Daisy Scan Mode for the GBT

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Abstract

We define and consider a scan pattern intended for use in commissioning the Penn Array.

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33.1 04dec03 Original Version (Brian Mason)

1 Introduction

Broadband continuum measurements, and measurements with single-dish telescopes, are often limited by systematics rather than thermal noise. This will be especially true during early 3mm observations with the GBT, as operation of such a large structure at high frequency represents an unprecedented technical feat and there will inevitably be much to learn about the instruments. Furthermore the GBT is not located at an optimal mm site. Potential systematics include: variable atmospheric emission and opacity; anomalous refraction; imperfections in the GBT pointing, focus and surface varying on uncertain timescales; ground spillover; and instrument gain fluctuations. These limit the sensitivity of both mapping observations. For the Penn Array a potential concern is an expected drift in the data zero-level; measurable variations could be present on timescales as short as 10 seconds and are different for each of the 64 detectors. Atmosphere variations are expected on a similar timescale.

A suitable observing strategy can significantly reduce the level of systematics enabling longer integrations, and can permit extensive cross-checks on data consistency provided the dataset is sufficiently redundant. Here we propose an observing mode which satisfies these criteria: a "daisy petal" 2D on-the-fly mapping mode. This mode

- provides a rich datastream to understand the instrument and distinguish systematics from sky signal
- provides reasonable sky coverage
- is easy to understand & relate to GBT constraints
- reduces sensitivity to telescope pointing errors.
- could be useful for beammapping and holography now.
- shouldn't be too hard to implement

An added advantage is that the modes we discuss here are closely related to an observing mode desired for continuum point source photometry. The photometry mode is documented in a separate memo.

The organization of this memo is as follows. § 2 summarizes the constraints all GBT scan patterns must obey; § 3 presents related 2-dimensional patterns (daisy scan and lissajous) and some examples; and § 4 concludes. Throughout we pay attention to practical considerations and attempt to identify limiting factors.

2 GBT Constraints

Any GBT scan pattern must comply with a number of constraints.

- **Drive Velocity** The software limits on the slew GBT rate are: $18'/sec\,(=18\,deg/min)$ in elevation and $36'/sec\,(=36\,deg/min)$. These are slightly downrated from the hardware limits. Note that these– and azimuth in particular– are *encoder* limits. The maximum "on-the-sky" speed in the azimuth direction is less by a factor of $cos(el)$.
- **Drive Acceleration** The software limit to the GBT acceleration is $4'.8/sec^2\,(=0.08\,deg/sec^2)$ in each axis. These are also encoder limits so the maximum on-the-sky acceleration in the azimuth direction is less by a factor of $cos(el)$.
- **Drive Servo Bandwidth** The error stream from the main drives is passed through a lowpass filter with a 3dB point at ~ 0.3 Hz. The secondary error loop is closed at a somewhat higher frequency but we do not consider motions of the secondary.
- **Resonant Frequencies of the Structure** The fundamental structural resonance is at 0.5 Hz. Motions with harmonic content near this frequency or its higher harmonics should be avoided.

- **Backend Sample Rate** Since the sky needs to be Nyquist sampled, there is a maximum slew rate imposed by the highest rate that GBT backends can sample. This rate is roughly

$$v_{max} = 40'/sec \times \left(\frac{115\,GHz}{\nu}\right) \times \left(\frac{1\,ms}{\tau_{integ}}\right) \tag{1}$$

  For most GBT data this is the key scan-pattern limitation. For 2D scans we assume an additional $\sqrt{2}$ oversampling, i.e., when this is the limitation we downrate the maximum velocity by $\sqrt{2}$. In addition some instruments have a finite time response: the Penn Array bolometers, for example, are expected to have exponential impulse responses with e-folding time constants of $1 < \tau < 20$ milliseconds. Unless τ values on the short end of this range are realized this will be the typical limiting factor for scan patterns with the Penn Array.

3 Daisy Patterns

Conceptually, with two orthogonal directions $\hat{x}$ and $\hat{y}$ on the sky defined, imagine moving the telescope as

$$\vec{p}(t) = r_o\,(\hat{x}\,cos\,\Omega t\, + \hat{y} sin\,\Omega t)\,sin\,\omega t \tag{2}$$

Here $\vec{p}(t)$ is the telescope pointing position as a function of time, and $\vec{p} = 0$ is the calibrator location, which is crossed every $t_{cyc} = \pi/\omega$ units of time. Think of this as a basis vector rotating with angular frequency Ω, and a "radial" oscillation with angular frequency ω along the direction of this rotating basis vector.

The intent would be to place a calibrator source in the middle of the map and obtain a check on the telescope pointing and anomalous refraction, instrument/telescope gain variations, and other variables every 10 to 20 seconds. For the Penn Array there are also additive $1/f$ drift terms from the SQUID multiplexer and this would help get a handle on these (which you wouldn't need a central calibrator for). It may also be possible to map extended sidelobes this way.

More realistically the map center should be *tracked* with coordinates in some specified mode as before, and Az/El offsets applied as:

$$\delta Az(t) = r_0\,\frac{cos(\Omega t + \phi_1)\,sin(\omega t + \phi_2)}{cos(El_{src})} \tag{3}$$

$$\delta El(t) = r_0\,sin(\Omega t + \phi_1)\,sin(\omega t + \phi_2) \tag{4}$$

This generates a roughly circular mapped patch on the sky. For generality we have added two specifiable phases. The circle isn't perfect since we have divided azimuth offset by the cosine of a fixed angle (the target location) rather than doing the full spherical trigonometry problem. This is an acceptable approximation except very close to the zenith. It would be possible for Daisy scans to apply the offsets in RA/Dec or some other celestial system, as:

$$\delta RA(t) = r_0\,\frac{cos(\Omega t + \phi_1)\,sin(\omega t + \phi_2)}{cos(dec_0)} \tag{5}$$

$$\delta Dec(t) = r_0\,sin(\Omega t + \phi_1)\,sin(\omega t + \phi_2) \tag{6}$$

Here dec_0 is the map center. Advantages can be imagined for both, although the resulting maps should look very similar. This scan pattern is illustrated in Figure 1.

A significant new capability which this mode provides is that of mapping an essentially *two-dimensional* area in a single scan, which reduces the level of systematics in the map by coupling distant pixels more strongly. The sensitivity in this map will not be uniform, since there are many crossings of the map-center; this is mitigated somewhat by the fact that the telescope is moving fastest at this point. I have simulated a Penn Array observation using IDL code; a 1σ sensitivity map is shown in Fig 2, and the distribution of pixel sensitivities in Fig 3.

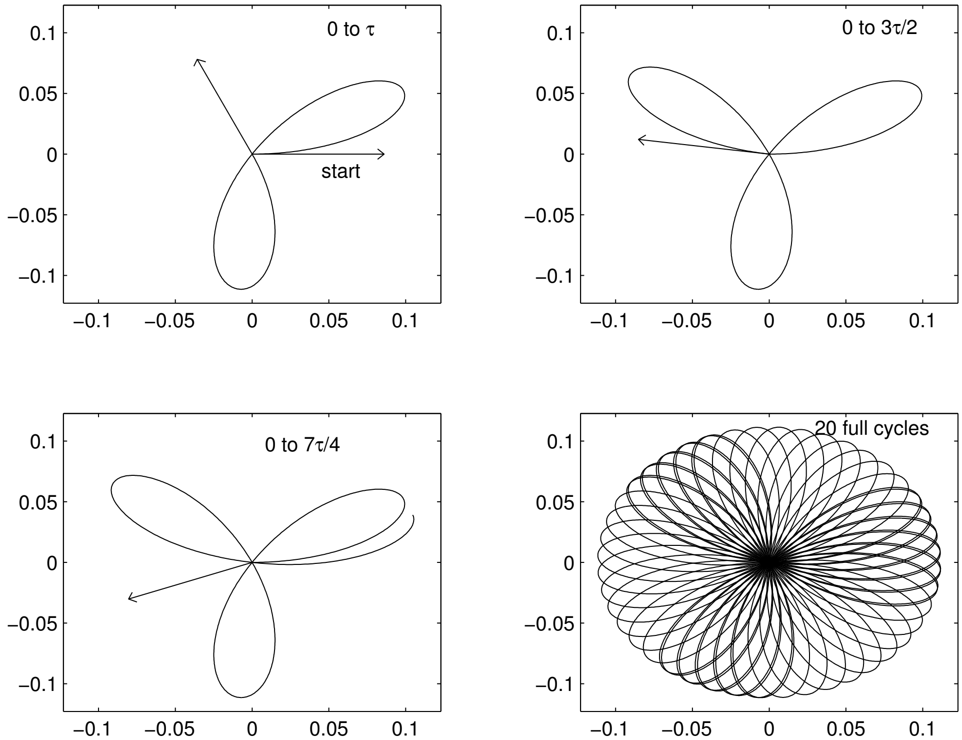

Figure 1: Illustrations of a daisy scan pattern. The location of the "basis vector" at the *end* of the cycle is shown for convenience in each panel; additionally, the location at the start ($t = 0$) is shown in the top left panel. All assume the ratio of the radial frequency to the basis vector precession frequency is π (arbitrary but convenient), and that the basis vector precesses clockwise. Top Left: a single cycle of the radial oscillation. Top Right: one and a half cycles, or one completion of the "daisy" pattern. Bottom Left: a quarter-cycle short of two full cycles. Note that the 3-petal pattern, for a frequency ratio less than about 4, precesses contrary to the precession of the basis vector. Bottom Right: 20 full cycles of the 3-petal pattern (elapsed time $t = 1.5 \times 20\tau$). Here τ is the period $2\pi/\omega$ of the radial component of the motion.

3.1 Properties of the Daisy Scan

The maximum velocities and accelerations are easy to calculate analytically. For the case $\omega > \Omega$ (radial oscillations faster than precession) we find

$$v_{max} = r_0\omega \tag{7}$$

$$a_{max} = r_0(\omega^2 + \Omega^2) \tag{8}$$

For any given choice of parameters r_0, ω, and Ω this can be checked against the GBT limits. Note that these are all *on the sky* numbers; for comparison to azimuth limits one must divide by $cos(el)$.

The harmonic content of this motion, perfectly executed, has no components higher than $\Omega + \omega$ (be careful with factors of 2π in comparing with structure numbers). I'm not certain if this can be directly compared with structural resonance frequencies.

For ω/Ω roughly in the 2 to 4 range it can be shown that the spacing between successive "petal tips" of the 3-petal pattern is

$$\frac{\tau\Omega}{4} - \left(\frac{7}{4}\tau\Omega - \pi\right) = \pi - \frac{3}{2}\tau\Omega \tag{9}$$

For our choice $\omega/\Omega = \pi$ this spacing, measured as an angle from the pattern center, is 0.14 radians or about 8 degrees.

With $\omega/\Omega = \pi$ the pattern covers a circle in 22 full radial cycles, or 7 minutes for τ of 20 sec.

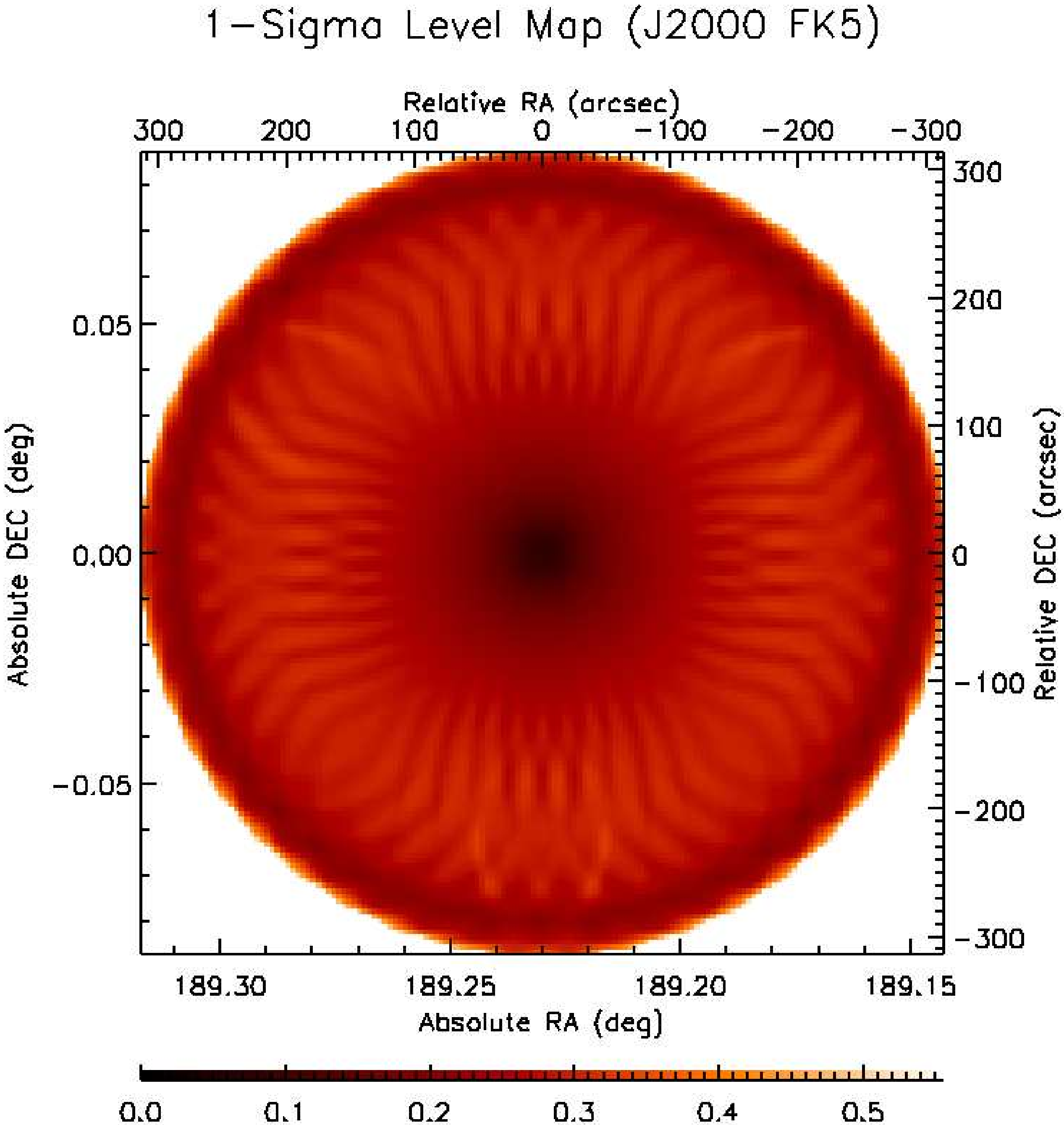

Figure 2: A 1σ noise map of a daisy scan comprising 22 full *radial* oscillations, which roughly closes. This case is identical to that described in § 3.2 except $r_0 = 6'$ not $6'.7$. Flux units are roughly equal to mJy per beam.

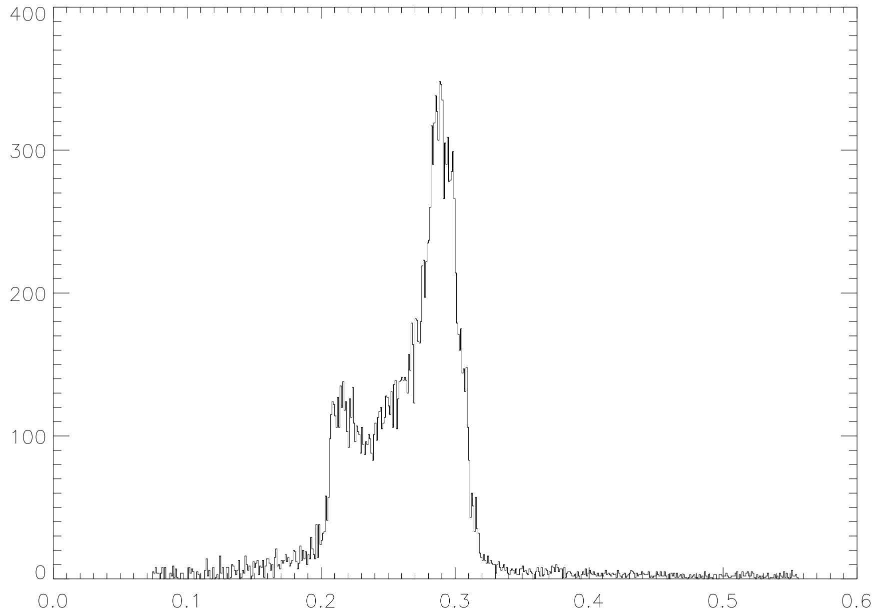

Figure 3: Histogram of pixels from Fig 2. 5% of pixels have noise levels less than 0.2; 91% have noise levels between 0.2 and 0.32; and 4% have noise levels greater than 0.32. Units of the x-axis are roughly mJy per beam.

3.2 Application: Penn Array Mapping

Suppose we are very paranoid and we want to check pointing and detector zero levels very $t_{cyc} = 5\, sec$. A set of parameters which achieves this, and is still consistent with GBT constraints is $\tau = 10\, sec$ for $\omega = 0.6$; $\Omega = \omega/\pi$ for a non-repeating pattern and reasonable 2D coverage per radial cycle; and $r_0 = 6'.7$, which yields a peak on-sky velocity of $2'.1/sec$. This is the speed limit for the slowest detectors we might get on the Penn Array. At zenith angles of less than $8°$ the encoder-based azimuth acceleration becomes the limiting factor (before antenna velocities) and a smaller circle would need to be mapped or a longer cycle time adopted. The highest frequency component of the motion is $0.13\, Hz$.

It's worth noting that the area mapped this way is more than 10 times the Hubble Deep Field area so it could be useful for astronomy, and not just commissioning. In a 50 hour integration there should be well over 100 starforming galaxies in this map. By relaxing the t_{cyc} constraint to 10 or 20 seconds, a significantly larger area could be mapped.

3.3 Application: Q-band Beam Mapping

Suppose one wanted to map the Q-band beam (FWHM$=$ $20''$ or so) or perform OOF holography at Q-band. Suppose further one used the DCR for this, with the resulting velocity limit of $0'.8/sec$. Assuming a cycle time of $t_{cyc} = 5\, sec$ (so again $\tau = 10\, sec$ and $\omega = 0.6$) and $\Omega = \omega/\pi$, we find that $r_o = 1'.3$ is the maximum allowed subject to the $0'.8/sec$ on-sky velocity limit. At this point the primary beam would be well over 100 dB down and this should suffice for a DC level determination. The peak acceleration is $0'.5/sec^2$, well away from the limits.

This approach would enable the datastream to be renormalized every 10 to 20 seconds (by a beam-center crossing) which would mitigate the effect of gain fluctuations if they are a concern.

My guess is that this pattern would provide pretty good sampling of the beam, but I haven't looked into this in detail. Some applications might require Nyquist sampling of the sky, in which case a series of scans with well-chosen values of the azimuthal phase ϕ_1 might be needed. It shouldn't be too hard to investigate this with simulations.

3.4 How to Choose Parameters

Here's how one might typically set the scan parameters (ω, Ω, r_o).

1. Choose t_{cyc} based on the effects that you're most worried about (eg detector offset drifts, gain fluctuations, anomalous refraction); typically much faster than $\sim 10\,sec$ will not be do-able, but this fast will be wanted if consistent with other constraints;
2. Set the radial period to $\tau = 2\,t_{cyc}$ (i.e. $\omega = \pi/t_{cyc}$);
3. Choose Ω equal to ω divided by some order unity irrational[1] number like e or π;
4. As your scan pattern in all likelihood is velocity limited (probably due to your backend sample rate or detector time constant) calculate this velocity limit (§ 2) and determine r_o using Eq. 7. If a smaller value of r_o is desired, use that.
5. Double-check that the acceleration limit is obeyed using Eq. 8. If not reduce r_o by a/a_{max} or increase τ by $\sqrt{a/a_{max}}$ to comply.

For cases that I have checked the acceleration only matters at elevations greater than $80°$, and the GBT *antenna* velocity limits don't come into play. This is how I chose parameters for the previous two subsections.

3.5 Lissajous Pattern

A Liassajous pattern, used to good effect by SHARC-II on the CSO, is a simple variation of the foregoing:

$$\delta Ra(t) = A\,\frac{cos(\Omega t)}{cos(Dec_0)} \tag{10}$$

$$\delta Dec(t) = B\,cos(\Omega' t + \phi) \tag{11}$$

Here Dec_0 is the map center. This would be a way to map a 2D area in a single scan *without* the frequent calibrator crossings that the daisy-scan is designed to provide. Here the Ra/Dec offsets will probably be strongly preferred since the point is to make a square map on the sky.

This pattern is amenable to the same simple analytic analysis which yielded the velocity, acceleration, and "harmonic content" expressions of § 3.1. However relating the Ra/Dec speeds to Az/El is more complicated and needs to take account of the field rotation; I've not done this in general. However a set of choices that would work is: $A = 6'$, $B = 2'$; a fast oscillation in the short (B or Dec) direction of $\tau = 10\,sec$ hence $\Omega' = 0.3\,sec^{-1}$; a slow oscillation in the long (A or RA) direction of $\Omega = \Omega'/\pi$. The peak velocity is then near our $2'/sec$ limit for the Penn Array's slowest possible detectors. Other quantities are well within limits.

3.6 Antenna Software Requirements

In addition to executing the above scan, it must be possible to easily reconstruct from the recorded FITS files the actual pointing position of each feed of the telescope in *celestial* coordinates at each sampled point in time, such as Ra and Dec.

It would also be desirable to have this mode, and other on-the-fly modes like RaLongMap, be able to raise an "on-the-fly" flag. This would tell the Antenna manager to start going to the area of interest immediately and in a reasonable way and not waste time trying to match velocities at the scan start, which fundamentally you don't care about for on-the-fly data.

[1] Initially I chose an irrational number in order that the pattern not close, but on simulation this actually seems not extremetly useful; any number ~ 3 gives patterns like those we present here, which have demonstrably useful properties.

4 Notes & Conculsion

The choice of a sinusoidal radial function was motivated by simplicity of implementation, and by the simplicity with which the resulting scan pattern can be checked against GBT constraints. More generally one could write

$$\vec{p}(t) = r_o\,(\hat{x}\,sin\,\Omega t\;+\hat{y}cos\,\Omega t)\;f(\omega t) \tag{12}$$

where f is any periodic function. Functions more sharply peaked than the sinusoid would allow wider area coverage, and more general functions also permit greater freedom in radial integration weightings. A drawback is that such an approach would require detailed analysis to notch out bad frequencies *etc*.

Placing a calibrator at the middle of your map may also limit the dynamic range of your map; this depends on how well we can characterize the $8'$ pedestal of panel-scattered flux[2], and how much structure this pedestal has. My back-of-the envelope estimate places this limitation at one part in 10^4 which even for a 50 mJy calibrator source corresponds to about the expected 1σ confusion level due to extragalactic sources, this might then be expected not to be a problem.

I've discussed only a very limited class of scan patterns. Preliminary indications are that other scan patterns– in particular the so-called "billiard ball" scan– will be more optimal for actual astronomy. This is partly because billiard balls are more nearly a "constant speed" scan pattern, allowing us to operate near our limiting factor (and simultaneously get more uniform sensitivity in our maps). However daisy scans should provide a high degree of redundancy necessary to shake down the system, and could be useful for other applications before the Penn Array is on the telescope.

To the extent that scan patterns are velocity limited by frontends or backends (like the DCR) a chopping tertiary does little for on the fly maps. On the other hand if GBT acceleration or servo bandwidth limits are a factor (not typically for cases we've identified here) a tertiary would be of use. If GSFC delivers detectors with time constants in the millisecond range, GBT limits *would* be the relevant ones and a tertiary would help. Other factors (like photometry and spectroscopy) also bear on the decision and are independent of this analysis.

Some open items for future work are:

- Better forms for $f(t)$? Maybe not necessary if what I've outlined here will do the job.
- Analysis to determine limits/pick parameters for Lissajous & Billiard Ball scan patterns;
- More careful choice of parameters for beammaps/OOF should this be desirable. **Nyquist sampling per beamsize criteria**
- add glish
- pointing case (only a few petals)

Acknowledgements I thank Joe Brandt and Don Wells for useful conversations.

[2] that is, at 90 GHz we expect in the best case half the power to be scattered onto angular scales of $2\lambda/d_{panel} \sim 8'$