High Performance, Full-Digital Control on the LMT and KVN Telescopes

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The LMT/GTM

- 50m Diameter (MT-M)
- 1-4mm (0.85mm)
- Fully steerable (Az/El)
- Mexico at 4,600m
- Primary surface in five rings (12, 24, 48, 48, 48 = 180 segments)
- Three rings in use
- Full-Digital Control

LMT Measurements

- Main Axis
  - Encoders
  - Tilt meters
  - Pointing observations
- M1 Segments
  - Laser metrology
  - Photogrammetry

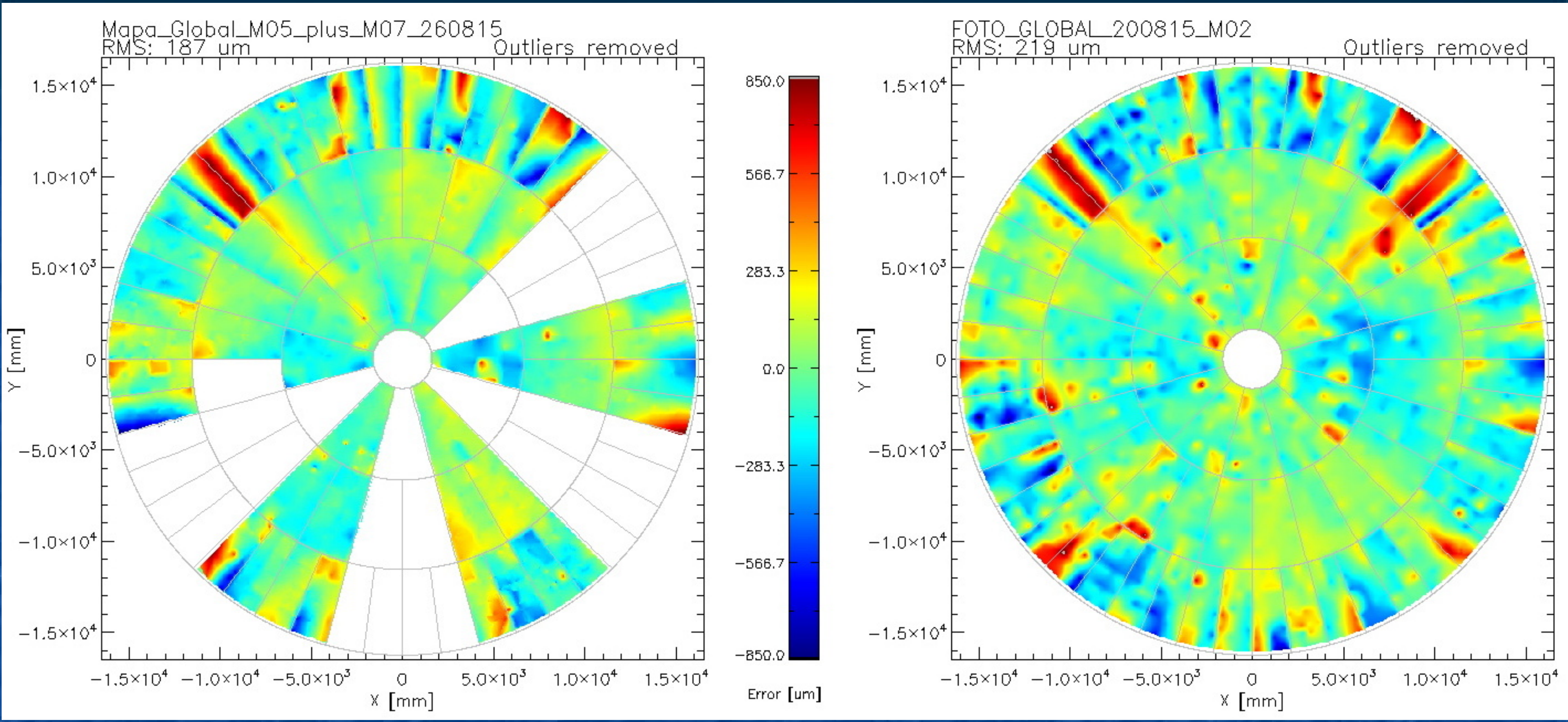
LMT Measurements

M1 Surface:

- Laser metrology
- Photogrammetry
- Holography (12 GHz, three elevations)
- Out of focus beam maps (incl. M2)
- Temperature sensors (>60)

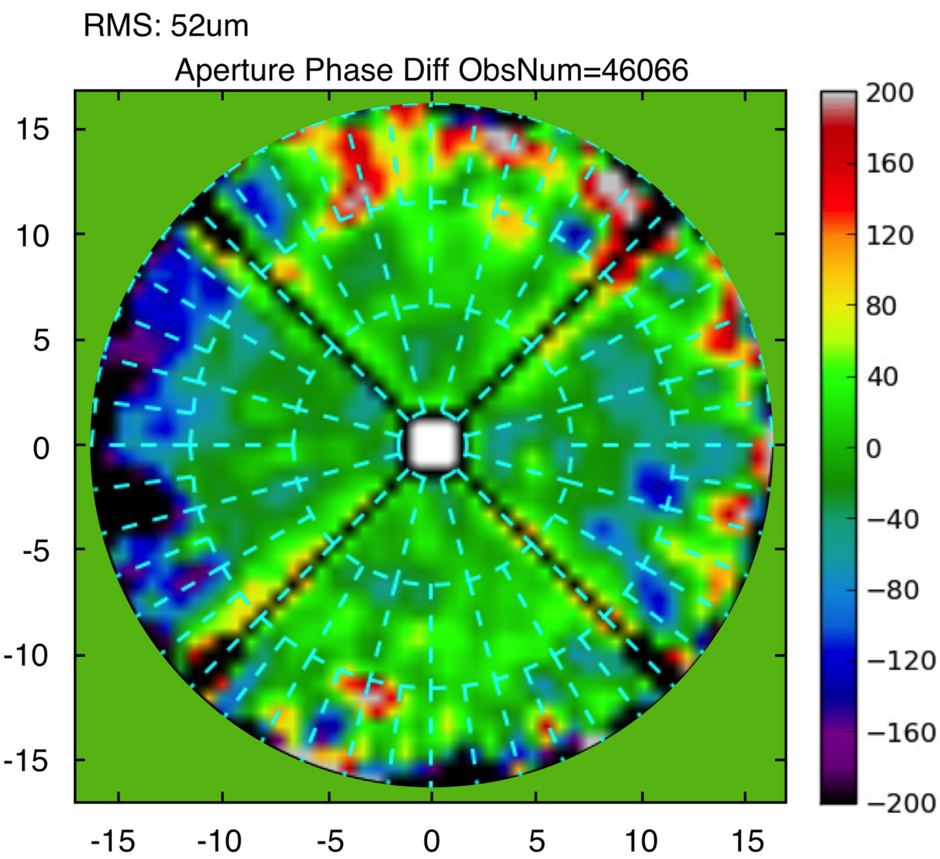
LMT Surface Metrology

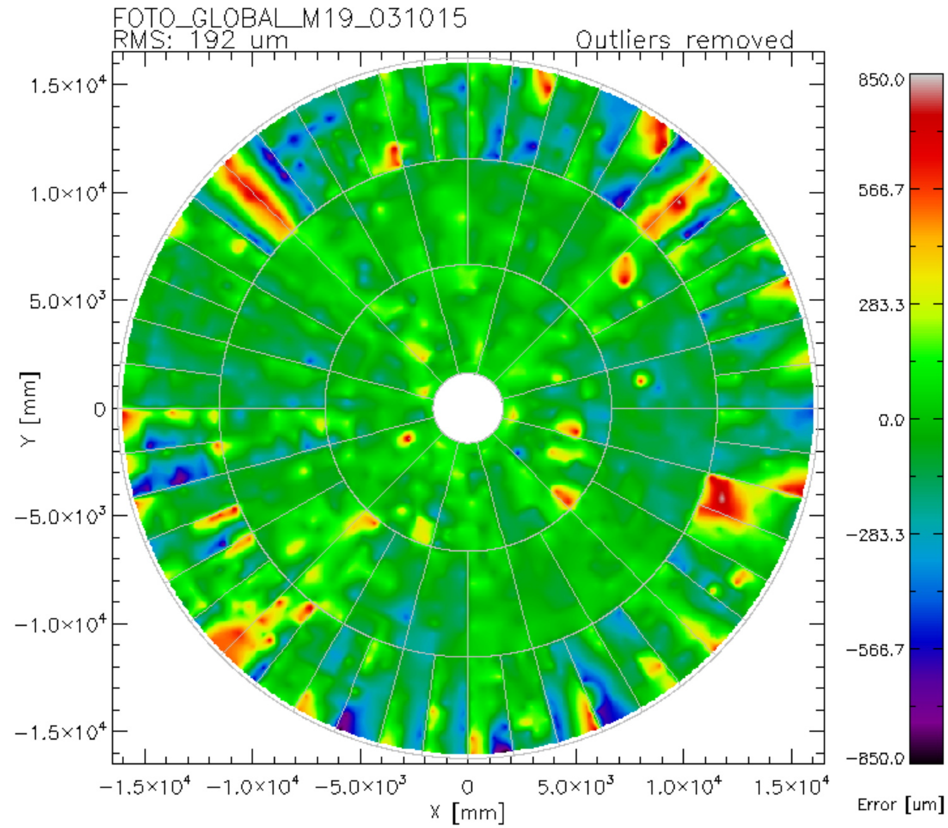
- Site: Total station to install to <500μm
- INAOE: 6 Metrology technicians + analyst
  - Three laser trackers
  - Photogrammetry camera
  - Calibration scale bars, etc.
- Segment setting to 20μm
- Surface mapping to 100μm



Laser tracker El 90° (5 hrs)

Photogrammetry El 90° (1 hr)





Holography El 61° (1 hr)

Photogrammetry El 60° (1 hr)

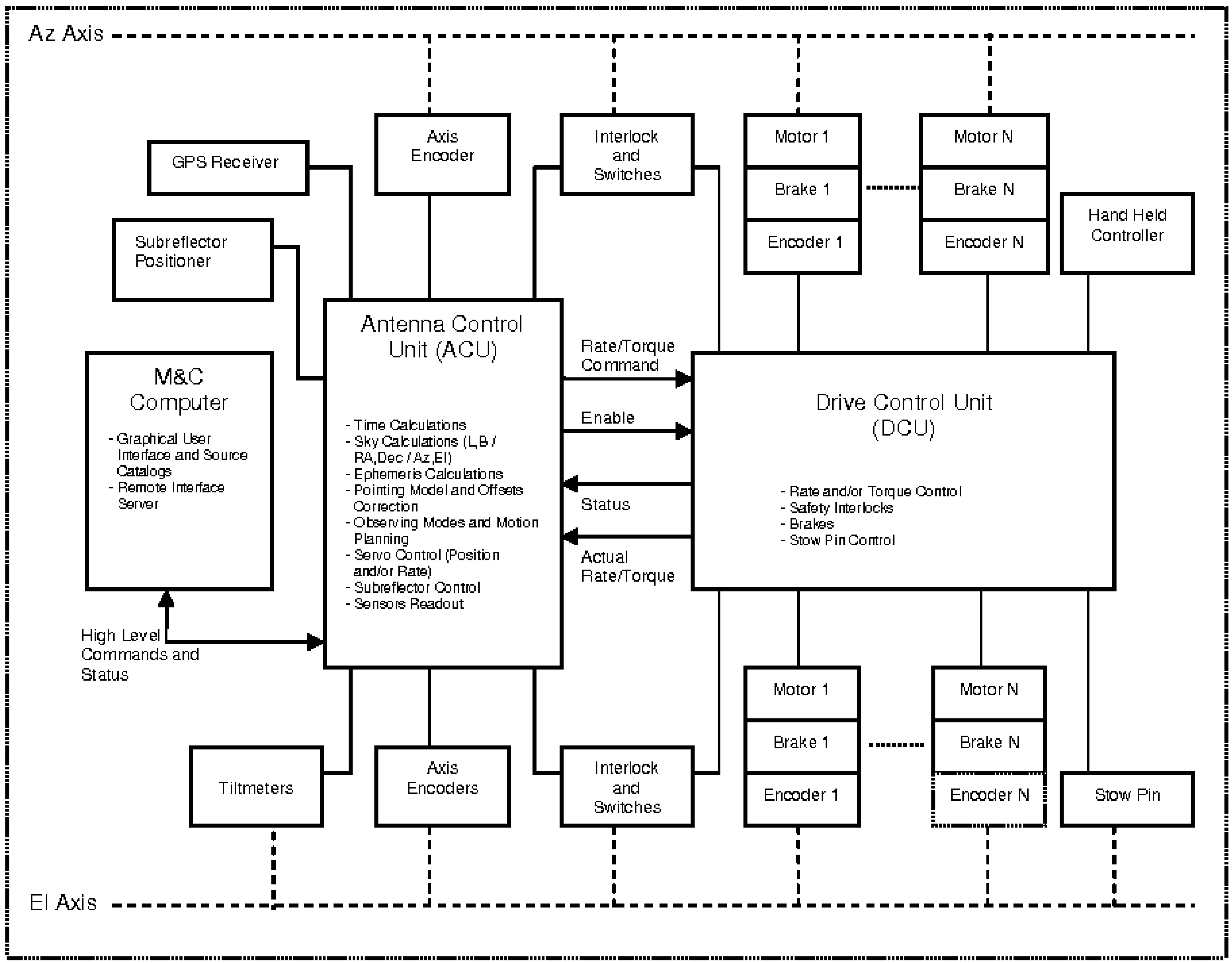
LMT Measurements

- Subreflector (M2) Surface
  - Laser metrology
  - Photogrammetry
- M2 Relative Position
- M2 Absolute Position
  - Focus
  - Beam Shape
  - Laser metrology

LMT Actuation

- Main Axis
  - 16 Azimuth Motors (all wheels)
  - 4 Elevation Motors
- M1 Figure
  - 336 Segment Actuators (32.5m)
  - 720 Segment Actuators (50m)
- M2
  - Hexapod

LMT Servo System



Main Axis Control

- Trajectory Generator
- P-PI with Feedforward
- Friction compensation
- Future work (when we get access again!)
  - State space (even elevation dependent)
  - Adaptive
  - Look-up table corrections

Active Surface Control

- Current Implementation
  - Elevation look-up table (holography)
  - Additional astigmatism correction
    - Out of focus (OOF) beam maps
- Future work
  - Corrections based on temperature sensors
  - Largest effects look like focus/astigmatism
    - Corrected with focus and OOF checks

M2 Position Control

- Pointing and collimation
  - Position only (tilt is equivalent)
  - Elevation look-up
- Focus
  - Checks during observation

LMT Performance

- Main axis accuracy:
  - Tracking: <0.5″ RMS
  - Mapping scans: <1″ RMS
- All-sky pointing accuracy (RMS):
  - Az: 3-4″
  - El: 6-8″ (known hysteresis in encoder mount)
- Surface accuracy (all optics): ~80-85μm
  - M1: ~60μm
  - M2: ~40μm (now being replaced)
  - Setting/other: ~40μm
- Hexapod accuracy: 20μm pos., 2″ tip/tilt

KVN Telescopes

- Korean VLBI Network (KVN) Telescopes
  - Three fully-steerable telescopes in South Korea
    - Ulsan
    - Yonsei
    - Tamna
  - 21m Az/El design (Antedo)
  - 2-7mm

KVN Challenges

- Surfaces and hexapod are conventional
  - Measurement by photogrammetry
- Main design challenge is fast switching
  - High axis rates
  - High axis accelerations
  - Smooth motions to avoid vibration

Fast Switching Requirements

2.5° on sky

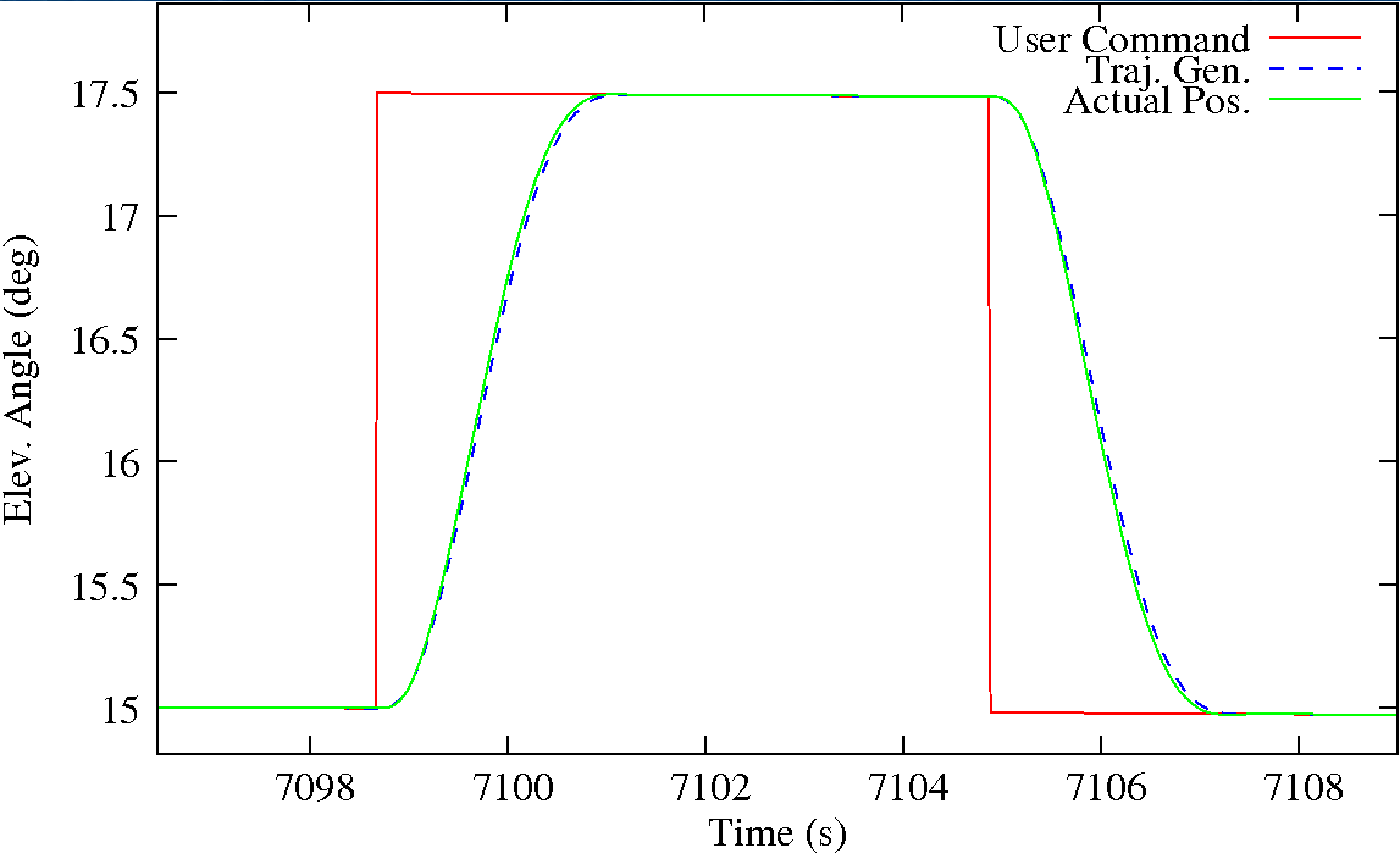
2.5s on source

2.5s on reference

Total cycle time, T

- Elevation switching: $T \leq 13s$
- Azimuth switching:
  - $El \leq 60°$, $T \leq 13s$
  - $60° < El \leq 80°$, $T \leq 26s$

Fast Switching



KVN Main Axis Specifications

Maximum velocity (Az/El): 3°/s

Maximum acceleration (Az/El): 3°/s^2

Minimum smooth rate: 1 arcsec/s

On-sky Pointing accuracy: 4 arcsec RMS

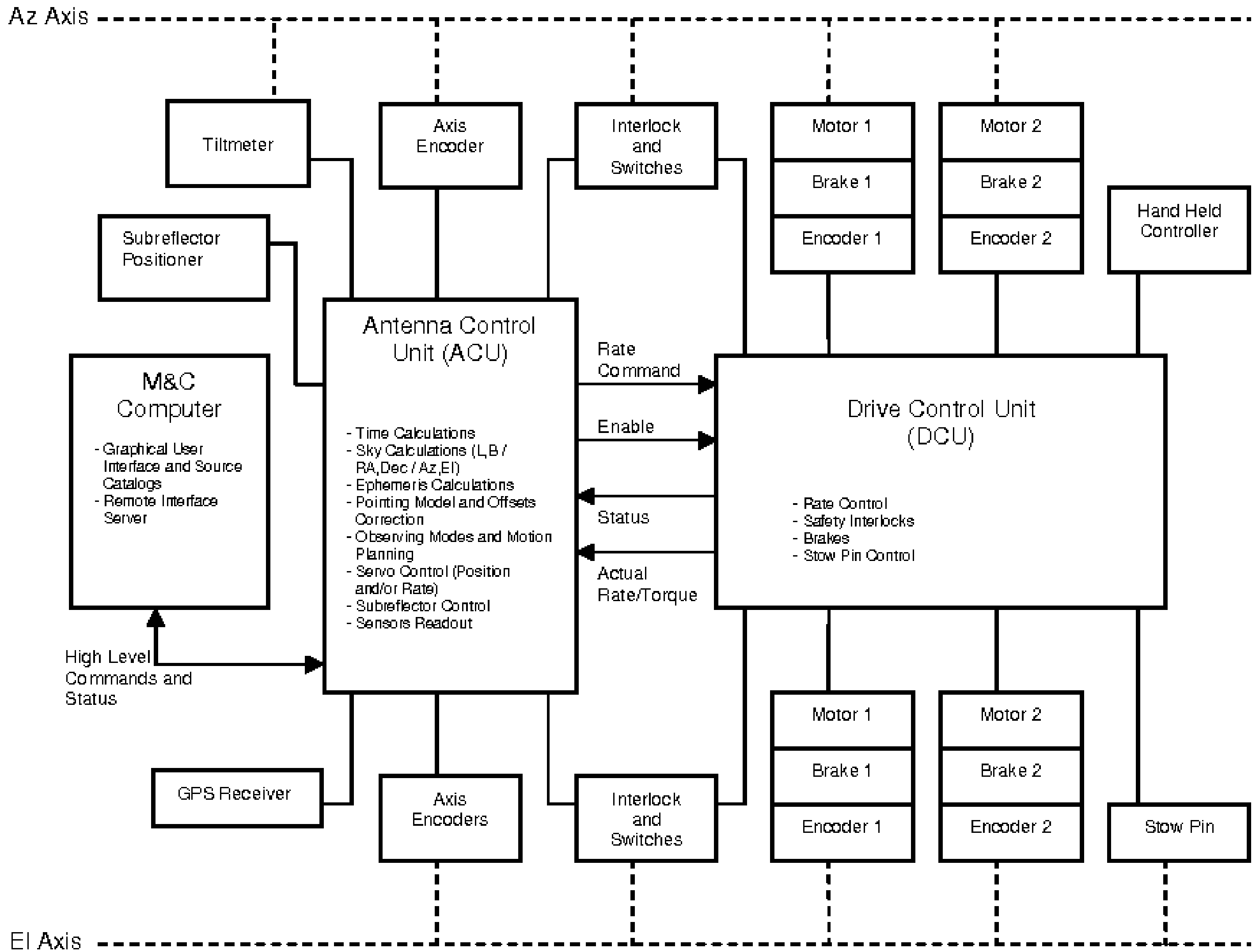
Servo pointing goal: 2 arcsec RMS

LRF (Az/El): 2.5 Hz

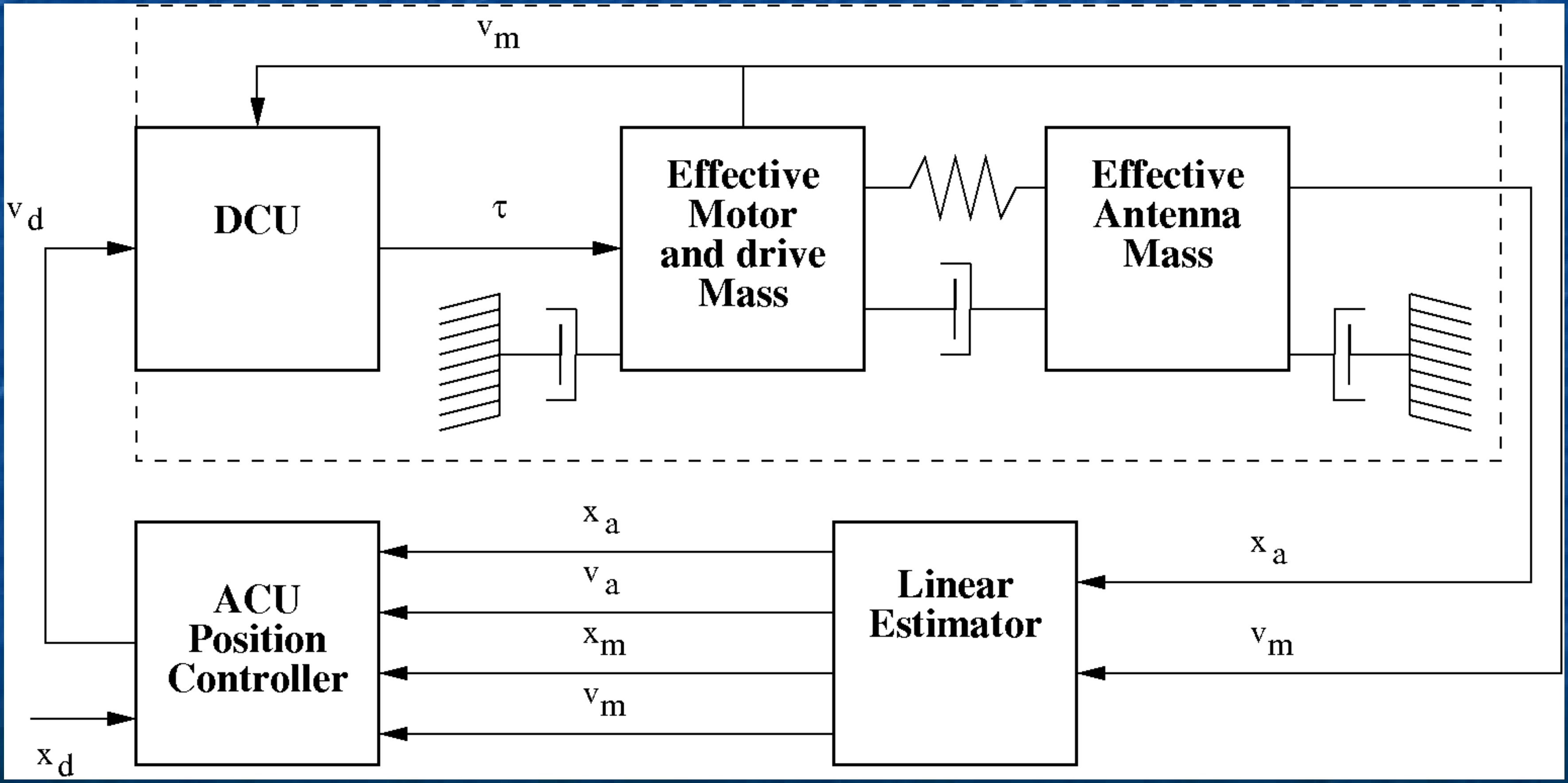
KVN Drive System

- Fast slew/slow tracking
  - Brushless servo motors
  - 2 million counts/rev motor feedback
  - Manufacturer proved low speed operation
- Amplifier issues
  - Rate loop performance superior to torque mode performance for this manufacturer

KVN System Architecture



KVN Controller Algorithm



KVN Controller

- DCU Rate Loop is nominally PI... but
  - Better than when closed with PI in torque
- Full-state optimal estimator to provide state vector
- Model-based control on two-mass model for the position loop. Also includes:
  - Integrator
  - Trajectory generator
  - Feed forward control

KVN Performance

- Usual metrics (estimates):
  - Tracking accuracy: <0.5″ RMS
  - Fast switching
    - Elevation: <13s
    - Azimuth: depends on elevation angle

KVN Fast Switching in Az

- Az +2.5° on sky (2.5°/cos(El))
- Large motions at high elevation angles
- Settling defined as peak error <4 arcsec.
- RMS <2 arcsec

Elevation Angle	Cycle Time (s)
15°	12.6
30°	12.0
50°	12.2
70°	13.7
80°	18.0

Digital System Advantages

- For both LMT and KVN, the digital system provides excellent performance in main axis control
- Architecture means we have access:
  - Torque, Rate, Position, Trajectory, Astro.
- LMT also has an active surface, improving the performance of the primary
- It's OK to be jealous...

Digital System Advantages

- What do we get with the digital system?
  - Usual (but improved):
    - Astronomical tracking
    - Position switching
    - Pointing offsets
    - Instrument holds
    - Raster scanning
- New capabilities also emerge

Digital System Capabilities

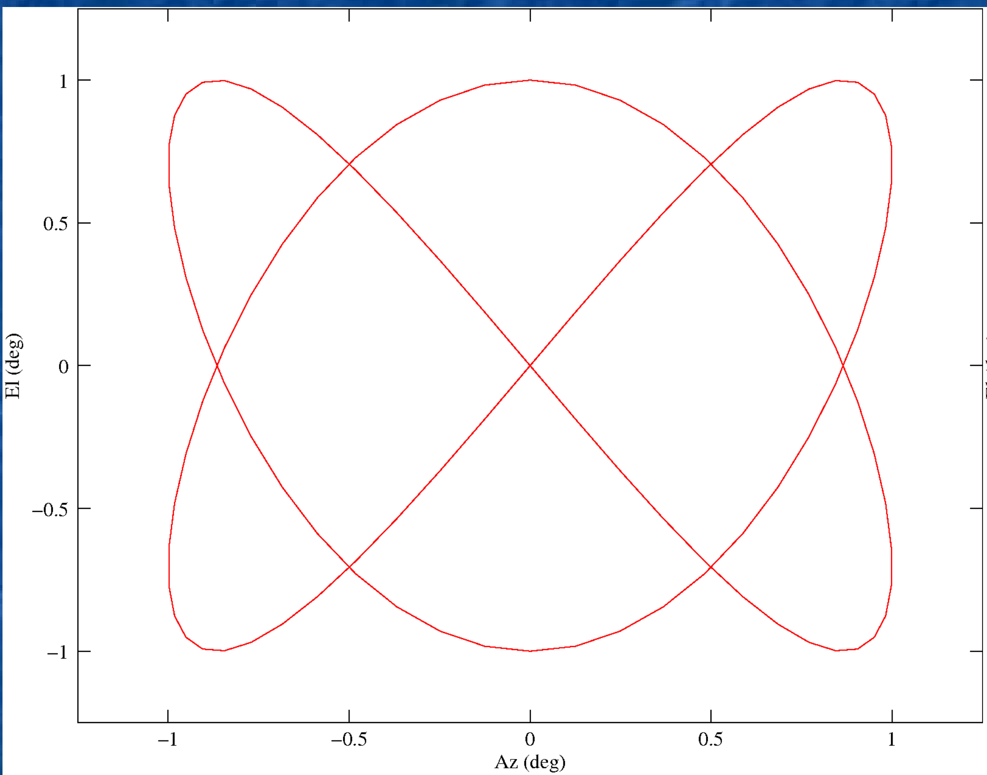
- Easier measurements
  - Balance
  - Controller frequency response
- New observing modes
- New surface corrections
- Design paradigm

Remember: the goal is time on sky

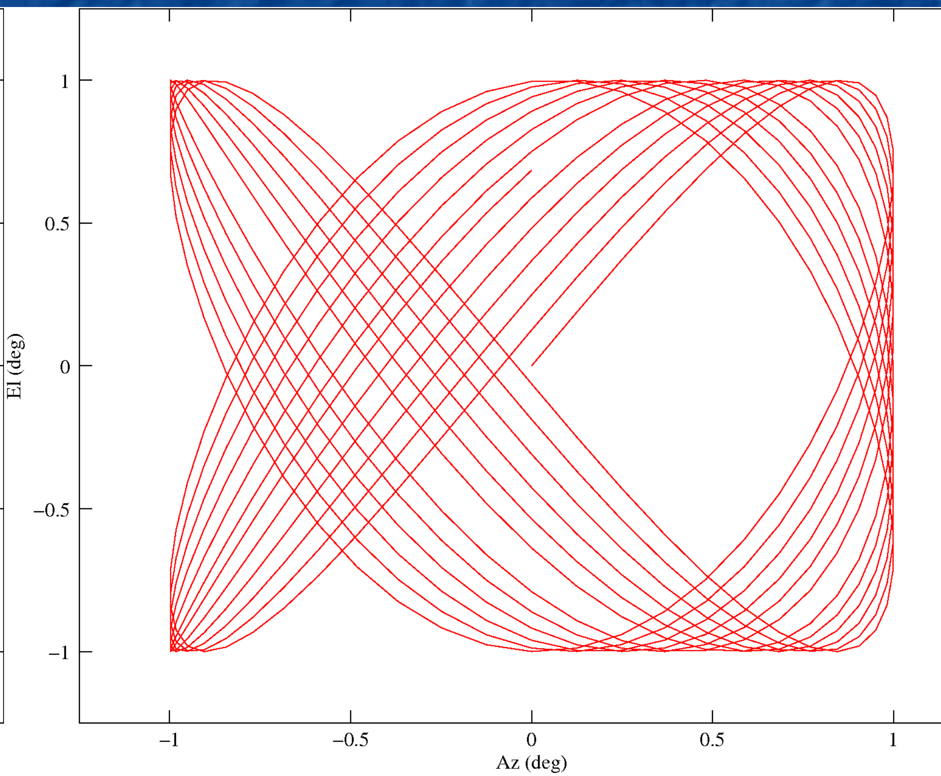
New Observing Modes

- Time parametric scan patterns
- Position parametric scan patterns

Time Parametric Scans

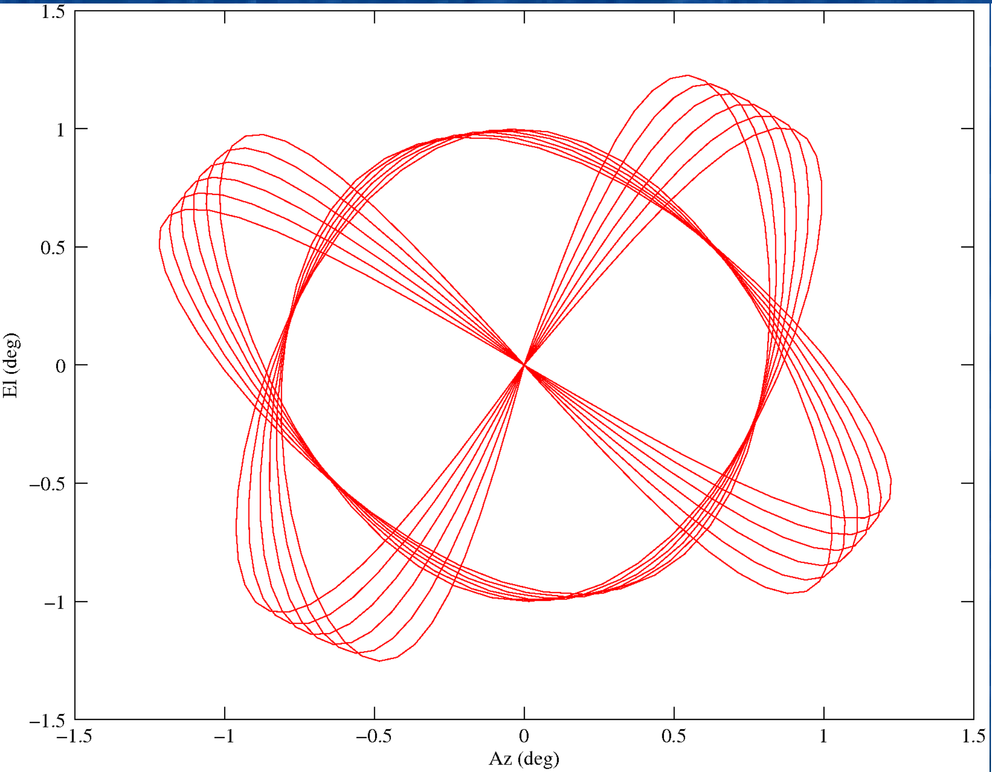


2:3 Lissajous

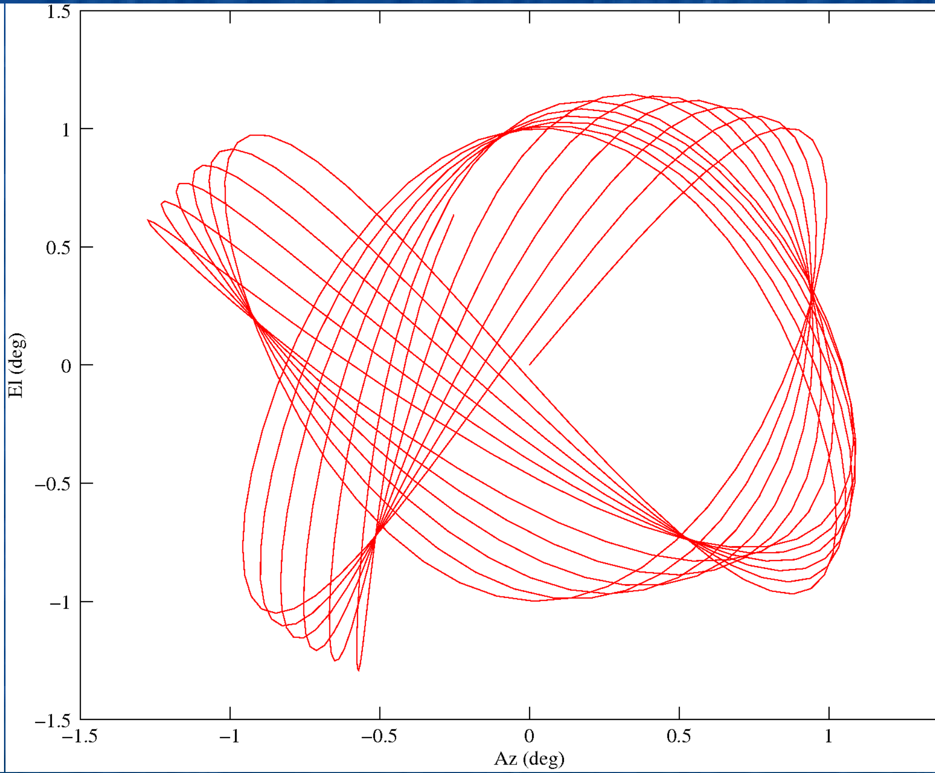


2:(3.02) Lissajous

Rotating Time Parametric Scans



2:3 Lissajous



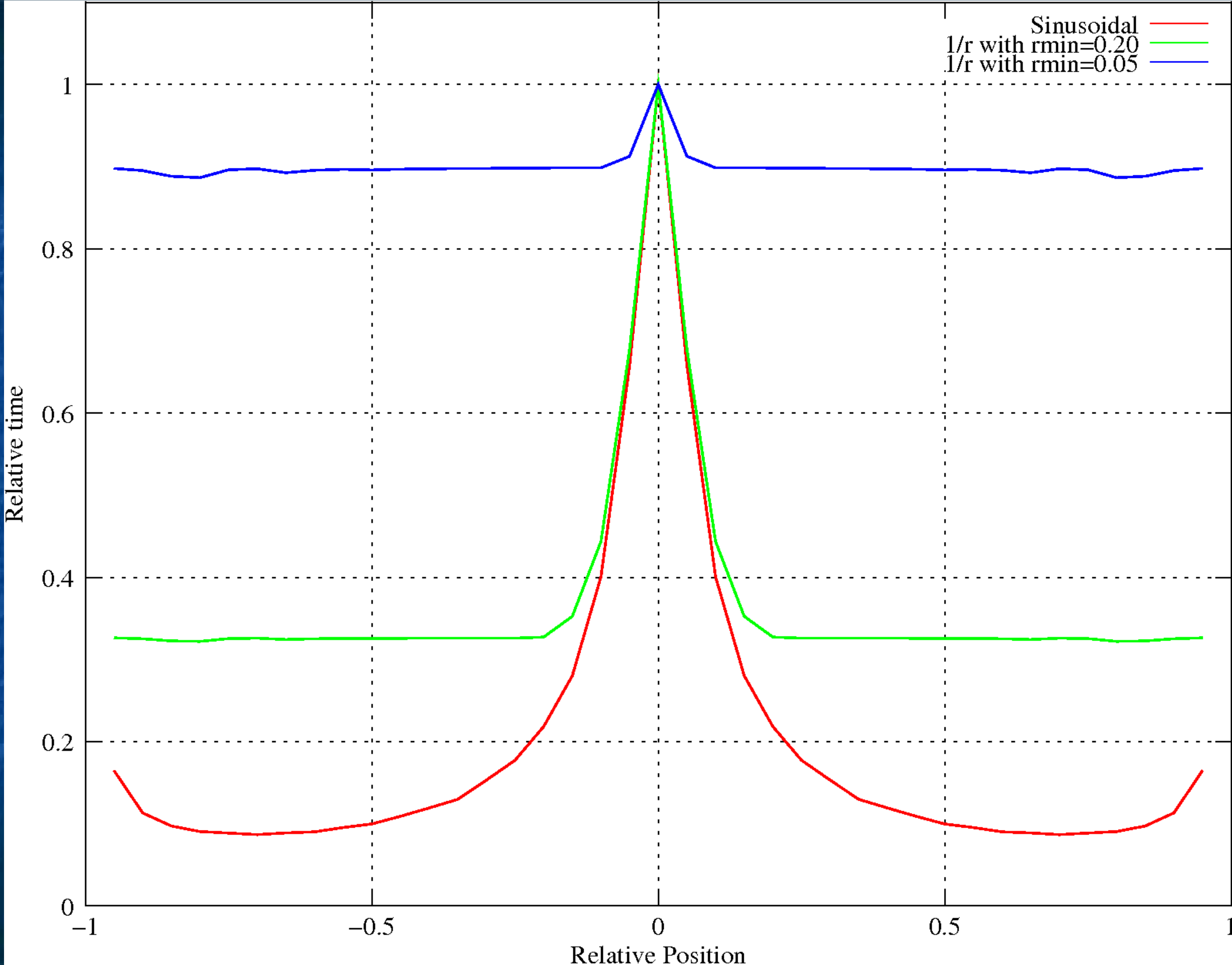
2:(3.02) Lissajous

Position Parametric Scans

- For Holography maps
  - Frequent return to center of the map
- Improved approach
  - Make radial cuts through the center
  - Rotate to a new starting point and repeat
  - Problem: Non-uniform time coverage

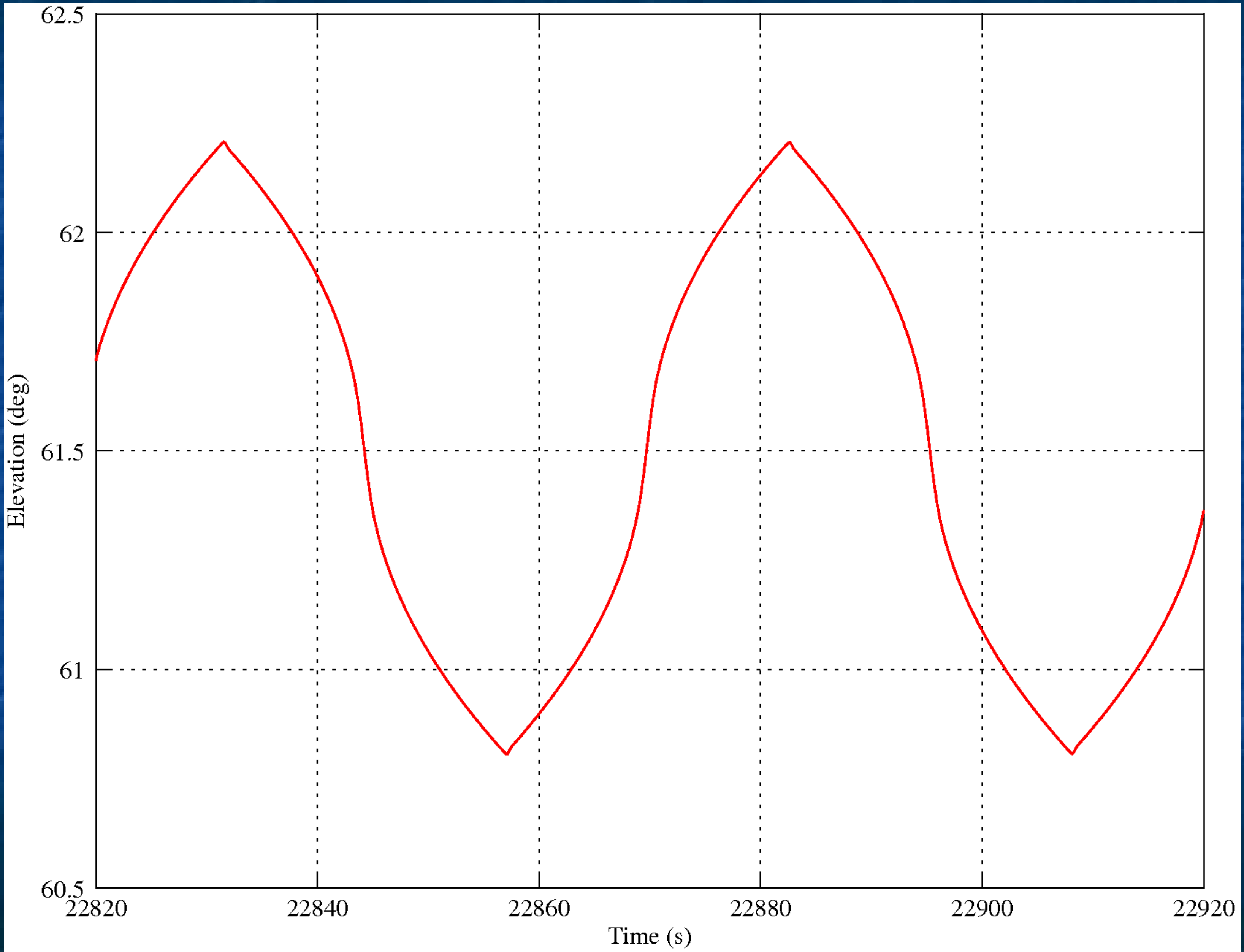
Radial Map Definition

- Parametric Scan Map, 1/r velocity profile
  - High velocity near map center
  - Smooth the transition to limited region
  - Time coverage is increasingly uniform as the limited region is smaller

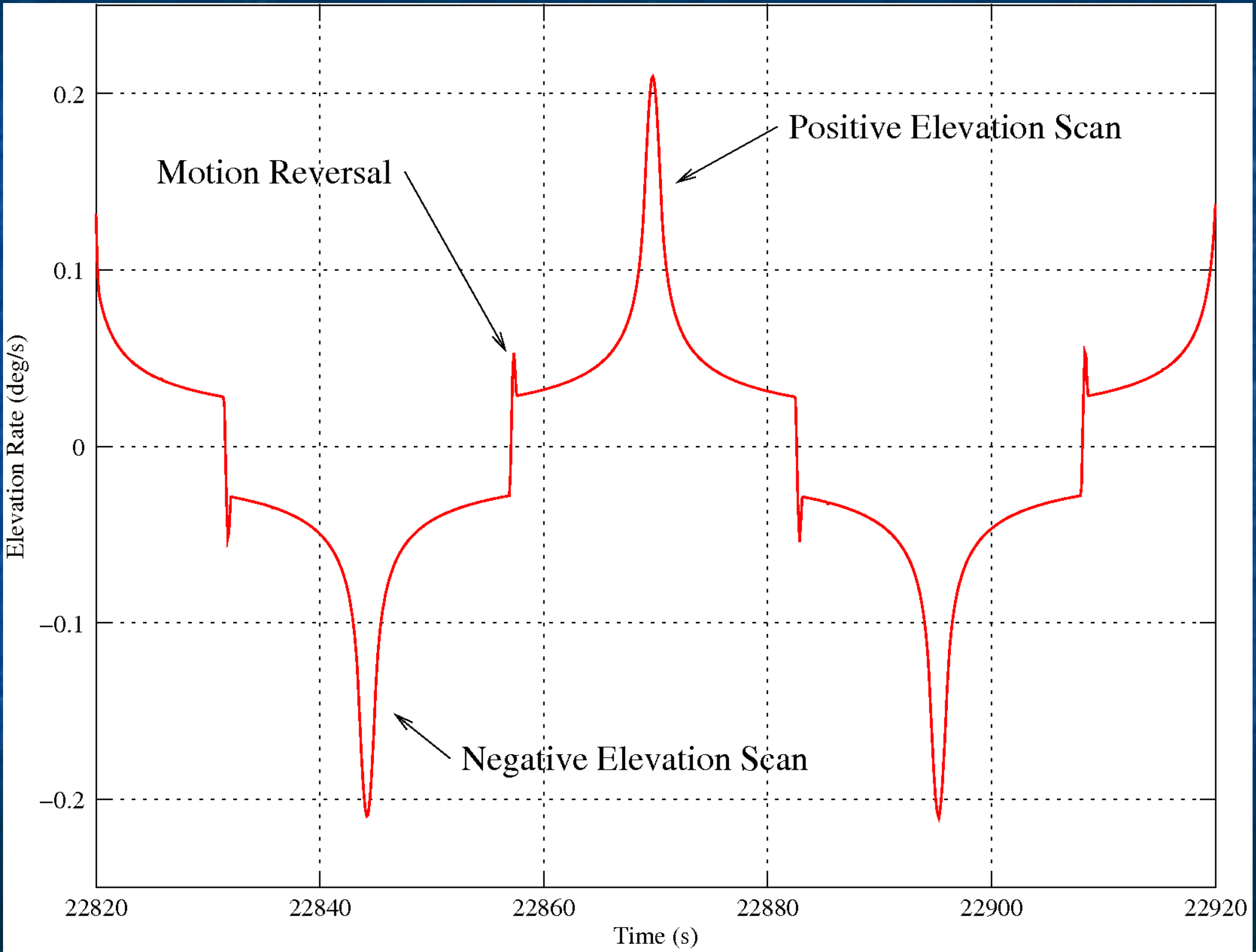


Sinusoidal
1/r with rmin=0.20
1/r with rmin=0.05
Relative time
1
0.8
0.6
0.4
0.2
0
−1
−0.5
0
0.5
1
Relative Position

Typical Results (Position)



Typical Results (Velocity)



New Surface Corrections

- Standard practice: Check pointing/focus
- OOF to measure astigmatic effects
  - Additional Zernike's can also be measured
  - Time trade-off
  - Astigmatism is most important
- Immediate active surface correction

New Design Paradigm

- Fully Digital Main Axis Control
  - Improves with higher LRF
- Active surface
  - Can remove gravity effects
  - Dominant residual effects
    - Pointing, focus, astigmatism, trefoil

Homology is not only not necessary, it can reduce performance for active telescopes

Questions?