$ is inserted before every scan so as to let the antenna move stably during the scan. If there is no OFF between two scans, a “transit-run” (from the end point of the scan to the start point of the next approach-run) is inserted.

We set the fundamental parameters as follows (see figure 1). In section 4 we discuss how to determine them. The dimensions of the mapping area are $l_1 \times l_2$ ($l_1$ along the scan, $l_2$ across the scan). The scan speed of the antenna on the sky is $v_{scan}$. The times to be taken in an approach-run, a main (on-source) scan, and a transit-run are $t_{app}$, $t_{scan} = l_1/v_{scan}$, and $t_{tran}$, respectively. The separation between the scan rows is $\Delta l$, the number of scans taken between a pair of OFFs is $N_{SEQ}$, and the grid spacing of a map to be made is $d$. The time to be taken to slew the antenna between the mapped region and the OFF position is $t_{OFF}$. The parameters $l_{app}$, $l_{tran}$, and $t_{OFF}$ depend on the performance of the antenna, the scan speed $v_{scan}$, the position on the sky, etc., and are typically in the range of a few to 10 s. Measurements of the performance of the antenna are described in subsection 6.1. The time interval between each dump from the spectrometer is $t_{dump}$.

3. Control of Related Instruments

In OTF, spectral data are dumped in a short interval ($\sim 0.1$ s), while the antenna is continuously driven across the sky. Consequently, the following difficulties arise:

**Antenna.** The antenna should be smoothly driven on a scan path. The sky coordinates, toward which the antenna is pointed, have to be recorded for each data dump.

**Spectrometer.** Data dump is done at short intervals, and must be synchronized with the antenna driving.

**Local oscillator.** Doppler corrections of the telescope with respect to a rest frame and the frequency switch (FSW) are difficult to be implemented in a conventional way, since exceedingly rapid control of the frequency is required.

**Data production and storage.** A high data production rate,
is managed with 1, 10, 50, and 100-Hz timing pulses, which produces calibrated data. The observer can view a Quick Look control instruments. MERGER receives outputs from LCs and Local Controllers (LCs) in the bottom layer, that directly by receiving instructions from observers and interacting with and MERGER exist. MANAGER controls the observation is provided in the top layer. In the middle layer, MANAGER and MERGER exist. MANAGER controls the observation by receiving instructions from observers and interacting with Local Controllers (LCs) in the bottom layer, that directly control instruments. MERGER receives outputs from LCs and produces calibrated data. The observer can view a Quick Look (QLOOK) of the data and check if the observation is running properly. The synchronization of instruments with each other is managed with 1, 10, 50, and 100-Hz timing pulses, which are generated and distributed from the standard clock system of the observatory.

3.1. COSMOS-3

The control software system of the telescopes is COSMOS-3 (Morita et al. 2003). It is designed to have a three-layer architecture, as illustrated in figure 2. An interface with observers is provided in the top layer. In the middle layer, MANAGER and MERGER exist. MANAGER controls the observation by receiving instructions from observers and interacting with Local Controllers (LCs) in the bottom layer, that directly control instruments. MERGER receives outputs from LCs and produces calibrated data. The observer can view a Quick Look (QLOOK) of the data and check if the observation is running properly. The synchronization of instruments with each other is managed with 1, 10, 50, and 100-Hz timing pulses, which are generated and distributed from the standard clock system of the observatory.

3.2. Antenna

Before every approach-run, the antenna LC instructs the antenna to settle on the starting point of the approach-run. When the antenna is judged to be steady (the positional error has been within a tolerance for a specified duration), MANAGER decides the timing and coordinates of the following approach-run(s), scan(s), and transit-run(s). The antenna LC instructs the antenna to follow an ideal scan path at the decided timing. The ideal coordinates, toward which the antenna is desired to point, is hereafter called PROG values. The PROG values for every 0.1 s are calculated and transmitted to the antenna, 0.2 s before being used. The antenna manages the timing to use the transmitted coordinates with the 10-Hz (0.1-s) timing signal. Two neighboring PROG values are linearly interpolated. The antenna is driven to follow the interpolated positions, while referring to the 50 and 100-Hz timing signals.

Meanwhile, the actual pointing of the antenna (hereafter referred to as REAL values) jitters around the PROG values. The amount of jitter (PROG—REAL) is measured, in case of the 45-m telescope, using the encoder readout of the master collimator and the pointing deviation between the master collimator and the main reflector. In the case of the 10-m telescope, the encoder readout of the antenna is used. The PROG (in both equatorial and horizontal coordinates) and PROG—REAL (horizontal coordinates) values are both written onto a file, the Antenna Log file, along with time stamps at every 0.1 s.

3.3. Spectrometer

It is essential to synchronize the timing of data acquisition with that of antenna driving, particularly in the case of OTF, since the data dump time is very short. The timing is managed as follows.

When an observation starts, the observing parameters, such as the interval of data dumps (0.1 s) and the number of datasets to be dumped, are calculated by MANAGER from instructions made by the observer. They are sent to the spectrometer LC, and then to the spectrometer, in advance of data acquisition. For each scan, MANAGER decides the time to start a scan, as mentioned above. The LC is informed of the time, waits until 1 s before it, and then sends a command to the spectrometer to start integration. After receiving it, the spectrometer begins to acquire the data, triggered by the next fall-down of the 1-Hz, 50%-duty timing pulse. It dumps the data at every 0.1 s during a scan.

Though the spectrometer outputs datasets at every 0.1 s, observers can specify \( t_{\text{dump}} \) to be \( 0.1 N \) (\( N = 1, 2, \ldots \)) s so as to reduce the data size. Every 0.1-s output is transferred to the LC. The LC averages successive \( N \) datasets if \( N > 1 \), and writes them down onto a file (the Spectrometer Log file) along with time stamps.

3.4. Local Oscillator

3.4.1. Doppler tracking

When a wide area is mapped, the radial velocity of the telescope \( (v_{\text{rad}}) \) with respect to the reference frame [e.g., the Local Standard of Rest (LSR)] significantly changes from point to point: the velocity gradient across the sky plane amounts to roughly \( 0.8 \text{ km s}^{-1} \text{ deg}^{-1} \) (LSR) at maximum in NRO. In PSW observations, the radial velocity of the telescope at each position is calculated and the local oscillator (LO) frequency is shifted before the integration starts, in order to track the Doppler shift caused by \( \Delta v_{\text{rad}} \).

However, in OTF observations, the antenna runs on a scan path (thus, \( v_{\text{rad}} \) gradually changes), during which the spectral data are continuously taken at a short interval. In this case it is difficult to track \( v_{\text{rad}} \) by shifting the LO frequency continuously during the scan. Therefore we do not make any shift of the LO frequency during OTF scans. Instead, the Doppler correction is carried out by software: in the production process of spectral data (MERGER; see below), \( v_{\text{rad}} \) for each ON integration is calculated, and then channel shift operation is made.

3.4.2. Frequency switching

When spatially widespread and/or narrow lines (e.g., CO in nearby molecular clouds) are mapped, the FSW observing
of an individual spectrum, $T_p/\sigma$, is high. Supposing an extreme case for the current system [peak antenna temperature, $T_p = 100$ (K); system noise temperature, $T_{sys} = 100$ (K); frequency resolution, $B = 1$ (MHz); and data dump time, $t_{dump} = 0.1$ (s)], we obtain $t_Q/t_\infty \sim (320/2^{2Q+1})^2$. For $Q = 8, 12, 16$, $t_Q/t_\infty \sim 0.40, 1.5 \times 10^{-3}$, and $6.1 \times 10^{-6}$, respectively. We adopted $Q = 12$ (4096 levels), for which the quantization noise is practically negligible, resulting in a maximum data rate of $\sim 1.3$ GB hr$^{-1}$.

In addition, MERGER supports options of channel trimming and channel binning. When these options are specified by the observer, MERGER trims and/or bins up channels of the spectra before writing them down on the Raw Data file.

It should be noted that 12-bit quantization may affect the data in the following situation: the bandpass becomes nearly 0 (i.e., $T_A^*$ diverges) at the band edges, or an extremely intense spurious signal appears. The observer should pay attention to the obtained spectra through QLOOK. This problem can be evaded by trimming the band edges and/or spurious signals, since the data are quantized after a trim.

### 4. Observing Parameters

#### 4.1. Requirements on Sampling

As a result of an observation, the mapped region is filled with data points. The data-sampling separation is $v_{scan}t_{dump}$ along the scan, $\Delta f$ across the scan. Mangum, Emerson, and Greisen (2007) discussed requirements on the sampling, as summarized as follows. It is requested that, at least, the sampling rates $v_{scan}t_{dump}$ and $\Delta f$ are both more frequent than the Nyquist sampling rate, $\lambda/(2D)$, where $\lambda$ is the observed wavelength and $D$ is the diameter of the antenna aperture. In the case of $\lambda = 2.6$ mm (115 GHz) observations with the 45.5-m telescope, $\lambda/(2D) \approx 6''$, which corresponds to $\approx 1/2.5$ of the half-power beam width (HPBW). Practically, sampling more frequent than the Nyquist rate is required to avoid aliasing noise and beam smearing effects. Since the data points do not align on any regular grid due to antenna jitter etc., data should be regridded onto a regular grid using a gridding convolution function (GCF) in the data-reduction process (see section 5).

#### 4.2. Estimation of Sensitivity

We now estimate the sensitivity of a single-beam observation. Application to a multi-beam receiver is discussed later.

The total number of scan rows in an observation is $N_{row} = l_2/\Delta f + 1$. The total on-source integration time becomes

$$t_{ON} = N_{row}t_{scan}. \quad (2)$$

The total time spent to run an observation including R, SKY, OFF, antenna slew, etc. is estimated to be

$$t_{tot} = N_{row}(t_{scan} + t_{OH} + t_{OFF}/N_{SEQ}) f_{cal}, \quad (3)$$

where $t_{OFF}$ is the integration time for an OFF, and $f_{cal}$ is an overhead of R–SKY calibration (if 1 min is consumed to obtain R and SKY data at every 15 min, $f_{cal} = 16/15$). The $t_{OH}$ is the overhead time per one scan row, which consists of go-and-return to the OFF point, $2t_{OFF}^{trans}$, time for approach- and transit-run $t_{app}$ and $t_{tran}$, and thus is written as...
and the noise due to OFF points becomes

$$\eta_{\text{ON/OBS}} = \frac{t_{\text{ON}}}{t_{\text{tot}}} = \frac{t_{\text{scan}}}{t_{\text{scan}} + t_{\text{OH}} + t_{\text{OFF}}/N_{\text{SEQ}}^2} \times \frac{1}{f_{\text{cal}}}$$

The total on-source integration time for a map grid point, $t_{\text{ON}}$, is the sum of time during which the beam scans within the grid cell. Since the data are convolved using a GCF to construct a regularly gridded map, effectively a factor $\eta$ is multiplied:

$$t_{\text{ON}} = \eta \times \frac{d^2}{l_{1}l_{2}}$$

$$\sim \frac{\eta_t}{l_{1}l_{2}}$$

The factor $\eta$ is a constant determined by the extent of the used GCF, and is calculated as follows. Suppose that observed points $i = 1, 2, \ldots$ are uniformly distributed around the grid point and each point has a spectrum $T_{i}(k)$ ($k = 1, ..., N_{\text{CH}}$), rms noise temperature $\sigma_i$, and a GCF weight $w_i$. We assume that the on-source integration time, $t_0$, and therefore the rms noise temperature, $\sigma_i = \sigma_0 = T_{\text{sys}}/(\eta_{\text{G}}\sqrt{Bt_0})$, of each point are both constant. Here, $T_{\text{sys}}$ is the system noise temperature, $B$ is the frequency resolution of the spectra, and $\eta_{\text{G}}$ is the quantization efficiency of the spectrometer. In the case of MAC, $\eta_{\text{G}} = 0.88$; whereafter $\eta_{\text{G}}$ is omitted from expressions. The convolved spectrum, $T(k)$, is written as $T = (\sum w_i T_i)/(\sum w_i)$, and its noise temperature, $\sigma$, becomes $\sigma = (\sum w_i^2/\sum w_i)\sigma_0 = T_{\text{sys}}/\sqrt{B_{\text{cell}}}$, where $t_{\text{ON}} = t_0 (\sum w_i^2/\sum w_i)$. If we take the grid spacing as the unit of spatial length and redefine $t_0$ as the on-source integration time per unit area (1 grid cell), summations can be rewritten with integrals: $t_{\text{ON}} = t_0 (\iint w^2 d\omega d\phi)^{-\frac{1}{2}} / \int w^2 d\omega d\phi$ $\equiv t_{\text{ON}}$. Approximate values of $\eta$ for GCFs Bessel, Gauss, Sinc, Gauss, Sinc, Gauss, Pillbox, and Spheroidal (see section 5) with default parameters are, respectively, 4.3, 1.2, 6.3, 1.0, and 10.

Redefining $B$ as the frequency resolution of a map to be made, the noise of the map due to on-source integration is estimated to be

$$\Delta T_A^*(\text{ON}) = \frac{T_{\text{sys}}}{\sqrt{B_{\text{cell}}}}$$

the standard radiometer equation. On the other hand, the number of OFF points used to make a map grid point is roughly written as $d/\Delta l$ (here, the extent of the GCF is neglected). Thus, the effective OFF integration time for a grid cell is

$$t_{\text{OFF}} \sim \frac{d}{\Delta l_{\text{OFF}}}$$

and the noise due to OFF points becomes

$$\Delta T_A^*(\text{OFF}) = \frac{T_{\text{sys}}}{\sqrt{B_{\text{cell}}}}$$

Therefore, the total noise level of the map is written as

$$\Delta T_A^*(\text{map}) = \sqrt{\Delta T_A^*(\text{ON})^2 + \Delta T_A^*(\text{OFF})^2}$$

and is minimized when $t_{\text{OFF}}$ is optimal:

$$\frac{\partial}{\partial t_{\text{OFF}}} \Delta T_A^*(\text{map}) = 0$$

leads to

$$t_{\text{OFF}} \sim \frac{\sqrt{t_{\text{scan}} + t_{\text{OH}} + t_{\text{OFF}}/N_{\text{SEQ}}^2}}{f_{\text{cal}}}$$

This formula is a generalization of the well-known relation $t_{\text{OFF}} = \sqrt{N_{\text{ON}}}$ for PSW observations, where $N$ is the number of ONs taken per one OFF. Toward $t_{\text{OH}} \to 0$, equation (17) resolves itself into the $\sqrt{N}$-relation.

The dependence of $\Delta T_A^*(\text{map})$ on $t_{\text{OFF}}$ is plotted in figure 3. For cases of $t_{\text{scan}} = 20, 40$, and 60 s (other parameters are shown in the caption), $\Delta T_A^*(\text{map})$ is minimized at $t_{\text{OFF}}^\text{optimal} = 7, 12$, and 17 s, respectively. If $t_{\text{OFF}}$ is shorter than the optimal value, $\Delta T_A^*(\text{OFF})$ dominates the map. On the other hand, a $t_{\text{OFF}}$ longer than $t_{\text{OFF}}^\text{optimal}$ is excessive, since the noise level of the map is limited by $\Delta T_A^*(\text{ON})$.

Using the above notations, it is quantitatively shown how the observing efficiency improves, by adopting appropriate parameters, compared with PSW observations. The following two factors contribute: (1) The ratio of the on-source time to the total time spent, $\eta_{\text{ON/OBS}}$, becomes larger because not only the dead time (antenna slew, etc.) is reduced, but also the OFF integration time is relatively shorter ($t_{\text{OFF}} \ll t_{\text{scan}}$); and (2) In general $t_{\text{ON}} \ll t_{\text{OFF}}$, and thus $\Delta T_A^*(\text{OFF})$ nearly equals $\Delta T_A^*(\text{ON})$ [instead of $\Delta T_A^*(\text{map}) = \sqrt{2\Delta T_A^*(\text{ON})}$], which is applicable to a PSW observation with $t_{\text{ON}} = t_{\text{OFF}}$. As $t_{\text{OH}} \to 0$ and $t_{\text{scan}} \to \infty$, both factors, respectively, correspond to a reduction of the observing time by a factor of 2. Thus, OTF is, theoretically, up to 4-times more efficient than PSW. In practice, the improvement of the efficiency amounts to a factor of $\sim 2$. 
The array is inclined with respect to the scan plane array.

4.4. Application to an Array Receiver

The above discussion is made for a single-beam receiver. In the case of an array (multi-beam) receiver, some expressions change. Here, we consider the case of BEARS, a 5 × 5 focal plane array.

Figure 4 schematically shows OTF scans with BEARS considered here. The array is inclined with respect to the scan direction by an angle \( \theta \); a neighboring couple of beams makes a pair of scans separated by a distance \( \Delta l = L \sin \theta \) (\( L = 41'1 \) is the beam separation). The next scan runs 5\( \Delta l \) away, and thus the number of scan rows is written as \( N_{\text{row}} = \frac{l_2}{(5\Delta l)} + 1 \). In this case scans made by 5 beams in each row of the array fill the mapped region at a separation of \( \Delta l \). Since the 5 rows of the array respectively cover the map,

\[
t_{\text{ON}} \text{cell} = \frac{5\eta_{\text{scan}} d^2}{l_1 \Delta l} \tag{18}
\]

and

\[
t_{\text{OFF}} \text{cell} = \frac{5d}{\Delta l} t_{\text{OFF}} \tag{19}
\]

The noise level of the map is obtained by substituting \( t_{\text{ON}} \text{cell} \) and \( t_{\text{OFF}} \text{cell} \) in equation (13) with equations (18) and (19). Following the transformation in the previous subsection, we have

\[
t_{\text{OFF}} \text{optimal} = \sqrt{(t_{\text{scan}} + t_{\text{OH}}) \frac{\eta d t_{\text{scan}}}{l_1} \sqrt{N_{\text{SEQ}}}} \tag{20}
\]

the same expression as equation (17).

The strategy mentioned above focuses on the mapping speed; compared to the case of a single-beam receiver, the mapped region can be covered 5-times faster and the integration becomes 5-times deeper. There may be another strategy that mainly considers the uniformity of the map. Using the same parameters as in the case of a single-beam receiver (each beam runs at a separation of \( \Delta l \)), the integration simply becomes 25-times deeper in the same observing time. The point is that every scan path is approximately traced by all 25 beams; the characteristics of the beams are expected to be averaged out. However whether this advantage is realized or not depends on the condition, since the system variation may spoil the uniformity if the observing time becomes too long.

5. Data Processing

5.1. Data Reduction

The reduction process of OTF data is done with NOSTAR (Nobeiyama OTF Software Tools for Analysis and Reduction), developed at NRO. It is designed to run on UNIX, or UNIX-like operating systems. Its core functions (baseline subtraction, creating cube FITS from spectra, etc.) are provided as command-line tools written in C/FORTRAN in order to enable batch processing. These command-line tools are wrapped in a graphical user interface (GUI) written in the Interactive Data Language (IDL).

An observation run produces a Raw Data file (see section 3). Spectra from all of the used spectrometers are contained within it. The first step of the data-reduction process is to extract the data to the user’s working directory. A task, named Split, does not simply copy the Raw Data file, but divides it into Split Raw Data files according to the spectrometers. Namely, a Raw Data file taken with BEARS is split into 25 Split Raw Data files. Accordingly, the following process can be separately applied for each Split Raw Data.

Subsequent procedures of data reduction (baseline subtraction, bad data flagging, etc.) are basically the same as those for PSW data, except for the large size of the data. The GUI is designed to be batch-oriented, to help users to conduct the reduction process rapidly without being bothered with a large quantity of data. Each process overwrites the Split Raw Data, itself, in order to avoid running out of space in the working directory.

Finally, a map (cube FITS) is made from the processed spectra. An OTF observation (or a series of observations) produces a set of data points that fills the mapped region with spacings smaller than the Nyquist sampling rate, as described in section 4. The data are convolved into the map using a GCF. The desired characteristics of GCFs and appropriate function forms are discussed below. The obtained map may suffer from the so-called scanning noise along the scan direction, in
addition to statistical noise. The scanning noise can be effectively removed by combining two maps made from orthogonal scans using the so-called basket-weave method. We have implemented the **PLAIT** algorithm described by Emerson and Grave (1988).

5.2. **Gridding Convolution Functions**

GCFs used to make maps are desired to have the following characteristics:

First: the form of a GCF is similar to that of the telescope beam, itself. Convolution with such a GCF corresponds to, in the Fourier domain, that a weighting function (Fourier-transformed beam pattern) is multiplied twice to the intrinsic spatial frequency distribution. Consequently, the best signal-to-noise ratio is achieved. Although we cannot know the beam pattern with infinite accuracy in practice, one should choose a GCF so that it mimics the telescope beam.

Second: the GCF’s energy concentration ratio is high. In practical convolution operation, the extent of the GCF is finite. Thus, in the Fourier domain, the GCF has artificial frequency lobes that are folded onto the primary component, resulting in so-called aliasing noise. In order to preserve the observed spatial frequency information, the aliasing effect must be as small as possible. As an index, the energy concentration ratio,

\[
\mathcal{R} = \frac{\int_0^1 |C(\eta)|^2 d\eta}{\int_0^\infty |C(\eta)|^2 d\eta},
\]

is introduced (Briggs et al. 1999), where the GCF is \(c(l, l = x/\Delta x, \Delta x is the grid spacing, \(C(\eta)\) is the Fourier transform of \(c(l)\), and \(A\) is the area in which \(\eta < 1\). Here, \(\mathcal{R}\) represents the degree of concentration of the GCF within \(A\); it is expected that the aliasing effect becomes small as \(\mathcal{R}\) becomes larger.

The following GCFs (their shapes are shown in figure 5) have been implemented so far:

**Bessel × Gauss:** a Gaussian-tapered Jinc function,

\[
c(r) = \begin{cases} 
\frac{J_1(\pi r/a)}{\pi r/a} \exp\left[-\left(\frac{r}{a}\right)^2\right] & (r \leq R_{\text{max}}) \\
0 & (\text{otherwise})
\end{cases}
\]

where \(J_1\) is a 1st-order Bessel function; \(r\) is the distance between the data point and the grid point (the unit is the grid spacing). The parameters \(a, b,\) and \(R_{\text{max}}\) can be arbitrary chosen, and are set as \(a = 1.55, b = 2.52, R_{\text{max}} = 3\) by default (see below).

**Sinc × Gauss:** a Gaussian-tapered Sinc function,

\[
c(r) = \begin{cases} 
\sin(\pi r/a) / (\pi r/a) \exp\left[-\left(\frac{r}{a}\right)^2\right] & (r \leq R_{\text{max}}) \\
0 & (\text{otherwise})
\end{cases}
\]

The default values for parameters \(a, b,\) and \(R_{\text{max}}\) are the same as those for the Bessel × Gauss function.

**Gauss:** a pure Gaussian,

\[
c(r) = \begin{cases} 
\exp\left[-\left(\frac{r}{a}\right)^2\right] & (r \leq R_{\text{max}}) \\
0 & (\text{otherwise})
\end{cases}
\]

The default parameters are \(a = 1, R_{\text{max}} = 3\).
is too much oversampled, since the spatial resolution is limited by the telescope beam. On the other hand, if \( d \) is too large, the effective beam broadens to \( \simeq 2d \).

6. Verification

6.1. Performance of the Antennas

In section 2, we introduced two parameters, \( t_{\text{app}} \) and \( t_{\text{tran}} \), which are the duration of an “approach-run” and a “transit-run”, respectively. They depend on the driving speed and performance of the antenna. In this subsection we describe measurements used to determine \( t_{\text{app}} \) and \( t_{\text{tran}} \). The amount of pointing jitter (PROG–REAL) is also measured.

6.1.1. NRO 45-m

First, we performed scans along both Azimuth (Az) and Elevation (El) at various scan speeds, \( v_{\text{scan}} \), in order to determine \( t_{\text{app}} \). The driving speed of the antenna is \( v_{\text{scan}}/\cos(\text{El}) \) for Az scans, and \( v_{\text{scan}} \) for El scans. Figure 7 shows some examples. The PROG–REAL difference on the sky is plotted against the time elapsed after starting the approach-run for three cases: (a) El scan with \( v_{\text{scan}} = 40^\prime \text{s}^{-1} \) at El = 54°; (b) El scan with \( v_{\text{scan}} = 160^\prime \text{s}^{-1} \) at El = 54°; and (c) Az scan with \( v_{\text{scan}} = 240^\prime \text{s}^{-1} \) at El = 74° (the driving speed is 870°s\(^{-1}\) along Az). Case (a) represents the typical scan at 115 GHz, while case (c) corresponds to the maximum scan speed at 22 GHz. The antenna ran stably after an initial delay and (for large driving speed) an overshoot. The time spent until the stable run begins was adopted to be \( t_{\text{app}} \). The determined \( t_{\text{app}} \) for the three cases, respectively, 5, 7, and 11 s.

Secondly, \( t_{\text{tran}} \) was determined in a similar way as \( t_{\text{app}} \): back-and-forth scans along Az and El were made using appropriate \( t_{\text{app}} \). Various \( t_{\text{tran}} \) were tried. The optimal \( t_{\text{tran}} \) is defined as the shortest one for which the antenna starts to move stably after the next approach-run. Figure 8 shows the derived \( t_{\text{app}} \) and \( t_{\text{tran}} \). Both of them monotonically increase with the driving speed. A slight jump of \( t_{\text{app}} \) was found at a driving speed of \( \simeq 200^\prime \text{s}^{-1} \). It is due to a “slow-start slow-stop” control of the telescope, which is implemented so as not to give any sudden and large acceleration to the antenna.

It is found that the PROG–REAL value does not converge to 0 when the driving speed is large (see figure 7). Instead, the PROG–REAL offset becomes almost constant, which amounts to \([\text{PROG–REAL}] \simeq 0.016s \times v_{\text{scan}}\). The offset does not affect the observations, since it is about 1/6 of the sampling separation along the scan for a \( t_{\text{dump}} \) of 0.1 s. Excepting the offset, the jitter of the antenna pointing is within a few arcseconds. The error of the sampling separation is determined by the differential of the jitter between the neighboring sample, which is almost within 1″–2″.

6.1.2. ASTE 10-m

For the ASTE 10-m telescope, \( t_{\text{app}} \), \( t_{\text{tran}} \), and the pointing jitter were measured in a similar way as for the 45-m. The \( t_{\text{app}} \) measurements for cases (a) El scan with \( v_{\text{scan}} = 50^\prime \text{s}^{-1} \) at El = 30° and (b) Az scan with \( v_{\text{scan}} = 100^\prime \text{s}^{-1} \) at El = 70° (the driving speed is 290°s\(^{-1}\) along Az) are shown in figure 9. Case (b) corresponds to the maximum scan speed at 350 GHz. The PROG–REAL values converge into \( \simeq 0 \) in a few seconds,
with jitters of $\lesssim \pm 1^\circ$. From this result, we adopted 4 s as $t_{\text{app}}$. The $t_{\text{ran}}$ value is also measured; for practical observing parameters, 2 s is sufficient. If receivers for higher frequency are installed in the future, the antenna performance should be measured again.

6.2. Comparison with PSW Map

In order to confirm the validity and efficiency of OTF observations, the same field has been observed with both OTF and PSW, and the resultant maps are compared with each other. Here, we describe ASTE CO $J = 3–2$ (345.8 GHz) test observations toward a field centered at $(l, b) = (37^\circ 45^\prime, -0^\circ 12^\prime)$.

The observations were made in 2005 August and September, as a part of a CO $J = 3–2$ Galactic plane survey (T. Sawada et al., 2008, in preparation). The frontend was a cooled SIS mixer receiver, SC345. The system noise temperature was typically 200–300 K in a double sideband (DSB) during the observations. The HPBW of the telescope at 350 GHz was measured to be 22$^\prime$. The main beam efficiency was $\approx 0.6$. The backend was a 1024-channel MAC, which covered an instantaneous bandwidth of 512 MHz (440 km s$^{-1}$) with a spectral resolution of 1.0 MHz (0.87 km s$^{-1}$). The pointing of the telescope was calibrated by tracking a compact CO source, W Aql, in every 1 or 2 hr, and was within an accuracy of 5$''$. We performed an intensity calibration by observing a standard source, M17 SW, every 2 hr. The reproducibility of $T_A^*$ was 5\% (1$\sigma$). By comparing the observed spectra with those measured with the Caltech Submillimeter Observatory (CSO) 10.4-m telescope with a single-sideband (SSB) filter (Wang et al. 1994), we obtained scaling factors to convert ASTE $T_A^*$ (DSB) into CSO $T_A^*$ (SSB). Hereafter, $T_A^*$ is shown in the SSB scale.

The OTF observations were carried out with parameters $\nu_{\text{scan}} = 50^\circ$ s$^{-1}$ and $\Delta l = 8^\circ$. Two longitudinal scans and two latitudinal scans (in the Galactic coordinates) were made. We made a map, whose grid spacing was $8^\circ \times 8^\circ \times 1$ km s$^{-1}$, using the Bessel $\times$ Gauss convolution; the map was then resampled onto a $10^\circ \times 10^\circ$ grid to match the PSW data. A small portion of the region was observed with PSW: $9 \times 9$ points separated by $10^\circ$. For each point, 10-s integration was made twice. We convolved the PSW data to make a map having the same resolution ($25^\circ$) and grid spacing as the OTF map. Since the convolution was highly incomplete at the outermost grid points, we used the inner $7 \times 7$ pixels for a comparison.

The 1$\sigma$ noise levels were 0.25 K (OTF) and 0.12 K (PSW). The obtained OTF noise level agreed with that derived using the equations in section 4, 0.26 K. It was thus proven that the system achieved the expected observing efficiency. Velocity channel maps of OTF and PSW are shown in figure 10. The OTF map is consistent with the PSW one. Figure 11 shows a pixel-to-pixel correlation plot between them. A least-squares fit gives the correlation $T_A^*$(OTF) = (1.045 $\pm$ 0.004) $T_A^*$ (PSW).

It is confirmed that the OTF map agrees with the PSW map within the accuracy of a relative intensity calibration, 5\% (reproducibility of the intensity of the standard source).
6.3. **FSW Observations**

We have implemented the FSW observing mode in OTF, as described in subsubsection 3.4.2. As a test of FSW-OTF observations, IRAS 04369 + 2539 (IC 2087) in the Taurus molecular cloud was observed. High-velocity wing (outflow) emission was found around the source in the $^{12}$CO $J = 1$–0 line (Heyer et al. 1987). Mapping wing emission in a widespread molecular cloud is a presumable science case for FSW observations. A stable spectral baseline is required.

Observations were carried out with the 45-m telescope and BEARS. The HPBW was $15^\circ$, and the system noise temperature was typically 350 K (DSB). The MAC was used in the high-resolution mode, i.e., having 32 MHz (83 km s$^{-1}$) instantaneous bandwidth and 63 kHz (0.16 km s$^{-1}$) resolution. The OFFs were taken at the starting point of approach-runs in order to reduce dead time to slew the antenna. The frequency throw of the LO, $\Delta v_{\text{LO}}$, was set to 12 MHz (corresponding to 31 km s$^{-1}$). The $T_A^*$ (DSB) was converted into $T_A^*$ (SSB) by comparing the spectra of a standard source measured with BEARS and an SSB receiver, S100. Linear baselines were subtracted, and a 7 $^\circ$5-grid map was made using the Bessel $\times$ Gauss convolution.

Figure 12 shows a set of velocity channel maps. Redshifted wing emission toward the north–south direction was successfully detected beyond the ambient cloud velocity, $v_{\text{LSR}}$ $\approx$ 6 km s$^{-1}$. Figure 13 shows line profiles at two positions, $(\Delta \alpha, \Delta \delta) = (-4', +6')$ (top) and $(-4', -1')$ (bottom, -2K offset). The positions are relative to $(\alpha, \delta)_{1950} = (4^h 36^m 54^s 6, 25^\circ 39' 17'').$

![Fig. 12. Velocity channel maps of IC 2087 $^{12}$CO $J = 1$–0 emission at an interval of 1 km s$^{-1}$. The contour levels are $T_A^* = 0.5, 1.0, 1.5, ...$ 5 K.](image)

**Fig. 13.** CO $J = 1$–0 line profiles at two positions: $(\Delta \alpha, \Delta \delta) = (-4', +6')$ (top) and $(-4', -1')$ (bottom, -2K offset). The positions are relative to $(\alpha, \delta)_{1950} = (4^h 36^m 54^s 6, 25^\circ 39' 17'')$. In general, OTF is particularly effective when a widely distributed and intense line is mapped, since a beam runs across a map grid within very short duration, typically (a few–10) $\times$ 0.1 s, without any overhead to point discrete positions. However, application to relatively small-field ($\sim$ several 10 mK, several 100 km s$^{-1}$) sources (e.g., external galaxies) has been successful. For example, Hirota (2008) observed a galaxy, IC 342, using the NRO 45-m and BEARS, and achieved 8 mK rms in $T_A^*$ at a velocity resolution of 5 km s$^{-1}$.

7. **Summary**

We have made spectral line OTF observations available at the NRO 45-m and ASTE 10-m telescopes. Digital autocorrelation spectrometers can be operated in the OTF mode (the data-sampling interval is as fast as 0.1 s) with heterodyne receivers mounted on the telescopes, including the 25-beam array receiver, BEARS. Improvements of the software and instruments to enable fast and synchronized controls...
(e.g., antenna driving, data acquisition, Doppler tracking, frequency switching) were described. The sensitivity of the obtained map was expressed using the observing parameters, and we showed how to determine and optimize them. The performance of the antennas was measured, and was proven to be sufficiently high for up to 115 GHz (45-m) or 350 GHz (10-m) observations. The OTF system has improved the observing efficiency by a factor of \( \approx 2 \), compared with PSW; its mapping capability opens a prospect in various fields of study.

Note added in proof (2008 May 28): A new spectrometer, “Wideband and High dispersion Spectrometer system with FFX correlator (WHSF)” (Iguchi & Okuda 2008) installed on ASTE can also be operated in the OTF mode.

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