# INCREASING THE YIELD OF OUR TELESCOPES

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## 1. Introduction

Obviously, we all wish to make the best possible use of our telescopes. Mostly, this means striving for the best possible efficiency of observing, and observing simultaneously over as wide a range of parameter space as possible. Some observing techniques are more efficient than others, but there also some pitfalls to avoid in attempts to improve observing efficiency. The emphasis here is on mm-wave observing, but many of the principles are equally applicable to other parts of the radio spectrum. The "Yield" in the title means "useful scientific output," which is much more difficult to quantify than simply bytes of data with a given signal-to-noise ratio.

For the purposes of this presentation, I distinguish between two different observing philosophies:

(1) Observations that use special-purpose instrumentation, or even a special-purpose telescope, and which are truly breaking new ground. If successful, such experiments may have enormous scientific yield, although the telescope efficiency in terms of acquiring bytes of data might be very poor.

(2) "Bread and Butter" observations. These may use an established telescope and instrumentation, and might include large scale surveys, or deep integrations. There is a well-defined goal, for which a considerable quantity of data may be required. The same telescope and instrumentation are used to support many different projects by many independent observers. Efficiency in data acquisition becomes very important; in some sense scientific yield may be proportional to the quantity of reliable data obtained, with some type of non-linear normalization for signal-to-noise ratio.

There are serious dangers in attempting to optimize the efficiency of a telescope. As yet undiscovered and unexpected phenomena might be filtered out and hidden from the observer – pulsars might have escaped detection for many years if today's software interference rejection algorithms had been available in the 1960s. In the name of efficiency, versatility may be lost; an instrument can be finely tuned for efficiency much more easily if it is only ever required to support a single, specialized observing mode. A loss of versatility may discourage observers from trying new, innovative techniques; this risks reducing the potential scientific output of a telescope much more than the possible increase in mean data rate resulting from improved efficiency.

Considerations of efficiency of data acquisition may have little place in mode (1) above. However, it is usually worth investing considerable effort optimizing the efficiency of observations in category (2), provided that the potential pitfalls are recognized.

## 2. Increasing Observing Efficiency

One philosophy is to instrument the telescope so as to observe over the biggest range of parameter space possible, with the highest possible sensitivity. There are potential pitfalls; some instrumentation upgrades help selected types of science, possibly even hindering other scientific studies. An example might be a multiple-beam system; it is often necessary, although still undesirable, to arrive at a compromise in sensitivity of individual elements of a multiple-beam system. It may simply not be feasible to lavish the care and attention on 10 or 100 individual feeds and receivers that could have been devoted to a single receiver system. Such a system may be extraordinarily efficient at mapping large areas, but may be significantly worse at point-source studies – such as searches for new lines in discrete objects – than the original single-beam system. Compromises like this often have to be taken. Some of the factors to be considered are:

1. Improve system noise. All other things being equal, the rate of acquiring data is proportional to $T_{\rm sys}^{-2}$ where $T_{\rm sys}$ is the system noise. This parameter affects **ALL** observing modes equally. Attempts to expand parameter space should not compromise $T_{\rm sys}$. Note that, with modern receivers, the **receiver** noise may only contribute a relatively minor part of $T_{\rm sys}$.

2. The receivers should respond to both orthogonal polarizations. This gives a factor of 2 in observing speed for all observations, discrete source or extended mapping, which are sensitivity limited. A side effect is that polarization studies may become more feasible, but the main incentive for a dual polarization **system** is to improve the sensitivity. This is equivalent to reducing the system noise $T_{\rm sys}$ by $\sqrt{2}$, which may be a much more dramatic improvement than "merely" reducing the **receiver** noise by the same factor.

3. Frequency space: multiple frequency bands. Increasing the instantaneous bandwidth of course helps continuum observations, but the ability

to observe several different spectral lines simultaneously may increase the scientific value of observations. The simultaneous observation may significantly improve the relative calibration of the lines. However, there may not **always** be multiple lines either accessible or of interest in a given source, and even if there are, they are unlikely to be matched in their requirements for signal-to-noise and hence integration time. On average, expanding this parameter space by a factor of $N$ will increase the useful telescope output by a factor significantly lower than $N$.

4. Spatial diversity: multi-beam systems. For $M$ feeds and receiver systems, the gain in mapping speed approaches a factor $M$. Note that, given a choice between $M$ dual-polarization systems and $2 \times M$ single-polarization feeds, receivers and backends, the dual-polarization system will almost always be more productive. It is important that $T_{\rm sys}$ of individual feeds not be compromised; a degradation of as much as 30% in $(T_{\rm sys}^{-1})$ will require a doubling of the number of feeds, receivers and backends just to break even on mapping observations. Observations of discrete sources would then take twice as long as they did before the upgrade. Nevertheless, the results of a good multiple-beam system can be outstanding; several spectacular examples of data taken with the FCRAO 15-beam QUARRY system (Erickson 1995) have been presented during this symposium.

## 3. Observing Techniques

The choice of observing strategy is usually a compromise between minimizing any systematic artifacts in a spectrum and minimizing the random noise. From the radiometer equation the uncertainty $dT$ on an observation, using bandwidth $B$ with integration time $t$ is given by $KT_{\rm sys}/\sqrt{Bt}$, where $K$ is a constant depending on the observing technique.

**Position Switching**. Position switching is perhaps the most common spectral-line observing technique at mm-wavelengths. For the usual case where the telescope is pointed away from the source to blank sky for half of the available time, $K = 2$. Taking account of overhead, in practice $K > 2$. One can do somewhat better by sharing one off-source measurement for several on-source observations. The optimum use of time, neglecting telescope overhead, is when, for $M$ on-source measurements per off-source integration, the telescope spends $\sqrt{M}$ as long integrating on each reference position. The effective value of $K$ then becomes $K = 1 + 1/\sqrt{M}$. As $M$ becomes very large, $K$ tends to 1, the best possible case. At mm-waves, with typical receiver and atmospheric instabilities, a given off-source measurement may only remain valid for about one minute; beyond that, baselines in the calibrated (on-off) spectrum begin to deteriorate. In practice this severely limits the number of on-source to off-source measurements.

**Frequency Switching**. Frequency switching is a very efficient observing mode, where it can be used. The spectrum being studied remains within the bandwidth of the telescope's spectrometer in both phases of the switching cycle, but is switched by an offset of a few MHz and differenced. Provided that the resulting 2 replicas of the spectrum, one now negative and one positive, are sufficiently separated, then one half of the spectrum may be inverted, shifted, and averaged with the other half. $K$ becomes $\sqrt{2}$, an improvement in observing speed of a factor of at least 2, compared with position switching. The disadvantages are (1) the requirement that the total extent of the line be narrower than the frequency switching offset and (2) notoriously bad baselines. The low level standing waves between different parts of the structure, which are always present in radio telescopes and which give rise typically to sinusoidal modulation of the spectral baseline, are not in general cancelled. These disadvantages can be overcome: some algorithm such as that used for restoration of dual-beam observations of extended sources (e.g., Emerson et al. 1979) could be applied in the spectral domain. Modifications to the antenna optics, such as modulation of the path lengths responsible for creating standing wave patterns (e.g., Payne & Ulich 1978) can substantially improve the spectral baselines.

**On-the-fly Observing**. This is a rapid-scanning technique for mapping extended features, either in continuum or in spectral line. It provides a remarkably efficient alternative to the more conventional point-and-step mapping mode and is applicable either to single-beam or to multi-beam systems. The telescope beam scans rapidly and continuously back and forth across the source, recording data all the time. Some of the advantages are:

(1) Telescope overhead is nearly eliminated. Because the true coordinates, rather than demanded coordinates, are recorded, it is possible to continue recording useful data even when the telescope is accelerating or decelerating at the start and finish of individual rows of a map. Telescope tracking tolerances are relaxed, permitting very fast telescope scanning.

(2) Since one coverage of a field can be completed very quickly, the data are much more consistent; in general, there is not time for weather to change dramatically or for receivers to drift significantly during one coverage. Sensitivity is achieved by averaging multiple coverages. Because each coverage is completed relatively quickly, the pointing within a single map coverage is likely to be much more consistent; if necessary, relative pointing between successive coverages can be corrected. Sometimes, a small part of one map coverage may have some defect—e.g., one bad mapping row, caused by a change in atmospheric conditions. When $N$ independent coverages are averaged, the small number of systematic errors is reduced by $(1/N)$ rather than by the $(1/\sqrt{N})$ that applies to Gaussian noise.

(3) If $M$ on-source measurements can share the same off-source refer-

ence observation, then there is a potential gain in sensitivity, for a given usage of telescope time, of $1 + (1/\sqrt{M})$. With the on-the-fly rapid scanning observing mode, there may easily be hundreds of independent on-source measurements per off-source integration – i.e., $M > 100$. The factor $K$ in the radiometer equation, $1 + (1/\sqrt{M})$, tends to $K = 1$. There is an improvement in sensitivity of nearly a factor of 2 compared with conventional position-switched observations, or a factor of nearly 4 in mapping speed.

(4) Although with a multi-beam system some slight compromise is sometimes necessary in the performance of individual receivers, the OTF technique does not require such a compromise; there is no adverse impact on point source observations.

Compared to conventional point-by-point mapping, the gain in observing efficiency can be considerable. The multiple on-per-off aspect (3) gains a speed factor approaching 4. The reduced overhead (1) is a factor of perhaps 1.3. Increased quality and better consistency of data, and greater immunity to systematic drifts, are difficult to quantity, but are certainly significant. Compared with conventional position-switched mapping, an effective overall gain approaching an order of magnitude in observing speed is feasible.

OTF observing has been a standard technique for many years for continuum mapping (e.g., Haslam 1974). However, it is only relatively recently that effective on-the-fly data acquisition with thousand-channel spectrometers has become feasible.

## 4. Example OTF Observations

Probably the most critical aspect of OTF observing is obtaining correct registration of data samples with the instantaneous telescope coordinates. Observations across the limb of the moon provide a very stringent test for potential problems. Figure 1a shows contours, plotted at intervals of 10% of the peak brightness, of part of the eastern limb of the moon. For these data, there was an unwanted 50 ms offset in timing between data acquisition and telescope encoder readout. Since alternate scans are made with respectively increasing and decreasing azimuth, a constant timing offset between data and encoder sampling corresponds to a position error which changes sign in adjacent scans. The scanning speed was 1 degree/minute, so 50 ms corresponds to an error of $\pm 3''$, which is readily seen on the moon edge, even with the $65''$ beam. The ripples in the edge contours of Figure 1a reflect the coordinate offsets between odd and even-numbered rows of the map. Figure 1b shows the same data corrected for this 50 ms timing offset. The relative registration of the gridded data is now within $\sim 1''$.

Figure 2 shows a complete continuum map of the moon at 90 GHz, made with the 12 m telescope in total power mode, using a scanning speed


*Figure 1.* The Moon limb, *a (left)* with and *b (right)* without data timing errors.

of 1 degree per minute. The telescope beam is 65″. The fully sampled 45′ by 45′ field, took only one hour to observe. No baseline corrections of any kind have been applied. The observations started at 10:37 UTC on 1 April 1994, and are shown in an az-el coordinate system, centered on the moon. This shows how relatively large areas of sky can be mapped successfully quite quickly, and are immune from the effects of tracking errors.

Figure 3 shows the data from Figure 2, but processed to enhance the contrast; a model of the large-scale moon emission has been subtracted from the data, which have then been edge enhanced. The many crater-like features visible are all real, and remained visible on successive moon maps taken one and two hours later. The line of the terminator can also be discerned, as a vertical change in contrast just to the right of the field center. The small features visible in this image differ from their surroundings by a peak temperature difference of typically $\sim 2$ K.

Figure 4 shows some individual spectral line maps of an interesting molecular cloud CME-1 (Emerson et al. 1996) in the Pleiades, observed at 230 GHz with the 12 m telescope. This area of 30′ by 30′ was observed in OTF mode during a few hours of mediocre weather conditions. After gridding, there are more than 50,000 fully sampled independent spectra in this data set. This demonstrates how substantial quantities of high quality and scientifically useful data can be obtained quite rapidly.

## 5. Conclusions

Expanding the range of parameter space sampled by a given radio telescope can increase dramatically the available useful scientific data. However, it is most important not to compromise the $T_{\rm sys}$ of the overall system in any attempt to increase telescope throughput. It may also be important that flexibility in observing, or in configuring the telescope, is not lost.

The correct choice of observing technique has an important impact on the scientific output of a telescope. The power of modern computer hardware, and the ability to handle large quantities of raw data at reasonable cost, permit techniques such as rapid scanning on-the-fly observing, to be


*Figure 2.* The Moon at 90 GHz, total power.


*Figure 3.* Moon image from Fig. 2, contrast enhanced.

exploited relatively easily even with thousand-channel spectrometers. This can lead to an almost unexpectedly high increase in useful scientific output from a telescope. The limiting factor today is often more in data analysis software capability than in the performance of the hardware.

The very first radio astronomical observations (Jansky, 1932) were made in a true on-the-fly mode. The 1932 observations were perhaps for the first time analysed in a way easily interpreted by astronomers some 46 years later (Sullivan, 1978). There is an important lesson to be learned here.

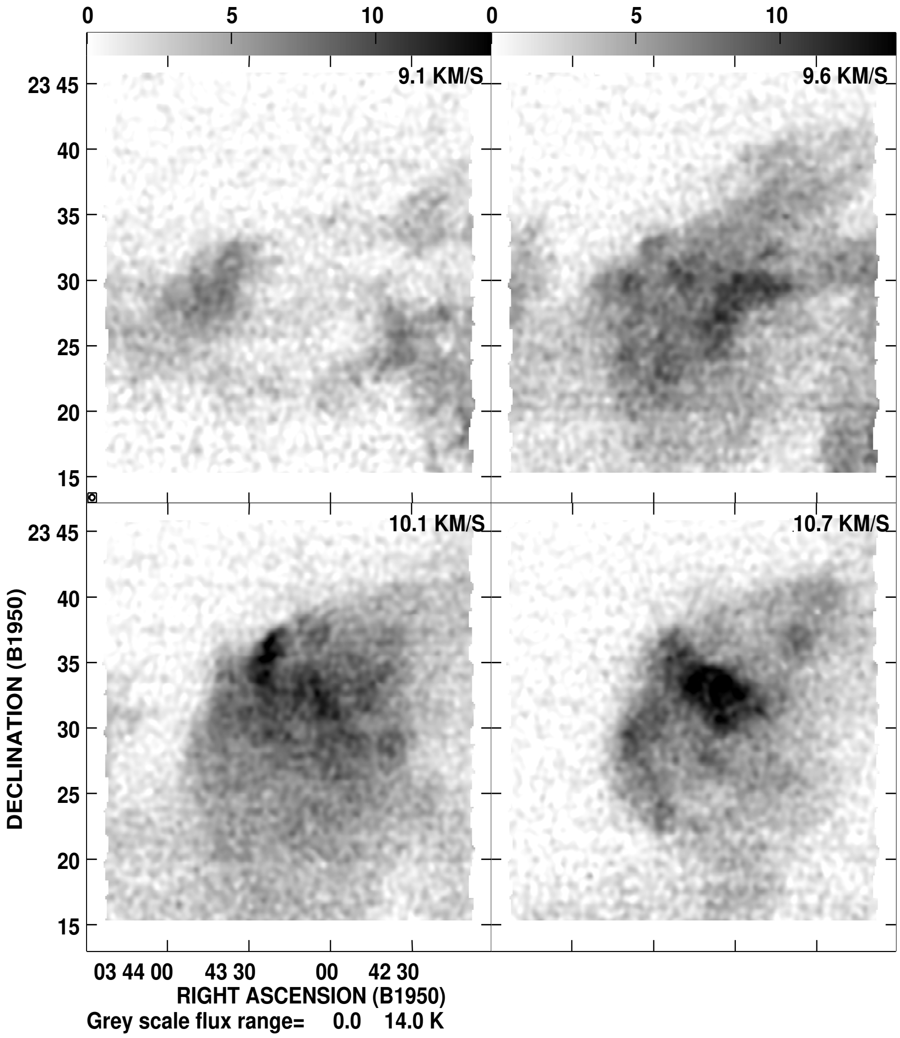


*Figure 4.* CME-1 CO J=2–1, 230 GHz, greyscale image of 4 channel maps.

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