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 <500 μm
INAOE: 6 Metrology technicians + analyst
  Three laser trackers
  Photogrammetry camera
  Calibration scale bars, etc.

Segment setting to 20 μm
Surface mapping to 100 μm
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
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:

$E_l \leq 60^\circ$, $T \leq 13s$

$60^\circ < E_l \leq 80^\circ$, $T \leq 26s$
KVN Main Axis Specifications

Maximum velocity (Az/El): 3°/s
Maximum acceleration (Az/El): 3°/s²
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 Controller Algorithm

Block diagram:
- DCU
- Effective Motor and drive Mass
- Effective Antenna Mass
- ACU Position Controller
- Linear Estimator

Inputs and Outputs:
- \( v_m \)
- \( v_d \)
- \( x_d \)
- \( x_a \)
- \( v_a \)
- \( x_m \)
- \( v_m \)
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(\text{El}))

Large motions at high elevation angles

Settling defined as peak error < 4 arcsec.

RMS < 2 arcsec

<table>
<thead>
<tr>
<th>Elevation Angle</th>
<th>Cycle Time (s)</th>
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<tbody>
<tr>
<td>15°</td>
<td>12.6</td>
</tr>
<tr>
<td>30°</td>
<td>12.0</td>
</tr>
<tr>
<td>50°</td>
<td>12.2</td>
</tr>
<tr>
<td>70°</td>
<td>13.7</td>
</tr>
<tr>
<td>80°</td>
<td>18.0</td>
</tr>
</tbody>
</table>
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
Typical Results (Velocity)

- Motion Reversal
- Positive Elevation Scan
- Negative Elevation Scan
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?