ngVLA Antenna Memo #13:
NGVLA Antenna On-the-Fly Mapping Use Cases

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Abstract

In order to inform ongoing antenna prototype design efforts we present a refined on-the-fly mapping system requirement reflecting total power requirements. We also present several scan strategies to illustrate the range of likely, practical use cases.

Revision History:

v1: January 27, 2022: 1st version

v2: February 4, 2022: first release after incorporating minor revisions suggested by the Antenna test group and TPWG

v3: July 28, 2022: fix typo in table 1 (3mm row spacing was incorrect; other numbers, analysis and conclusions unaffected).

v4: March 8, 2023: clarified tracking rate limitations imposed on OTFM performance; maximum tracking rates defined as 45 and 21 arcsec/sec for (Az,El) (roughly sidereal for elevation 70 deg), and that antenna requirements ANT0906 and ANT0907, maximum tracking rate in azimuth and elevation, respectively, do not apply. Added Appendix to provide details.

1 Introduction

NGVLA total power antennas will predominantly be used in an On-the-Fly Mapping (OTF or OTFM) observing mode, in which the antennas are continuously scanned over a region of scientific interest while (typically high cadence) averages of radiometric total power or spectra are recorded. Since this characteristic motion is considerably different from the dominant, interferometric observing pattern — and since it is a goal for a single antenna design to meet both the NGVLA interferometric and total power requirements — we present in this memo the OTFM requirement that we expect to adopt for total power antennas, as well as two specific scientific use cases illustrating its application. Detailed discussion of OTFM, as applicable to total power radio astronomical observations, is given by Mangum et al. [2007].

2 Total Power OTFM System Requirement

The NGVLA Total Power Working Group (TPWG) was convened in 2021 in order to scrutinize the NGVLA conceptual design as regards total power performance. The TPWG was tasked with identifying any new or modified requirements which might be needed in order to achieve its scientific goals. The goal of this work is to identify and factor in any needed changes before the NGVLA system PDR. The TPWG has critically reviewed existing system requirements against single dish observing best practices, as well as identified and key science use cases [Mason et al., 2022]. We note in passing that this difference in characteristic motions will also have lifecycle implications which will need to be considered.

One area the TPWG identified as requiring further clarification is *antenna motion*, and in particular, the requirements for OTFM. As a result, we are currently recommending the following TP-specific extension of SYS0106:

> **Total Power On-The-Fly Mapping (OTFM)**
>
> *It shall be possible to Nyquist sample a 60 Nyquist pixel by 60 Nyquist pixel region of the sky in 9 minutes or less at* $\lambda = 2.7mm$*, and 60 minutes or less at* $\lambda = 21cm$*, while maintaining:*
>
> - *a referenced pointing accuracy of* $1/10th$ *of a beam or better;*
> - *uniform integration time per sky pixel to within 10% within the region of interest; and*
> - *all with at least 50% of the total time spent within the region of scientific interest.*

This requirement will apply while scanning relative to a tracked location on the sky in arbitrary celestial coordinates (Equatorial or Galactic, for instance); these celestial coordinates can be assumed to change slowly compared to the sidereal tracking rate. It will apply for all required elevations $< 70°$, and it should be possible to conduct OTFM up to at least 80° with pointing and tracking speeds above 70° on a best efforts basis. Maximum tracking rates are assumed to be 45 and 21 arcsec/sec in (Az,El) (roughly sidereal at elevation $< 70°$— see Appendix A.1 for details.). "Pointing accuracy" is the 2-dimensional RMS of the referenced pointing error (commanded minus actual position, after removing slowly varying local pointing corrections). For TP OTFM in particular, it would be acceptable to meet this requirement on the basis of indicated minus actual positions, so long as the Nyquist sampling and integration time smoothness provisions are still met. For the sake of simplicity we do not consider oversampling recommendations as part of this specification. These recommendations are discussed by Mangum et al. [2007], and while likely to be implemented in practice, will result in small modifications of the executed trajectories that would not substantively impact antenna requirements *per se*.

The scientific use cases which drive this requirement are NGA8 (Key Science Goal 3.3.3) and NGA2 (Key Science Goal 3.3.5). Both of these use cases aim to map spectral lines in and around nearby galaxies. NGA2 is focused on the 21cm hyperfine transition while NGA8 is focused on the ^{12}CO and ^{13}CO near $\lambda = 2.7mm$.

3 Example Scan Patterns

3.1 Raster Scans

Two example scan strategies which satisfy these requirements are shown in Figure 1 and Table 1. Both examples use a raster-scanning approach in which the antenna is continuously scanned back and forth (or up and down) in celestial coordinates around a target, with approximately uniform speed within the region of scientific interest. *We emphasize that these solutions are intended to be illustrative, not prescriptive.* Further note that:

- Rows are Nyquist-spaced.
- the integration (dump) time is taken to be the scan speed divided by the Nyquist pixel size. If the antenna positioning errors are smooth and well-behaved (e.g. including the impact of any structural resonances excited at turn-arounds), then the antenna positions may not need to be sampled this rapidly.
- Time per row does not include turn-around overhead, although these are included in the total time.
- Turn-around overheads in this example are set to be less than or equal to the integration time on one row divided by three based on observing efficiency considerations.
- As noted in § 2, these example strategies provide the minimum theoretically viable sampling of the sky, and in particular do not account for practical considerations that lead to slightly denser sampling [as discussed in Mangum et al., 2007].

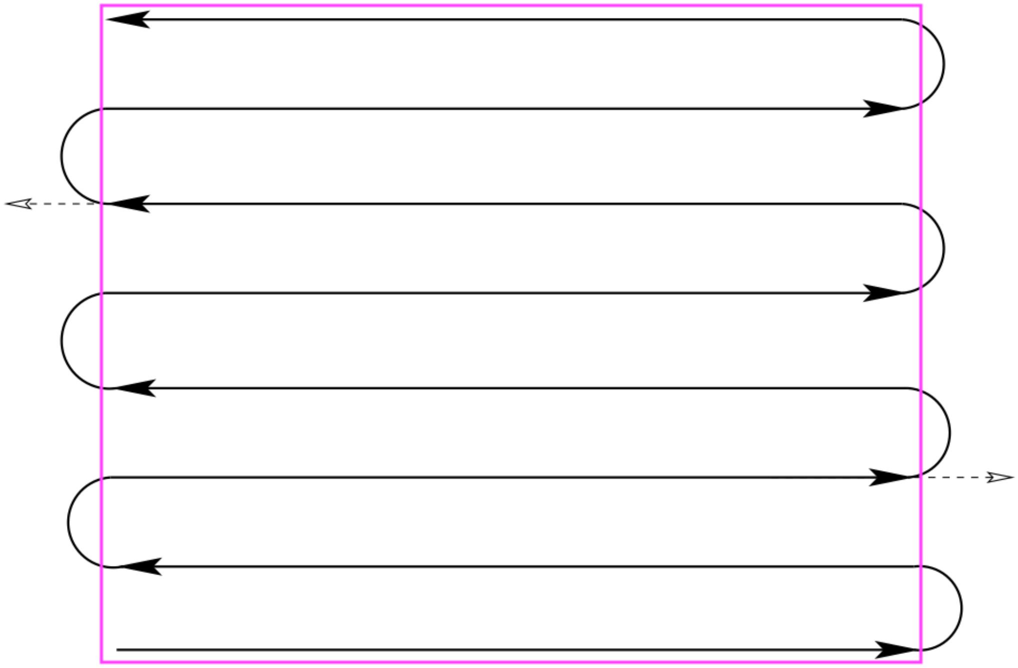

Figure 1: Schematic representation of a total power raster (Boustrophedonic[1]) scan. The scan begins in the lower left. The black solid line indicates the antenna trajectory relative to sky coordinates, with data acquired continuously throughout. The region of scientific interest is indicated by the magenta square; details of the "turn-arounds" are notional (i.e. not explicitly constrained). The open-headed arrows every third row indicate slews to two anti-symmetric off-source reference positions; these are an important practical consideration, but not part of this use case or the OTFM requirement. Adapted from fig.9 of Mangum et al. [2007].

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[1] `http://www.worldwidewords.org/weirdwords/ww-bou1.htm`

parameter	use case: $\lambda = 21cm$	$\lambda = 2.7$mm
row spacing (*arcmin*)	20.15	0.248
scan speed (*arcmin/sec*)	30	3
integration period	0.67 *sec*	82.7 *ms*
map size	20.15°	$14'.9$
time per row	40.3 *sec*	5.0 *sec*
turn-around time	13.5 *sec*	1.6 *sec*
total duration	60 *min*	8.7 *min*

Table 1: Example raster scan patterns which meet the total power OTFM system requirement (*not intended to be prescriptive*).

3.2 Other, Variable Speed Scan Patterns

In order to illustrate the range of likely use cases we include two, further examples of scanning trajectories which could be useful for OTFM, for science as well as for verification testing.

First is the so-called Daisy scan, shown in Figure 2. This scan strategy is based on simple sinusoidal motions in each axis with appropriately chosen periods, and for this reason its basic properties are easily understood analytically. While it does not provide uniform coverage[1] to 10%, it does provide high-cadence resampling of a fixed position on the sky (the center), a property which is useful for continuum and solar observations and a variety of calibration observations such as beam mapping. It has been in routine use on the GBT for many years; see [Mason, 2003, 2004] for details of the implementation, and [Romero et al., 2015] for one example of its scientific application. Figure 1 of Romero et al. [2015] illustrates in particular the slow dithering of the scan center point as well as the use of multiple, distinct central pointing positions. A version of this scan pattern has been used for holographic measurements of the ALMA antennas— where it is referred to as a "star" scan— and is proposed for use in ngVLA holography [Mangum, 2022].

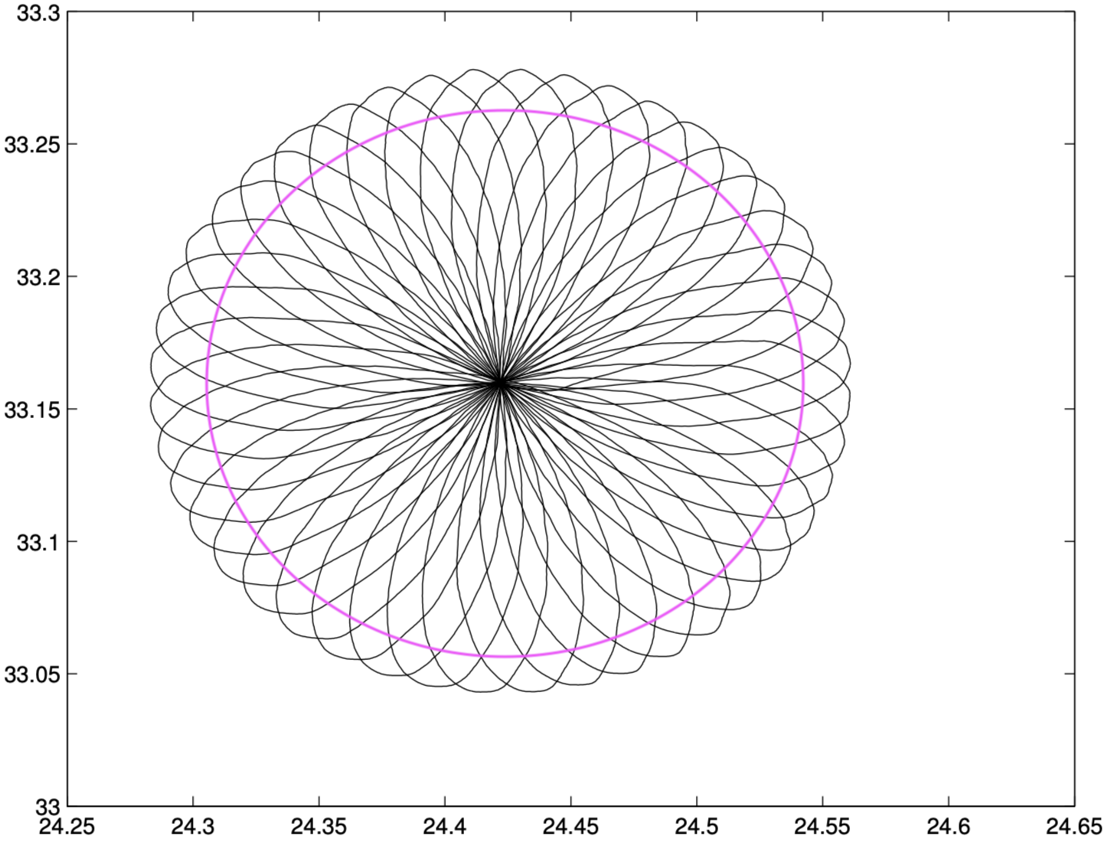

Figure 2: Daisy scan trajectory executed on the GBT. Axes are J2000 Right Ascencion and Declination in Degrees, centered on the calibrator 3C48; the magenta circle indicates a hypothetical region of scientific interest. Adapted from Mason [2004].

The second is a Billiard-ball or box scan pattern, illustrated in Figure 3. This scan strategy comprises a triangle wave in each dimension, but retaining only the first few terms in a Fourier

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[1] The effects of the non-uniform coverage are mitigated by having many feed horns or pixels; by slowly dithering the center point; by scanning in el/x-el relative to a fixed celestial position; and by using several center points. Most or all of these mitigations are usually used in practical daisy-scanning scenario on the GBT.

expansion of the motion so as to minimize high accelerations and jerks, which can excite structural resonances. This scan strategy is well-suited to providing approximately uniform coverage, while at the same time providing higher-cadence cross-linking than is feasible with a raster scan. It has been used on the GBT [e.g. Dicker et al., 2009] and on the JCMT [Scott and van Englin, 2005, Kackley et al., 2010].

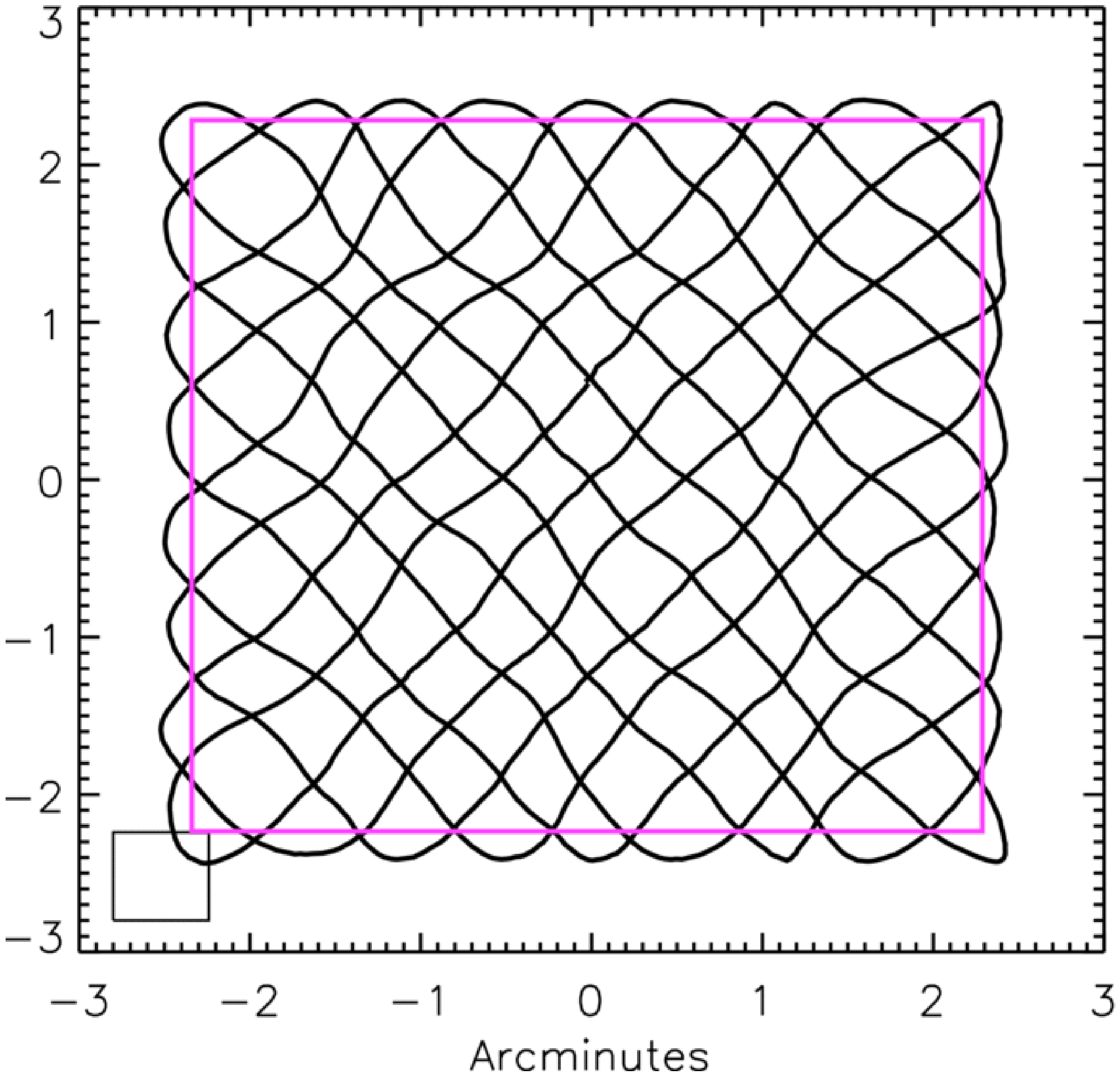

Figure 3: Billiard-ball scan pattern. Axes represent Right Ascencion and Declination offsets from a central astronomical coordinate; the magenta box indicates a hypothetical region of scientific interest, and the small black box in the lower left corner shows the instantaneous field of view of the 64-pixel radio camera used on the GBT for this particular application. Adapted from Dicker et al. [2009].

Acknowledgements

We would like to thank Karl Jansky for inventing the On-the-Fly observing technique [Mangum et al., 2007].

A Appendix

A.1 Sidereal Tracking Limits

The equations that govern the changes in azimuth and elevation as a function of time due to sidereal motion only are as follows Mangum [2011]:

$$\frac{dA}{dt} = \frac{d\tau}{dt}\left[\frac{\sin\phi\cos E - \cos\phi\sin E\cos A}{\cos E}\right] \tag{1}$$

$$\frac{dE}{dt} = \frac{d\tau}{dt}\cos\phi\sin A \tag{2}$$

where

- $\frac{d\tau}{dt} \equiv$ Rotational period of the Earth divided by the length of a UT1 day
- $\frac{d\tau}{dt} = 1.002737811906$ rotations per UT1 day, or $1.002737811906 \times 15 \simeq 15.041$ arcsec/sec
- $\phi \equiv$ Observatory latitude (34.078749 deg for the VLA)
- $A \equiv$ Target azimuth at the telescope
- $E \equiv$ Target elevation at the telescope

Note that if you want to project $\frac{dA}{dt}$ onto the sky you need to multiply by $\cos E$. Figure 4 shows the distributions of differential sidereal motion as a function of (Az,El) at the VLA site.

A.2 ngVLA Antenna Tracking Requirements and On-the-Fly Mapping

The ngVLA antenna requirements [Dunbar, 2022, ANT0906 and ANT0907, Section 5.10, "Axis Rates"] state that the ngVLA antenna must maintain the applicable absolute pointing error requirement while tracking at ≤ 7.5 or 3.5 deg/min (≤ 450 or 210 arcsec/sec) in azimuth or elevation, respectively. The absolute pointing error requirements are given by antenna requirements [Dunbar, 2022, ANT0611 and ANT0621, Sections 5.6.1 and 5.6.2, "Pointing Accuracy in (Precision|the Normal) Operating Environment"] as 18 and 30 arcsec RMS (goals of 15 and 25 arcsec RMS, respectively) for precision and normal operating conditions, respectively. Note also that the maximum tracking rates correspond to approximately 10 times the sidereal rates at an elevation of 70 degrees.

In Section 2 two exceptions to the ngVLA antenna requirements [Dunbar, 2022] are specified:

- At all frequencies the pointing requirement is defined as $\leq \frac{1}{10}$ of a primary beam width (which is, strictly-speaking, neither the "absolute" nor "referenced" pointing error requirements (ANT0611 and ANT0612) in the Antenna Technical Requirements [Dunbar, 2022].
- The maximum tracking rate is defined as 45 and 21 arcsec/sec, which is roughly the sidereal tracking rate at an elevation of 70 degrees. Note that this is $\frac{1}{10}$ the maximum tracking rates of 7.5 and 3.5 deg/min (450 and 210 arcsec/sec) in azimuth and elevation, respectively, as defined in [Dunbar, 2022].

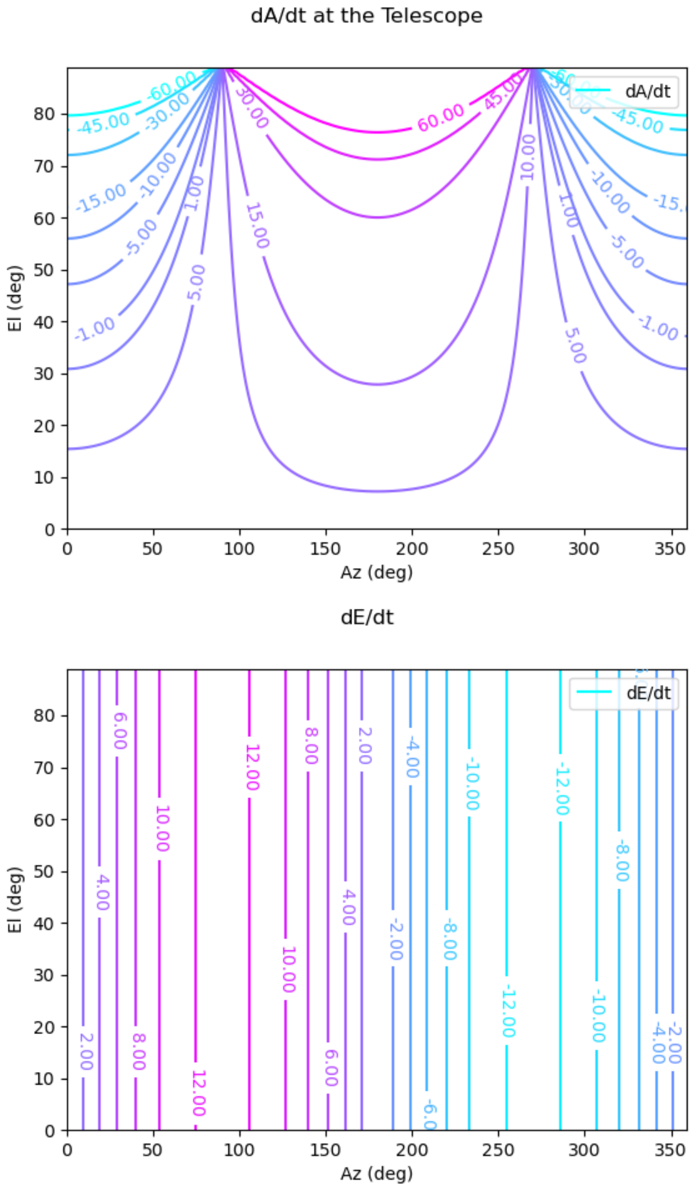

Figure 4: Differential sidereal tracking rates for azimuth and elevation in arcsec per second at the VLA site.

Since the OTF scanning pattern that an antenna must execute is observed relative to the position (sidereal or ephemeris) tracking rate toward an astronomical target, the total tracking in azimuth or elevation that the antenna must execute, and during which the antenna must meet the applicable absolute pointing requirement, is given by:

- Relative Pointing Requirement: $\frac{1}{10}$ beam at wavelength of observation:
  - $\lambda = 21\,\mathrm{cm}$: $2418/10 = 241.8\,\mathrm{arcsec}$ ($4.03\,\mathrm{arcmin}$) RMS
  - $\lambda = 2.7\,\mathrm{mm}$: $29.76/10 = 3.0\,\mathrm{arcsec}$ ($0.05\,\mathrm{arcmin}$) RMS
  - $E < 70\,\mathrm{degrees}$
- Azimuth Tracking:

  - Tracking Only: $|\frac{dA}{dt}| \leq 45\,\text{arcsec/sec}$ (0.0125 deg/sec))
  - Tracking Plus OTF:
    - $\lambda = 21\,\text{cm}$: $|\frac{dA}{dt}| \leq 45 + 1800 = 1845\,\text{arcsec/sec}$ (0.5125 deg/sec)
    - $\lambda = 2.7\,\text{mm}$: $|\frac{dA}{dt}| \leq 45 + 180 = 225\,\text{arcsec/sec}$ (0.0625 deg/sec)

- Elevation Tracking:
  - Tracking Only: $|\frac{dE}{dt}| \leq 21\,\text{arcsec/sec}$ (0.0058 deg/sec))
  - Tracking Plus OTF:
    - $\lambda = 21\,\text{cm}$: $|\frac{dE}{dt}| \leq 21 + 1800 = 1821\,\text{arcsec/sec}$ (0.5058 deg/sec)
    - $\lambda = 2.7\,\text{mm}$: $|\frac{dE}{dt}| \leq 21 + 180 = 201\,\text{arcsec/sec}$ (0.0558 deg/sec)

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