Early Satellite Tracking Results from SLR2000

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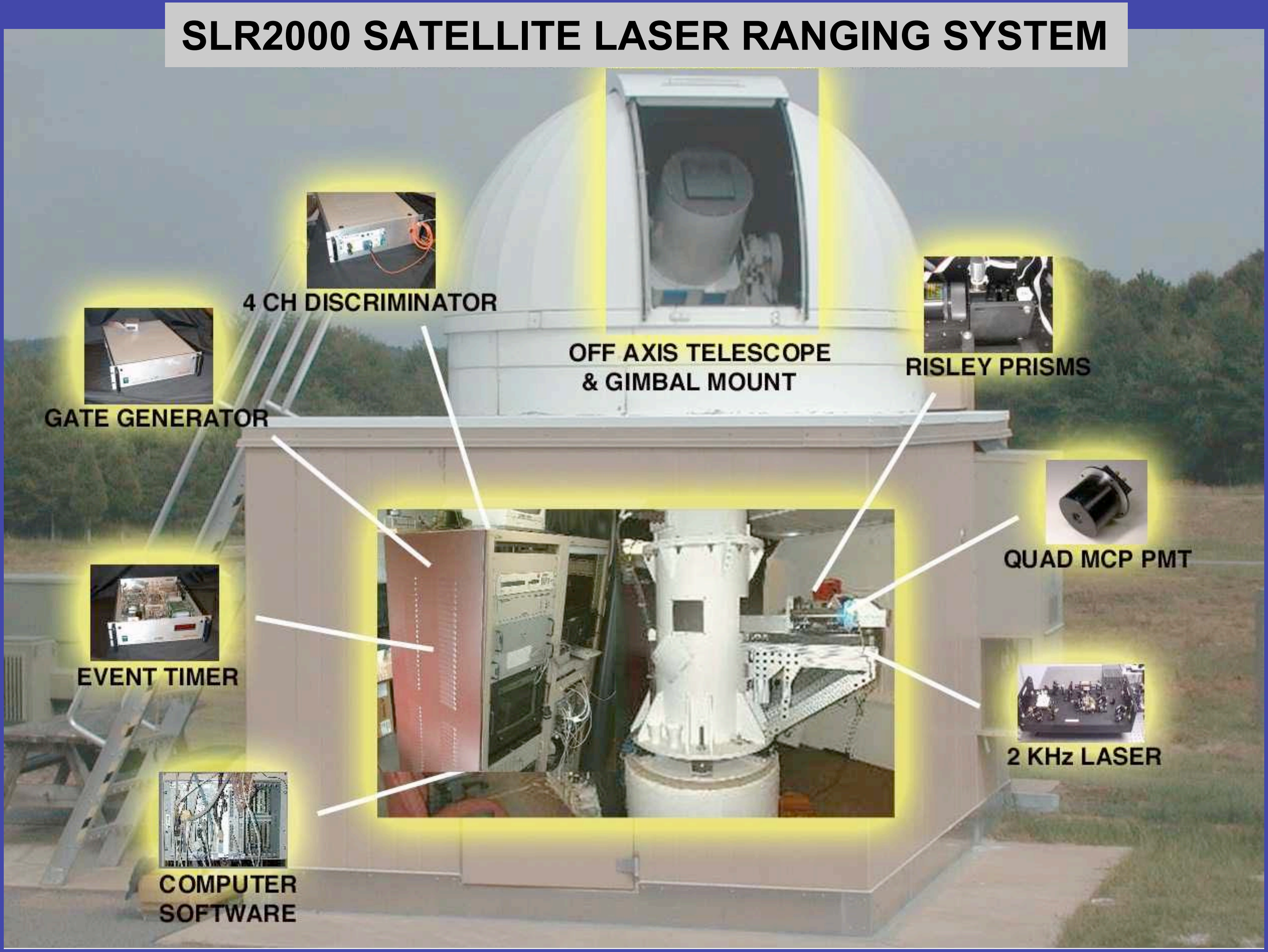
SLR2000

Design Goals for SLR2000

- Unmanned, 24/7 tracking to satellites up to 22,000 km range
- Free of optical, electrical, and chemical hazards
- ~ 1 cm (RMS) single shot ranging (or better)
- 1 mm normal points for LAGEOS
- Mean time between failures: > 4 months
- Automated two-way communication with central processor
- Ability to operate for days without communication
- Reduce replication and operations costs through standardization, COTS technology, and automation

System Characteristics

Laser: Nd:YAG	Diode pumped Osc/Amp
Fire rate:	2 kHz
Pulse energy:	135 uJoules/pulse at exit aperture
Beamwidth:	Variable: 10 to 40 arcseconds (FWHM)
Point ahead:	Risley prism pair (0-11 arcseconds)
Detector:	Photek quadrant MCP PMT
Gain:	3.E+6
QE:	13% at 532 nm
Image area:	6mm diameter quadrant centered
Receiver:	4 independent channels
Field of view:	10 to 40 arcseconds
Discriminator:	Phillips Scientific 708
TIU:	HTSI 1.5 psec resolution Event Timer
T/R switch:	Passive (Polarization insensitive)
Tracking mount:	Xybion Corp Ax/El gimbal
Command Rate:	50 Hertz
Tracking error:	~ 1 arcsecond RMS
Telescope:	OSC 40 cm off-axis


SLR2000 SATELLITE LASER RANGING SYSTEM
4 CH DISCRIMINATOR
GATE GENERATOR
OFF AXIS TELESCOPE
& GIMBAL MOUNT
RISLEY PRISMS
QUAD MCP PMT
EVENT TIMER
2 KHz LASER
COMPUTER
SOFTWARE

Current Progress toward Meeting System Goals

- Star calibrations are routinely performed and completely automated.
- Ground ranging is also routinely performed and is semi - automated.
- System can track LEO satellites under operator control.

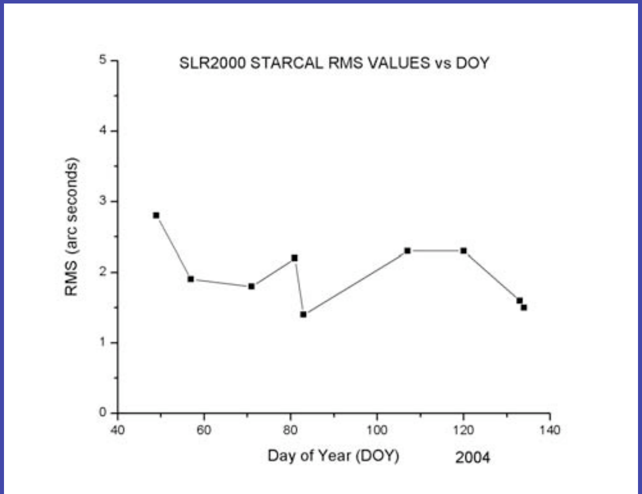
Star Calibrations

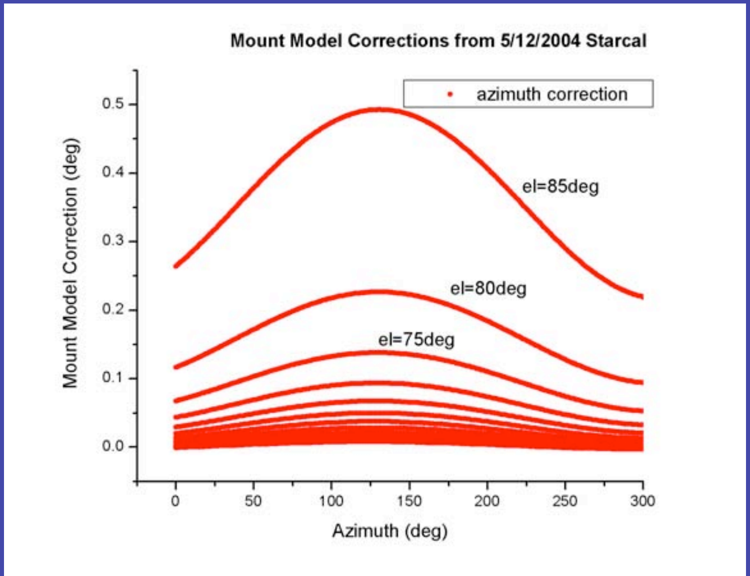
• System pointing is at the few arc second level and appears very stable.

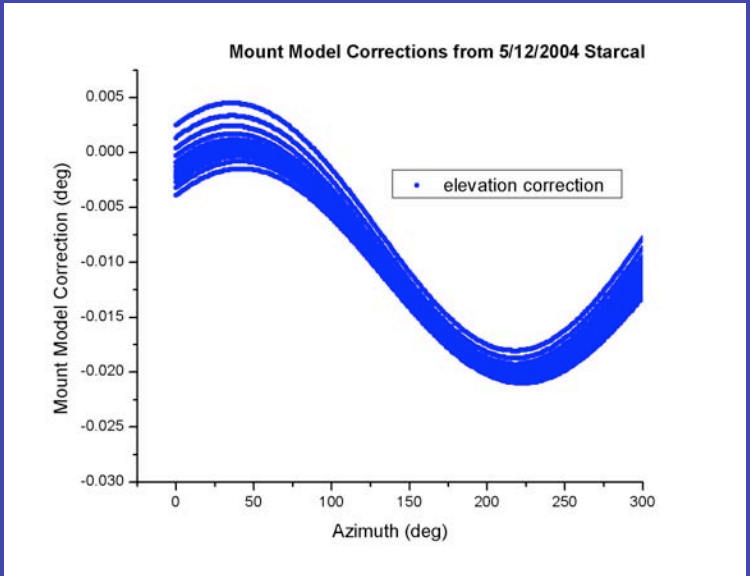
• Current mount model (22 terms) provides a good fit (~2 arc seconds) for elevations from ~10 degrees to 90 degrees.

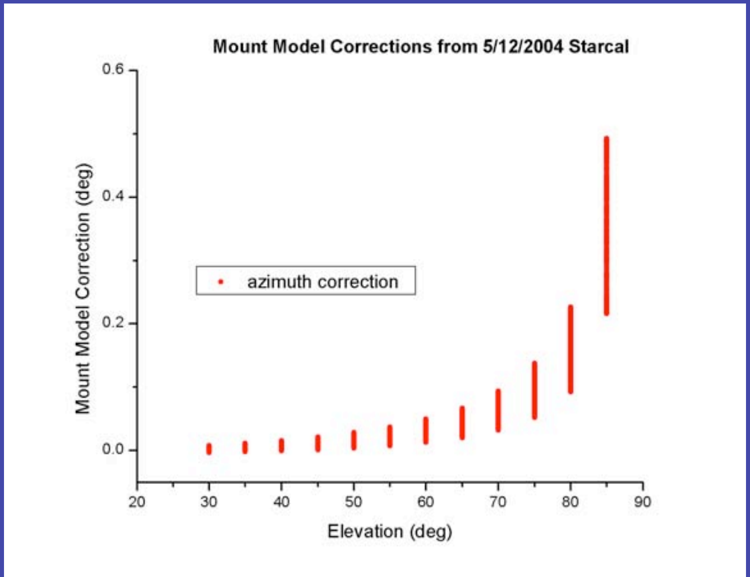
• Once the dome is opened, star calibrations are completely automated and take approximately 30 minutes to gather data from 66 stars. Solution is calculated by least-squares fit of the data to the 22 term trigonometric model.

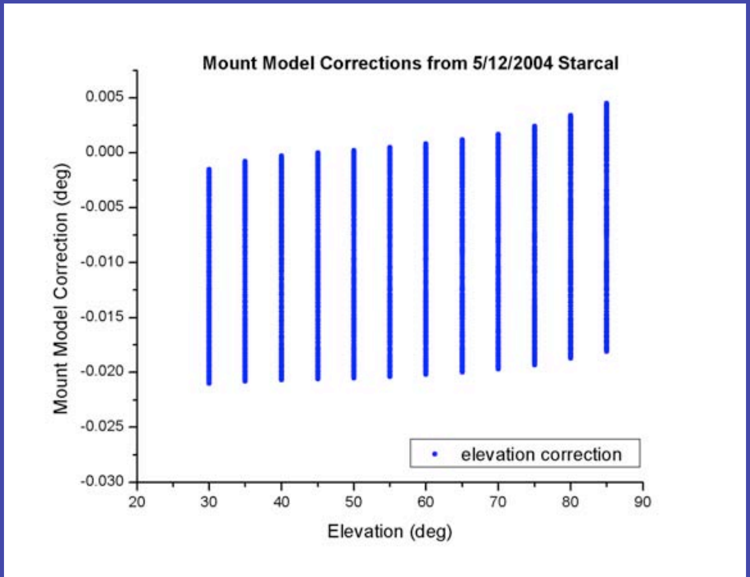
• CCD camera (EDC 1000m) image is 242 x 242 pixels over ~ 2 arc minute field of view. Five images are summed (and background removed) to allow processing software to register images down to 5th magnitude. Software determines image centroid and calculates pointing biases from centroid location.




Mount Model Corrections from 5/12/2004 Starcal
azimuth correction
el=85deg
el=80deg
el=75deg
Mount Model Correction (deg)
0.0
0.1
0.2
0.3
0.4
0.5
0
50
100
150
200
250
300
Azimuth (deg)

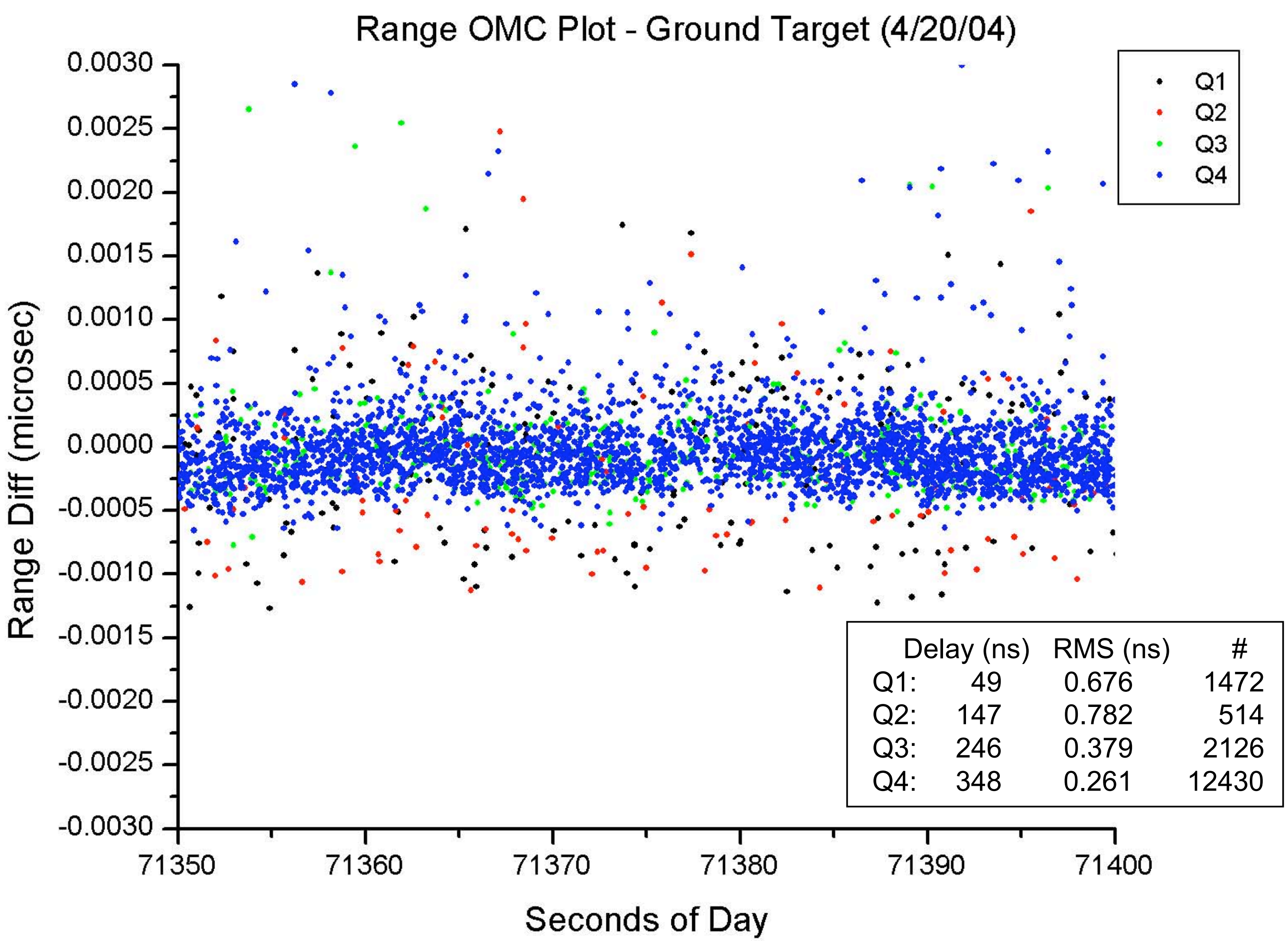

Mount Model Corrections from 5/12/2004 Starcal
elevation correction
Mount Model Correction (deg)
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
0
50
100
150
200
250
300
Azimuth (deg)


Mount Model Corrections from 5/12/2004 Starcal
azimuth correction
Mount Model Correction (deg)
0.6
0.4
0.2
0.0
20
30
40
50
60
70
80
90
Elevation (deg)


Mount Model Corrections from 5/12/2004 Starcal
elevation correction
Mount Model Correction (deg)
0.005
0.000
-0.005
-0.010
-0.015
-0.020
-0.025
-0.030
20
30
40
50
60
70
80
90
Elevation (deg)

Ground Calibrations

- System Delay measurements are taken for all four quadrants.
- Successful real-time signal processing of ground target range data is now routine.
- Automated angular search and acquire works well on ground target (uses signal processing to determine when target has been acquired).
- RMS is high. May be reduced by upgrade of discriminator to a constant fraction Canberra CFD no. 454.
- High signal return rate causes higher noise rate (beyond signal): still being investigated.
- Our next step is to use the quadrant information to optimize the pointing.


Range OMC Plot - Ground Target (4/20/04)
Range Diff (microsec)
Seconds of Day
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
-0.0005
-0.0010
-0.0015
-0.0020
-0.0025
-0.0030
71350
71360
71370
71380
71390
71400
Q1
Q2
Q3
Q4
Delay (ns) RMS (ns) #
Q1: 49 0.676 1472
Q2: 147 0.782 514
Q3: 246 0.379 2126
Q4: 348 0.261 12430

Visual Satellite Tracks

• Initial testing of system pointing (Fall 2003 and early 2004) was done using sunlit AJISAI and TOPEX passes.

• Images were captured using the star CCD camera.

• Telescope is currently pointed ahead of satellite - so image should move in the CCD field of view as the difference between the point-ahead of the telescope and the point-behind of the sunlight from the satellite.

• Complicating the image motion is the Coude path rotation.

• Conclusion of tests was that system open-loop pointing was good.

• These tests are also good for checking our calculation of point-ahead minus point-behind.

Point-Ahead Equations

- Telescope points along R_B, Laser beam must point along R_A :

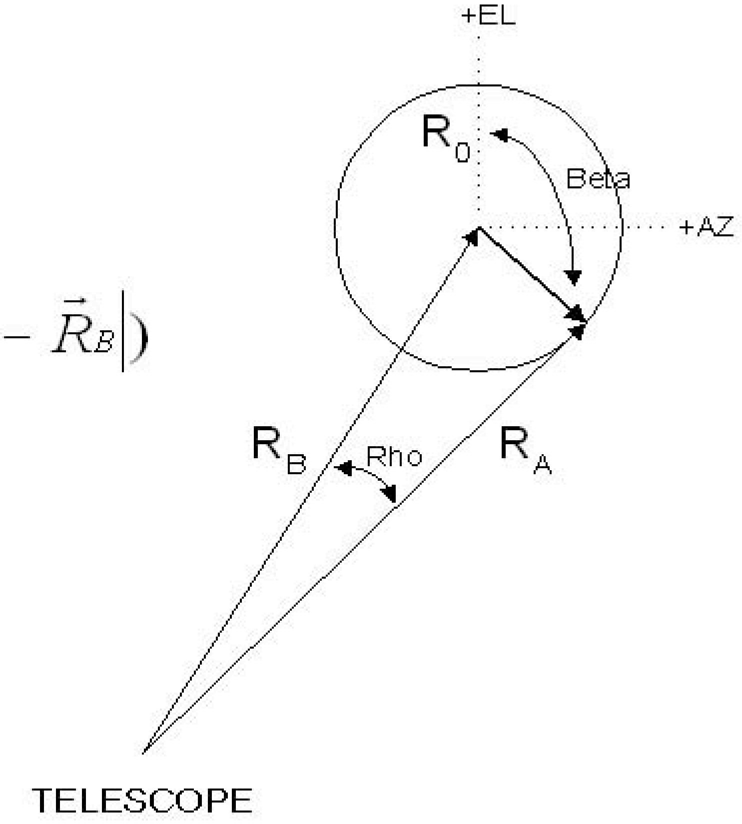
$$\cos(\rho) = \vec{R}_A \bullet \vec{R}_B \,/\, \left|\vec{R}_A\right| \cdot \left|\vec{R}_B\right|$$

$$\cos(\beta) = \vec{R}_0 \bullet (\vec{R}_A - \vec{R}_B) \,/\, \left(\left|\vec{R}_0\right| \bullet \left|\vec{R}_A - \vec{R}_B\right|\right)$$

which equivalently is:

$$\rho = \sqrt{(\Delta Az)^2 \cdot \cos(El)^2 + (\Delta El)^2}$$

$$\beta = \tan^{-1}(\Delta Az \cdot \cos(El) \,/\, \Delta El)$$



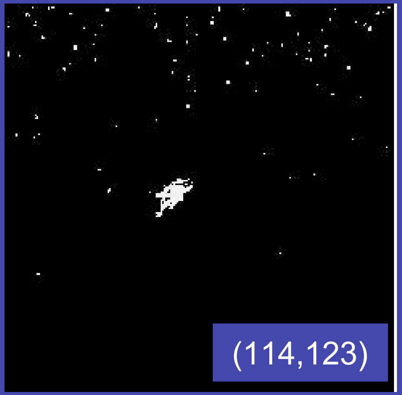
where:

ρ = Magnitude Angle (0 - 11 arcsec).

β = Orientation Angle (0-360 deg).

ΔAz, ΔEl = difference between point ahead and behind command angles.

Visual AJSIAI images: 3/12/2004 (GMT 072/23:40)

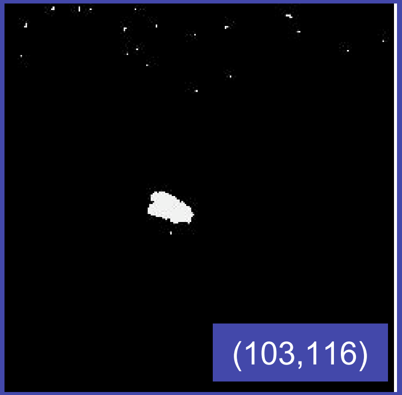


23:49:06 EL= 37°

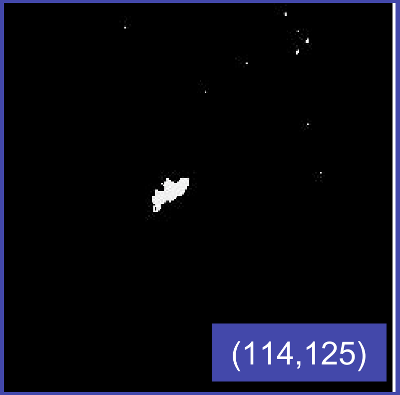
Images intensify, rotate and move away from FOV center as elevation increases.

FOV center is (120,120).

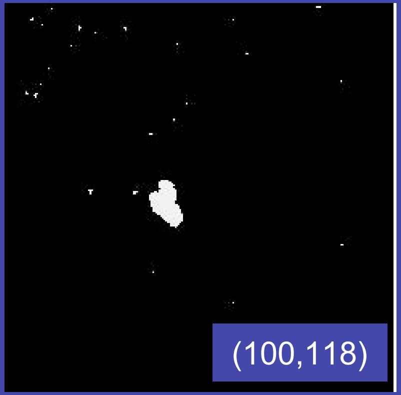
Centroid location is shown on each image.



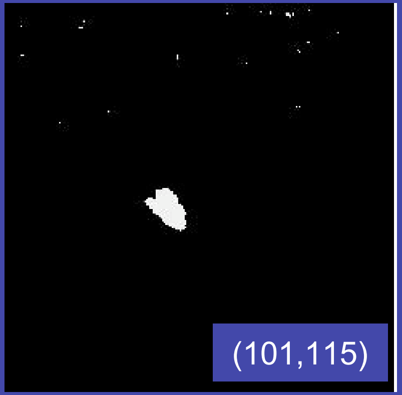
23:52:58 EL= 75°



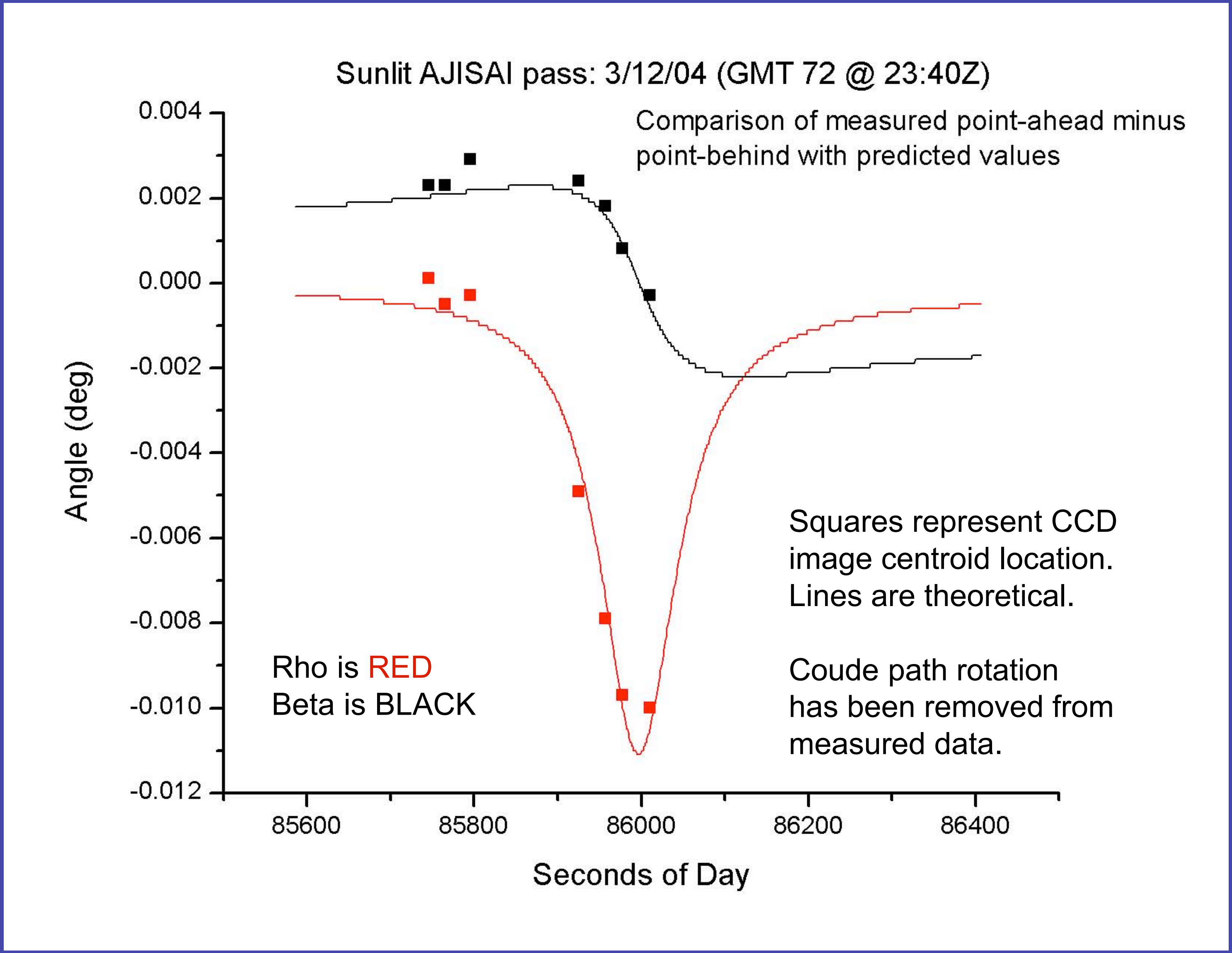
23:49:26 EL= 40°



23:52:06 EL= 68°



23:52:26 EL= 73°


Sunlit AJISAI pass: 3/12/04 (GMT 72 @ 23:40Z)
Comparison of measured point-ahead minus point-behind with predicted values
Squares represent CCD image centroid location. Lines are theoretical.
Coude path rotation has been removed from measured data.
Rho is RED
Beta is BLACK
Angle (deg)
0.004
0.002
0.000
-0.002
-0.004
-0.006
-0.008
-0.010
-0.012
85600
85800
86000
86200
86400
Seconds of Day

Satellite Tracking

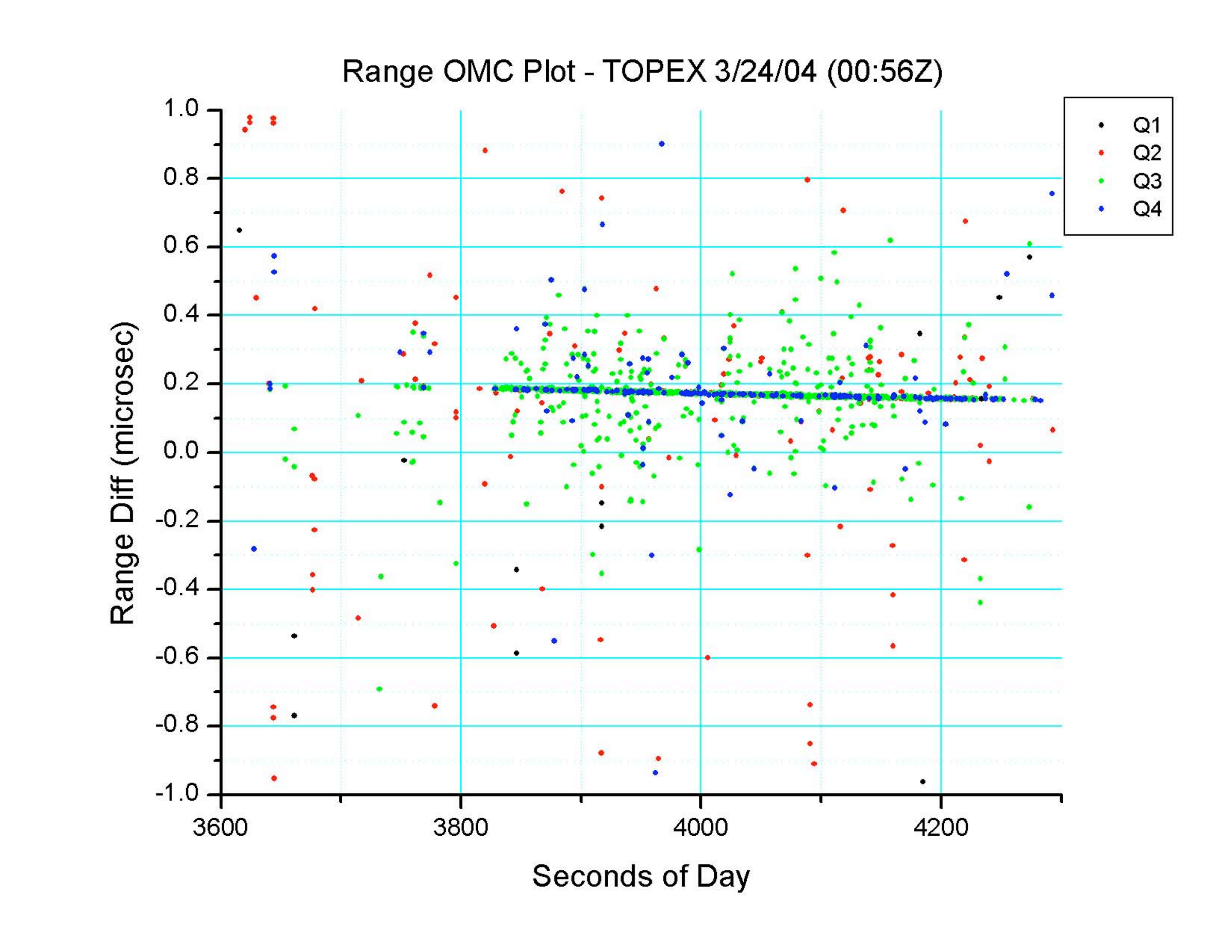
- We have tracked portions from ~ dozen satellite passes – all LEO with relatively high lidar cross-sections, and all under operator control.

- Final laser (300 microJoule output) is ~ 1 year behind. We are currently operating with a laser whose output energy is ~60 microJoules. Return signal strength is low even with the 10 arcsecond beam divergence.

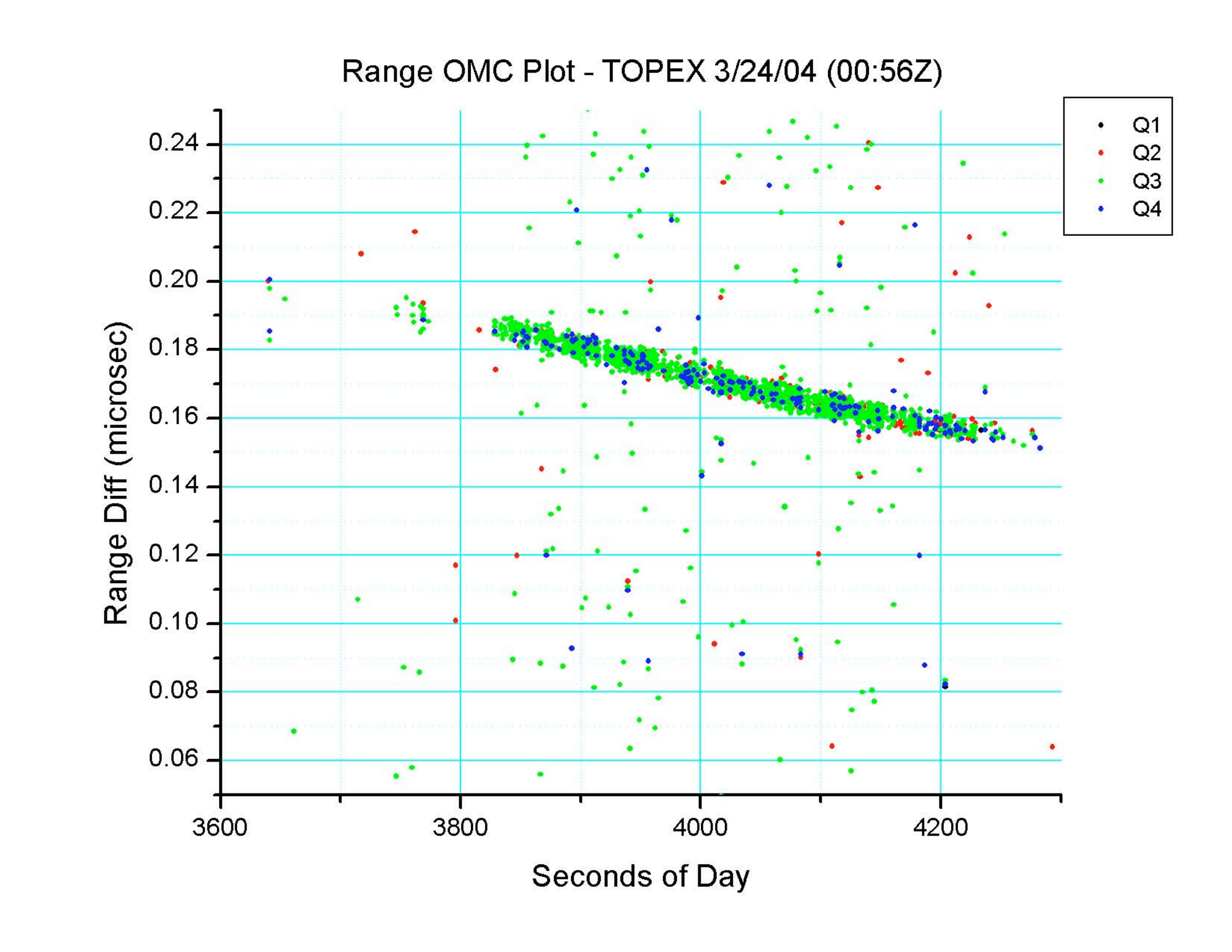
- Open-loop pointing of predictions is extremely good. Predictions are in a form similar to that proposed by the Prediction Format Study Group.

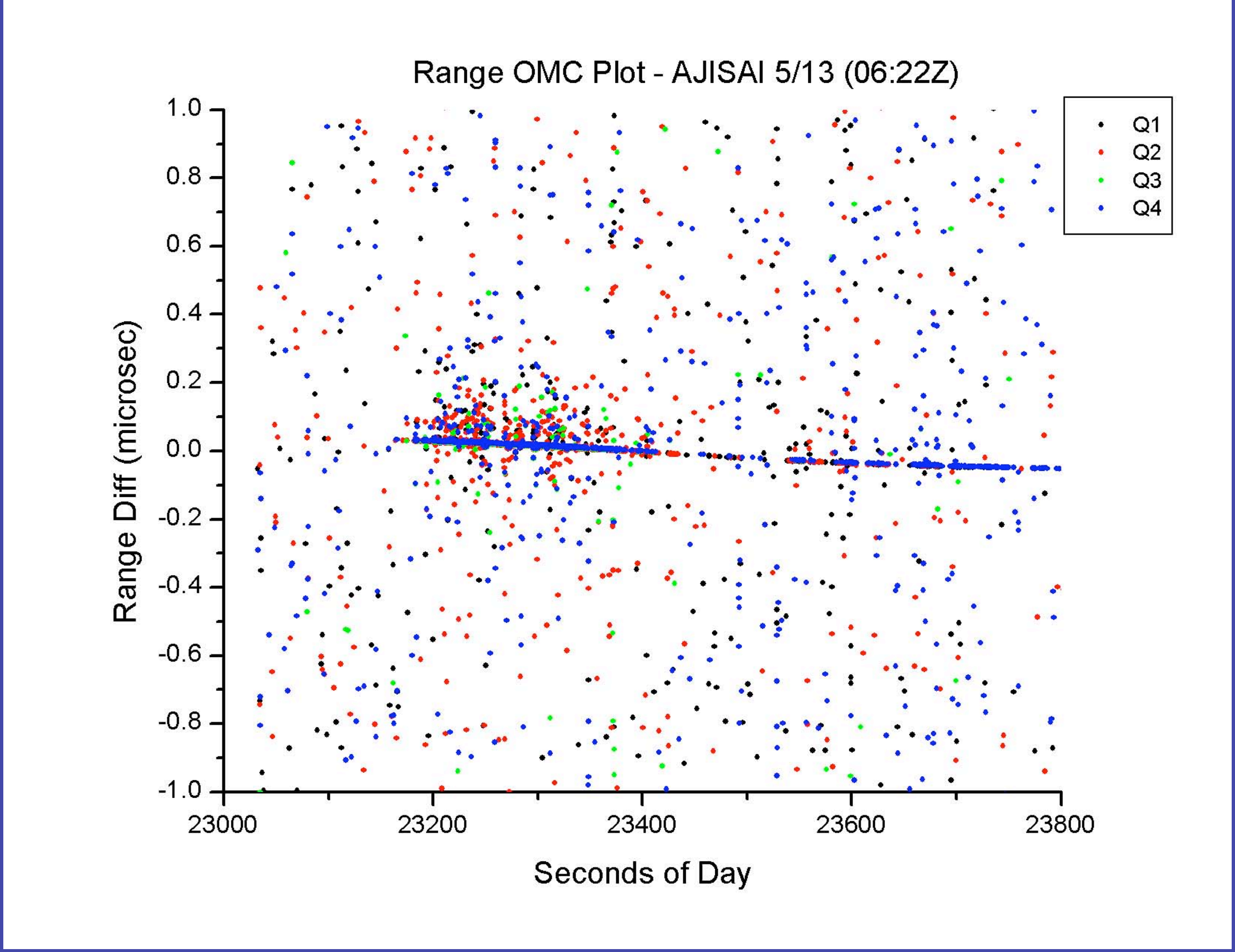
- Signal processing works on satellite tracks when return rate is high enough.

- Telescope is currently pointed ahead of satellite (no Risley Prism point-ahead has yet been implemented). Detector is opened to 40 arcseconds.

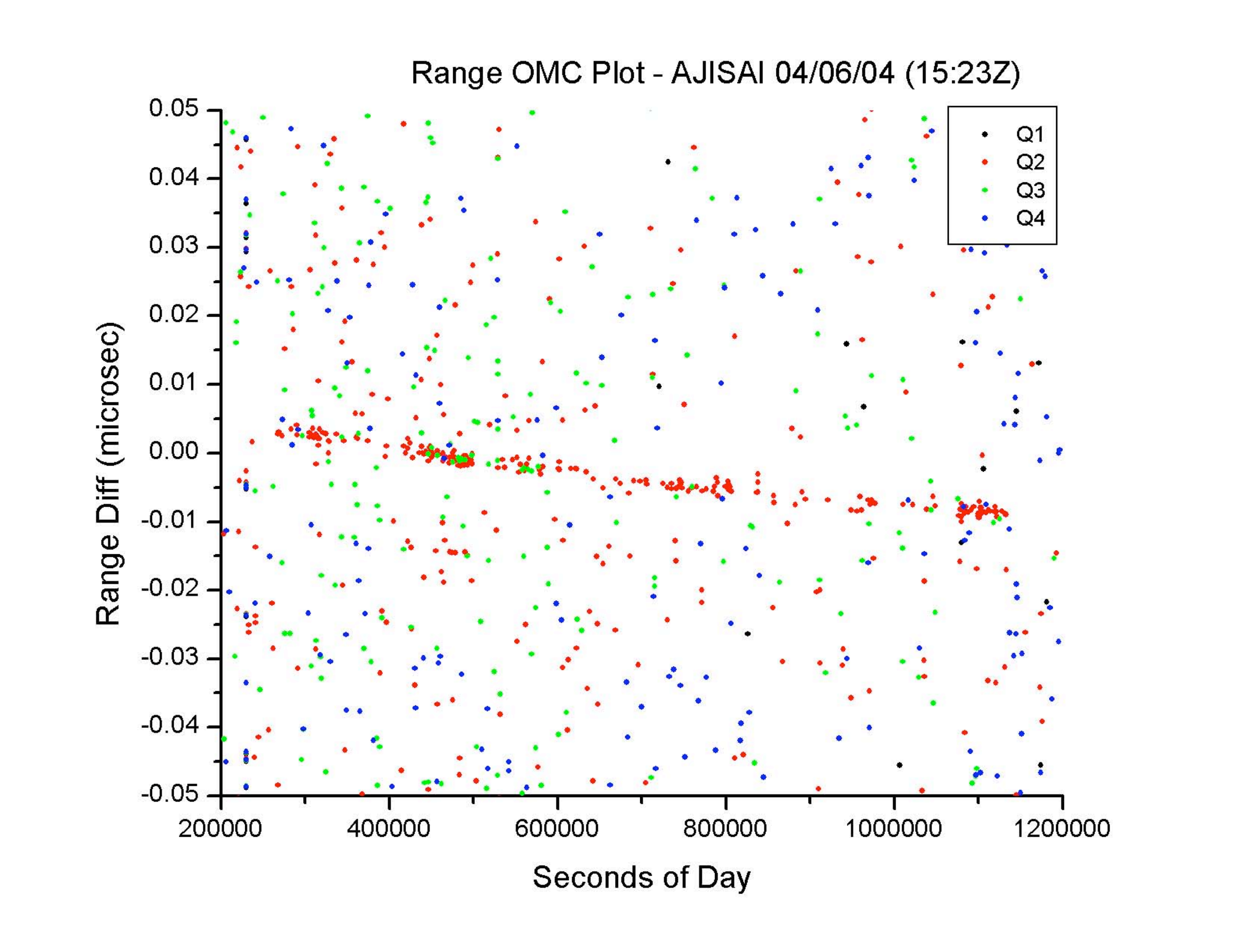

Range OMC Plot - TOPEX 3/24/04 (00:56Z)
Range Diff (microsec)
Seconds of Day
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
3600
3800
4000
4200
Q1
Q2
Q3
Q4

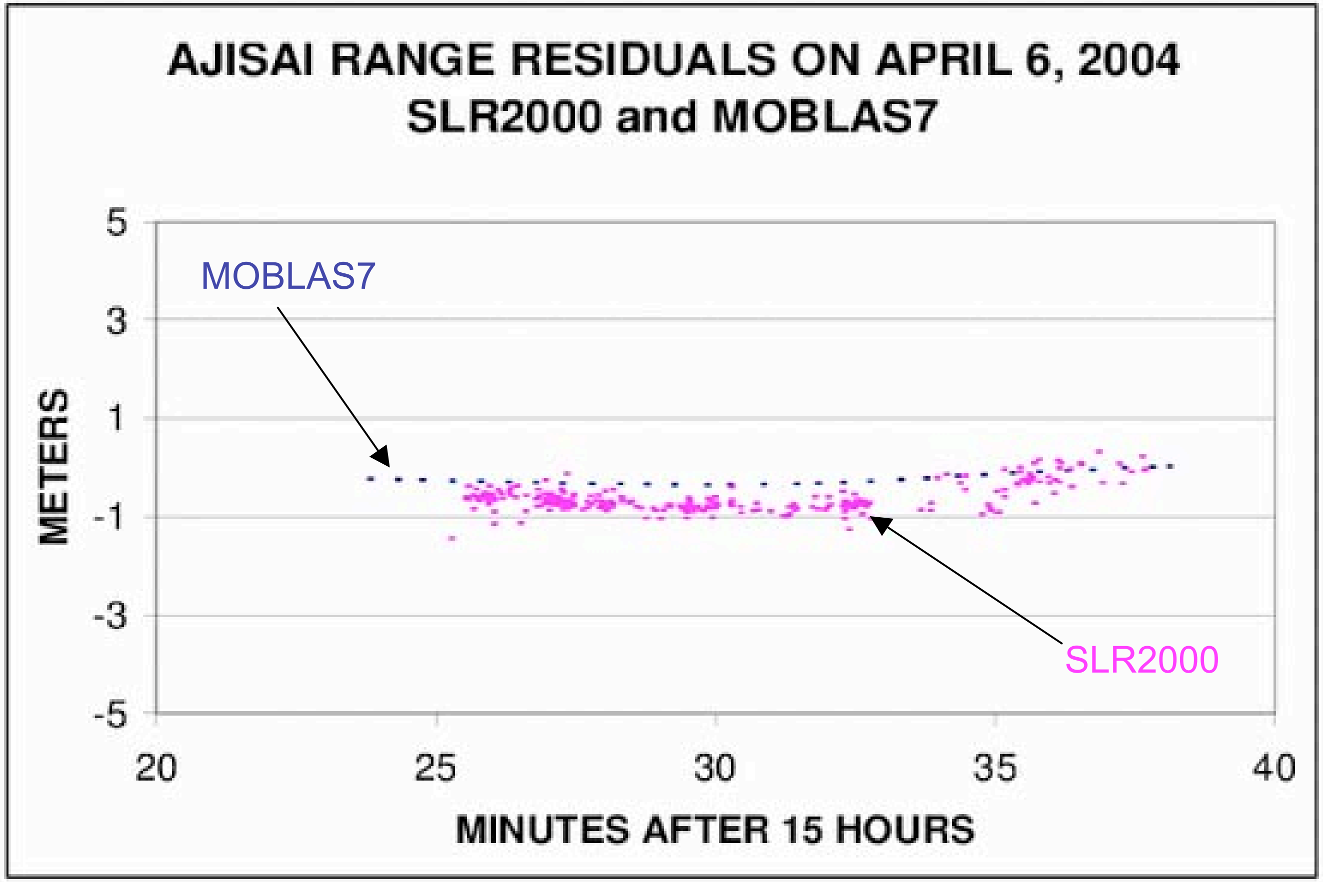
Zoom into previous plot




Range OMC Plot - AJISAI 5/13 (06:22Z)
Range Diff (microsec)
Seconds of Day
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
23000
23200
23400
23600
23800
Q1
Q2
Q3
Q4

Daylight pass collocated with MOBLAS-7




AJISAI RANGE RESIDUALS ON APRIL 6, 2004
SLR2000 and MOBLAS7
METERS
5
3
1
-1
-3
-5
20
25
30
35
40
MINUTES AFTER 15 HOURS
MOBLAS7
SLR2000

Where do we go from here?

- Laser must be completed by Q-Peak or upgraded in-house.
- Discriminator to be upgraded constant fraction Canberra model no. 454.
- Receiver optics replaced will include: appropriate daylight / twilight bandpass filters, adjustable iris field of view stop, and more angular sensitive focusing elements to optimize quadrant detector closed loop operation.
- Range data problems (high noise in high signal environment) must be resolved.
- Transmitter Point-Ahead will be implemented. The telescope will be pointed behind (so receiver can be centered on returns) and the laser pointing will be offset using Risley Prisms to steer the beam ahead to where the satellite will be when the light reaches it.
- Once the Point-Ahead has been implemented, closed-loop tracking using the quadrant detector can be completed.

GOAL: completion of these tasks this year

Summary

- The SLR2000 prototype is now tracking satellites but there is a lot to do before the system is considered operational (even in a semi-automated state).

- We expect to have a system that can perform semi-automated tracking of LAGEOS and ETALON within the next year.

- Real-time determination of signal processing parameters and selection of satellite tracks based upon the sky map should occur sometime in CY2005.

- There do not appear to be any insurmountable technical issues – we just need to work out the remaining problems.

- Funding is the real question at this point.