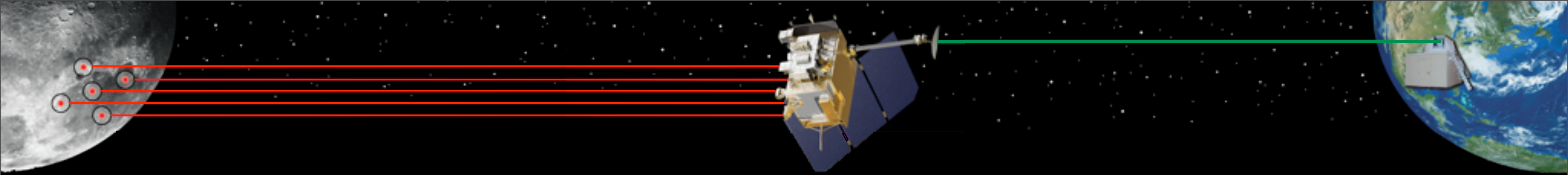


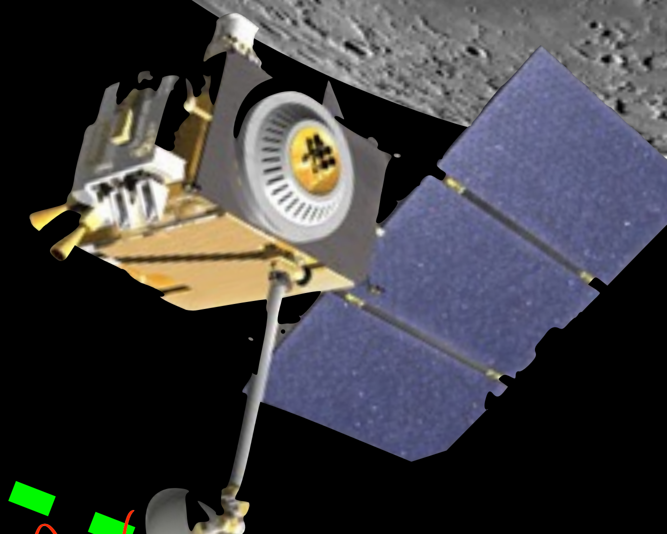
Laser Ranging Experiment on Lunar Reconnaissance Orbiter: Timing Determination and Orbit Constraints

D. Mao[1], E. Mazarico[2,4], M. Torrence[3], J. McGarry[4], X. Sun[4], G. Neumann[4], D. Rolands[4], D. Smith[2], M. Zuber[2], M. Barker[1], J. Golder[1], T. Zagwodzki[4], J. Cavanaugh[4]
[1]Sigma Space Corporation, [2]MIT, [3]SGT, [4]NASA/GSFC

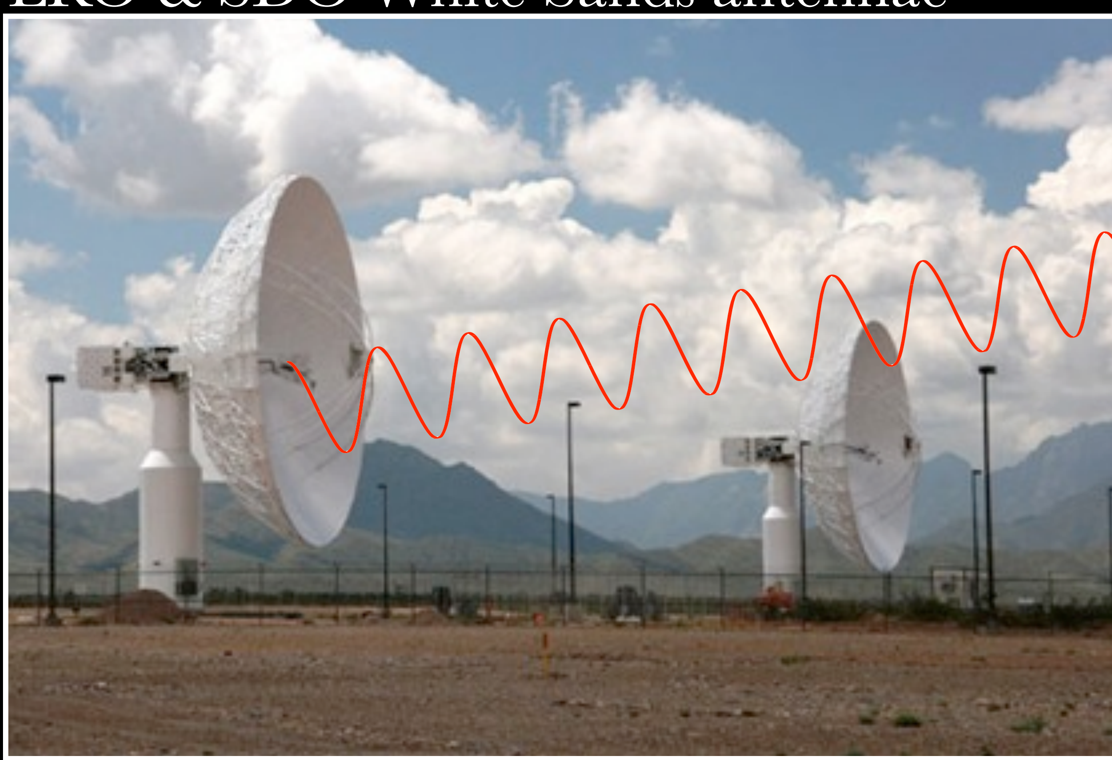
Laser Ranging Data

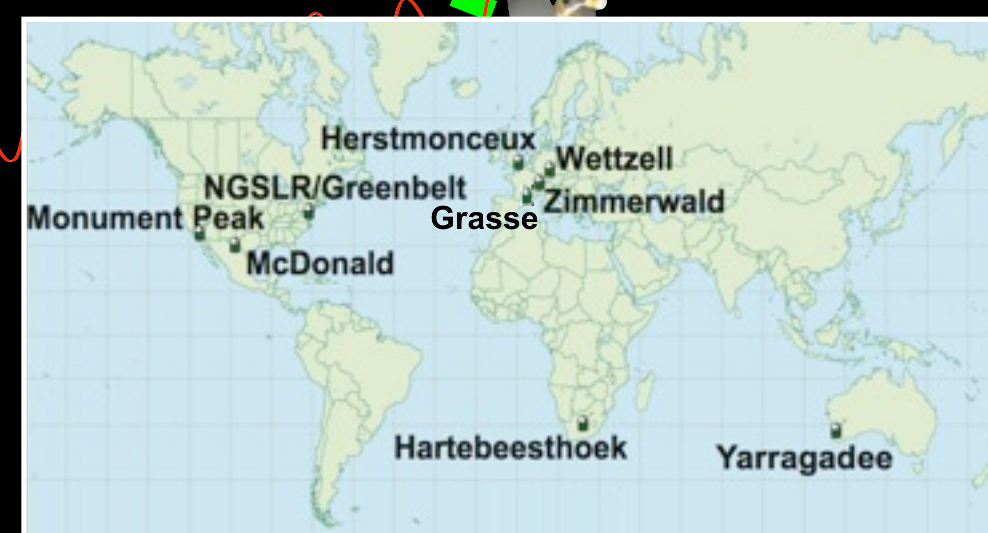
Greenbelt SLR station (NGSLR)

- 532-nm 28Hz laser
  - line-of-sight measurements
  - ~15cm precision
  - NGSLR + international stations



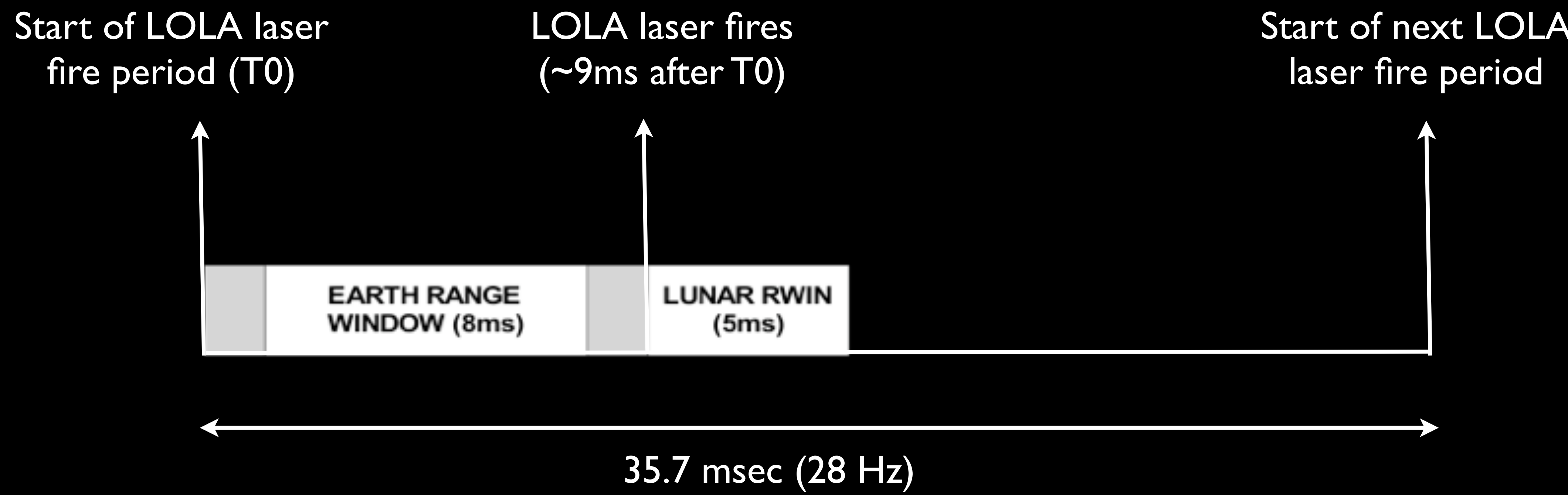
LRO & SDO White Sands antennae





over 1000 hours of LR tracking

One-way LR range determination



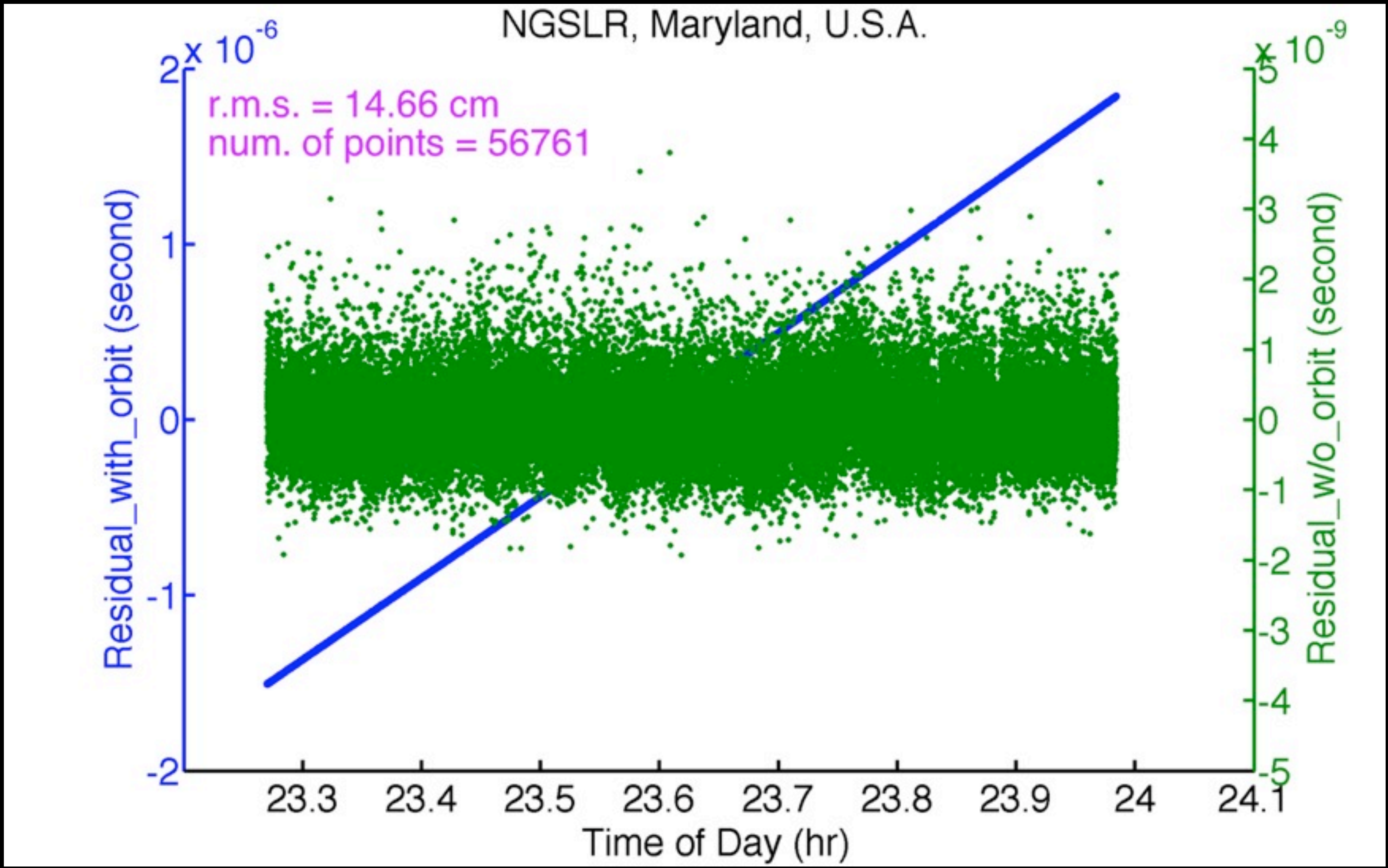
- Use predictions (CPFs) generated by GSFC Flight Dynamics Facility (FDF) with accuracy better than 1km

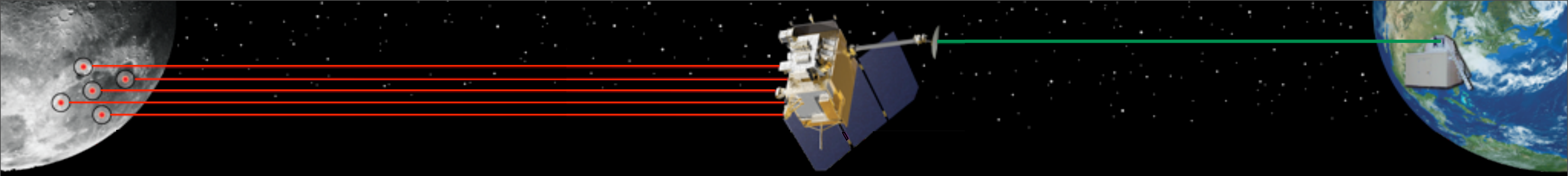
- Event arrival times recorder by LOLA

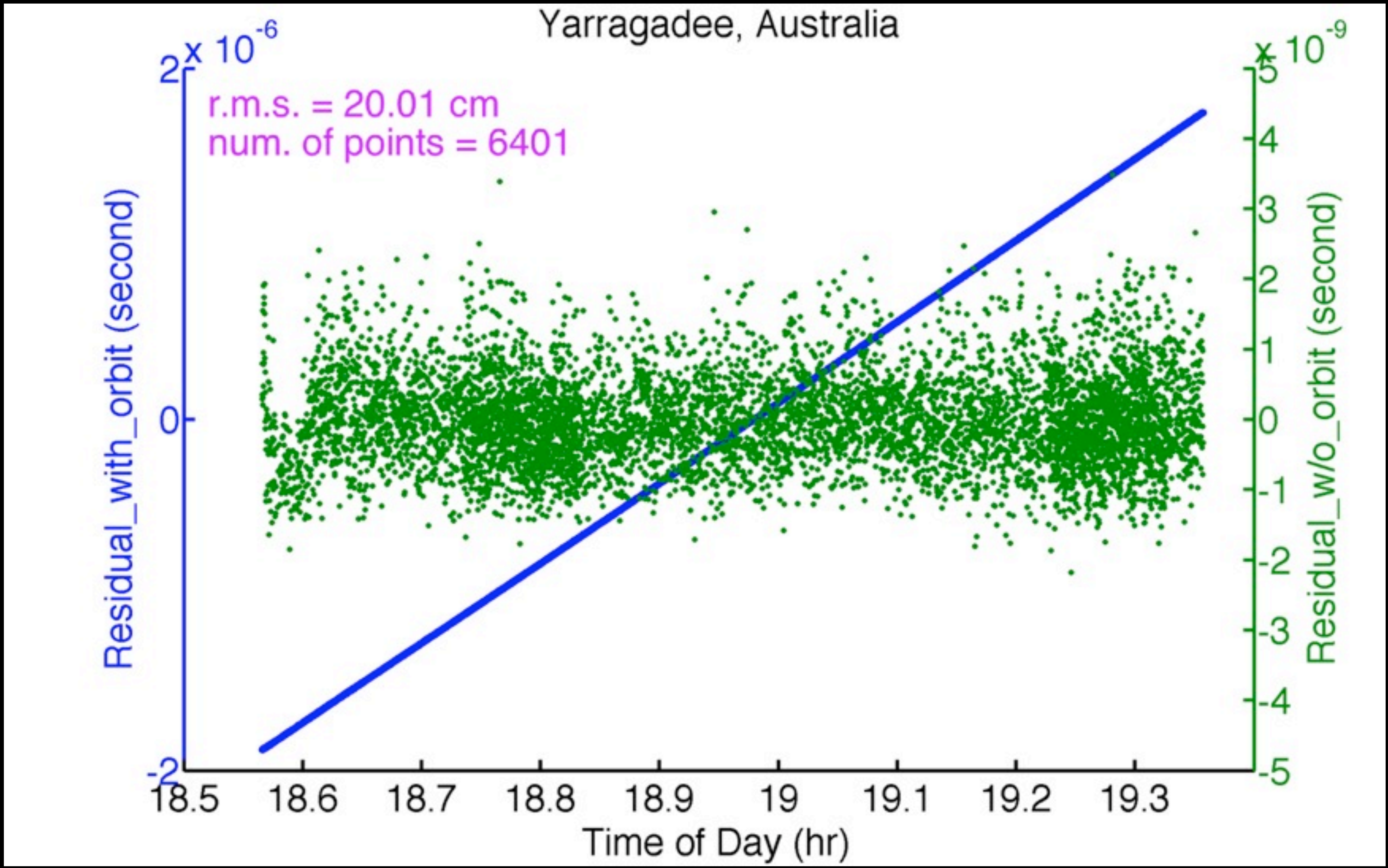
- Earth tracking stations fire time files are combined with LOLA “Earth window” receive times calculating time of flight not considering relativistic effects to match the fire and receive times

Tuesday, May 24, 2011

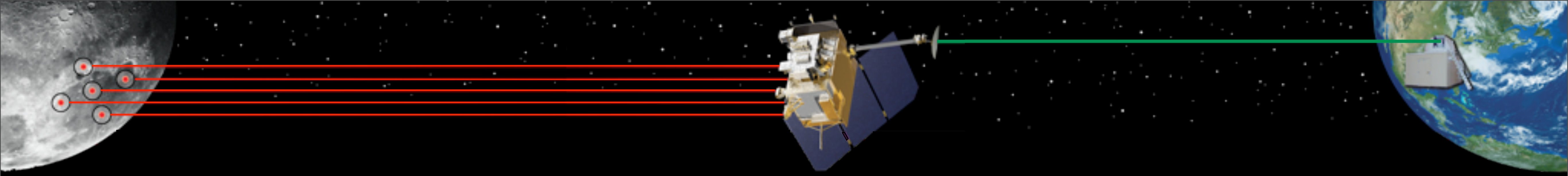
LR Stations: precision

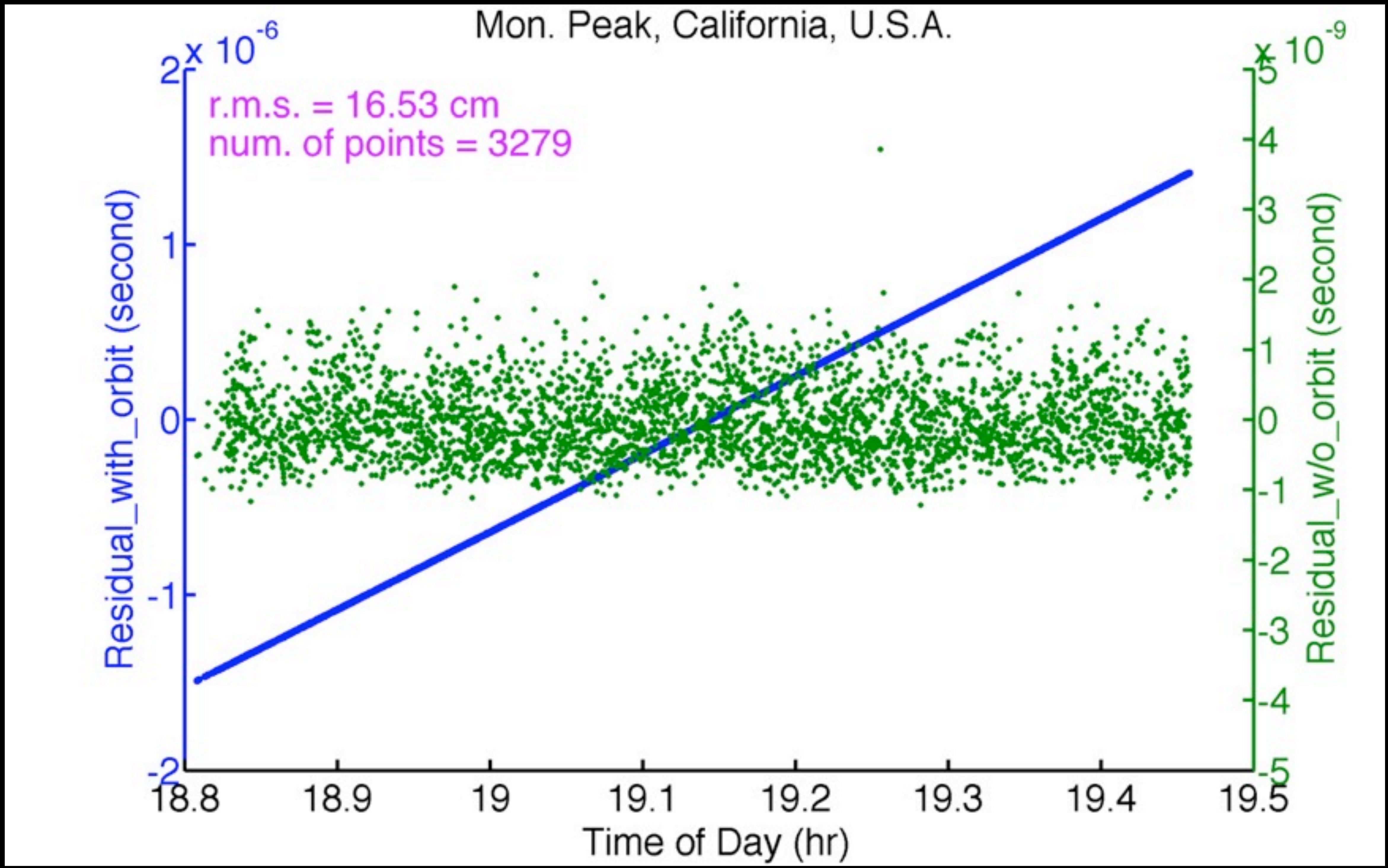


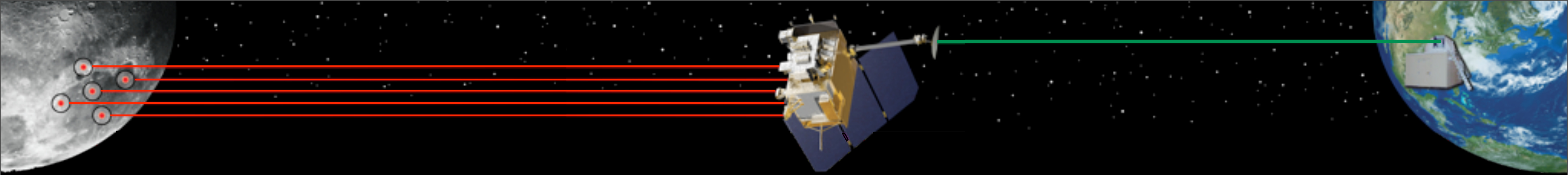


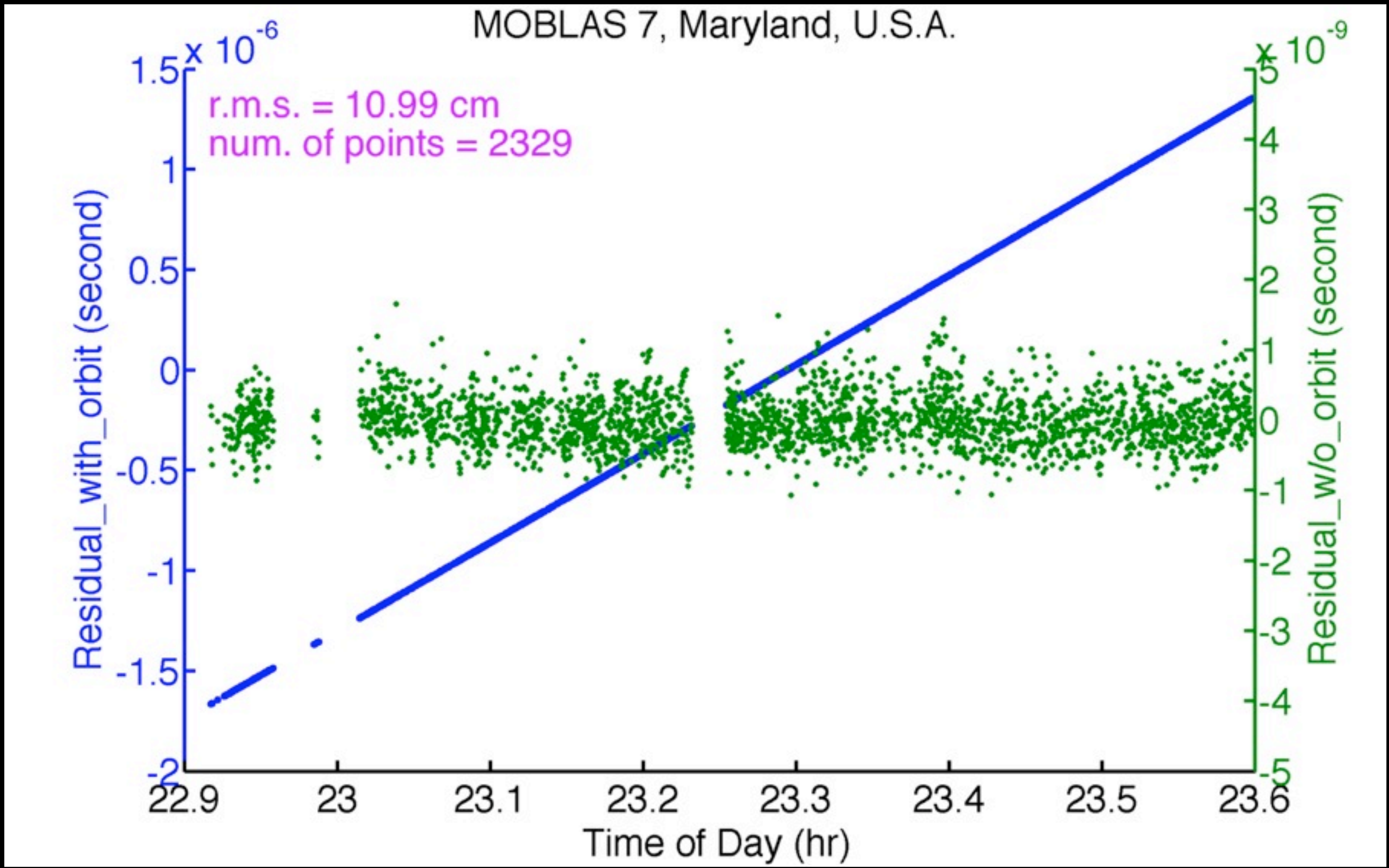


Yarragadee, Australia
x 10^-6
x 10^-9
r.m.s. = 20.01 cm
num. of points = 6401
Residual_with_orbit (second)
Residual_w/o_orbit (second)
2
0
-2
5
4
3
2
1
0
-1
-2
-3
-4
-5
18.5
18.6
18.7
18.8
18.9
19
19.1
19.2
19.3
Time of Day (hr)

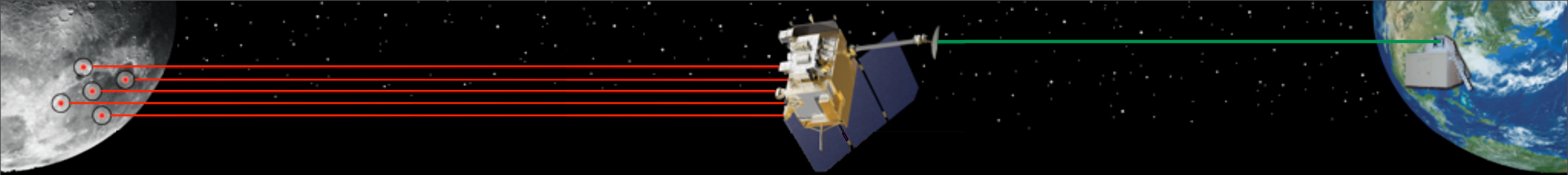


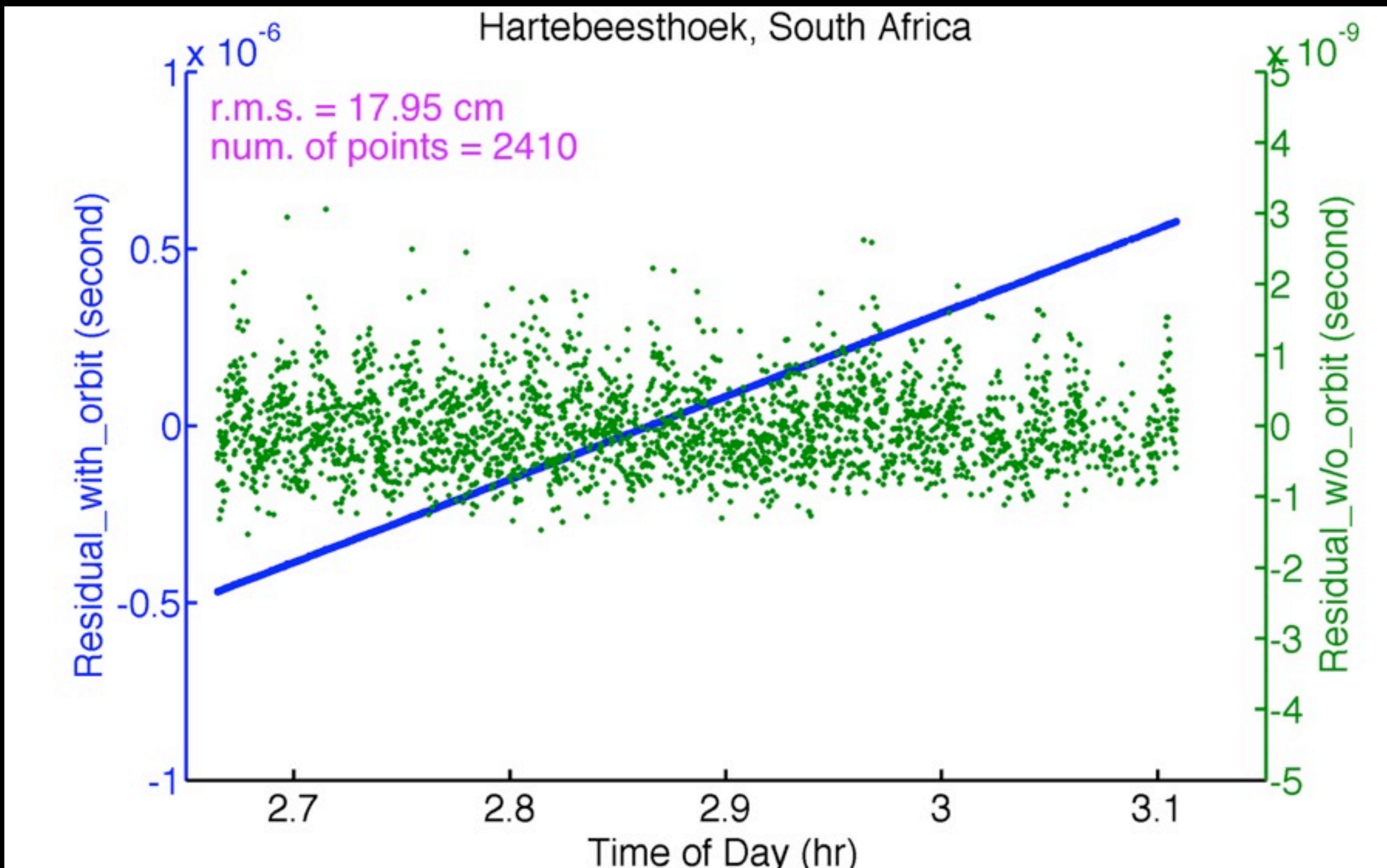

Mon. Peak, California, U.S.A.
r.m.s. = 16.53 cm
num. of points = 3279
x 10^-6
Residual_with_orbit (second)
2
1
0
-1
-2
x 10^-9
Residual_w/o_orbit (second)
5
4
3
2
1
0
-1
-2
-3
-4
-5
18.8
18.9
19
19.1
19.2
19.3
19.4
19.5
Time of Day (hr)

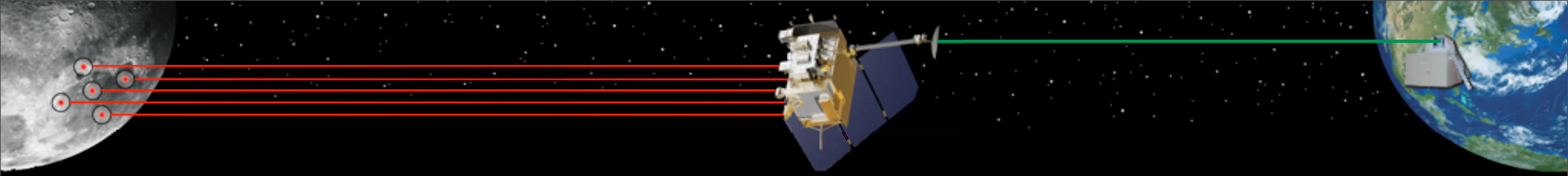


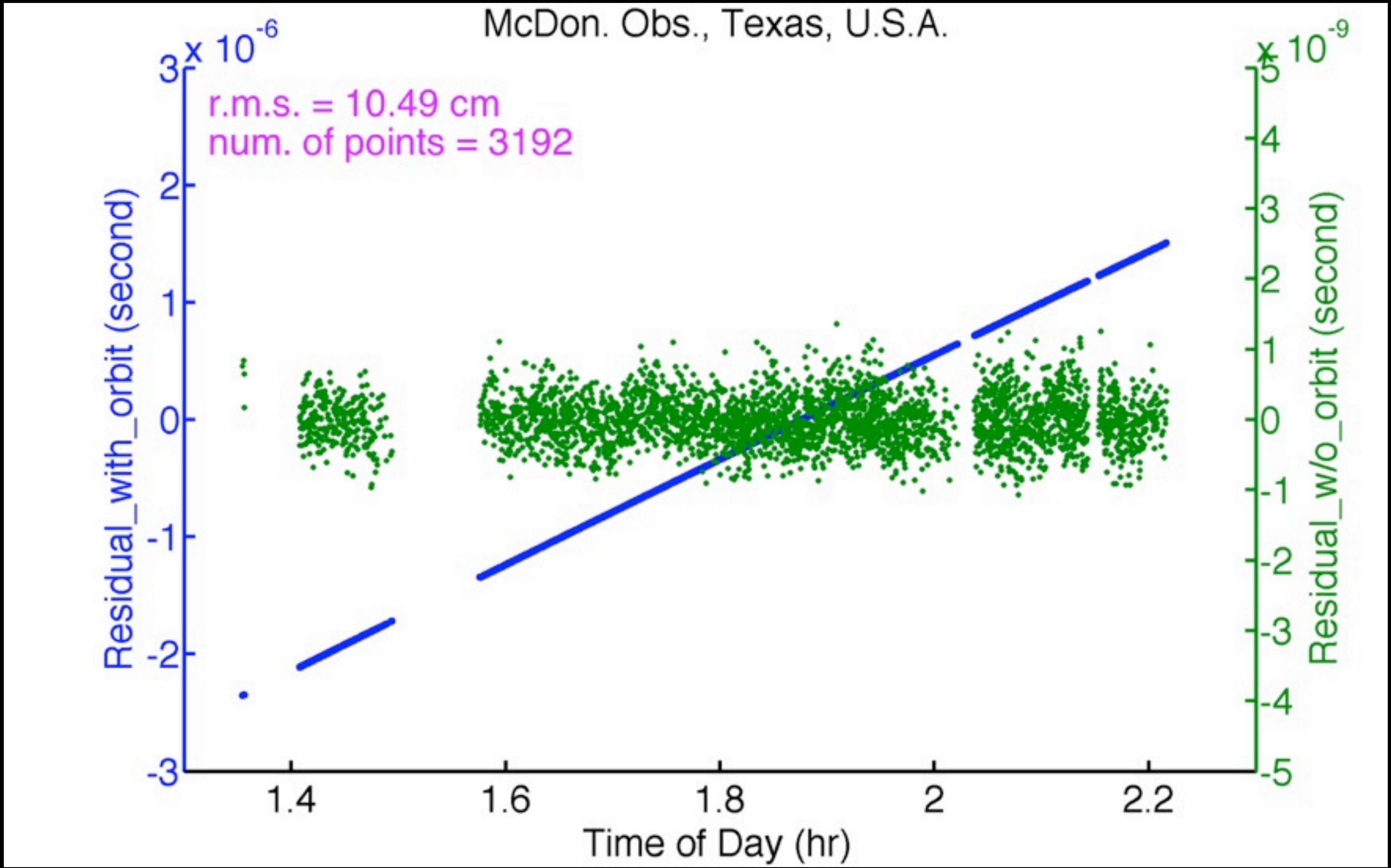


MOBLAS 7, Maryland, U.S.A.
x 10^-6
x 10^-9
r.m.s. = 10.99 cm
num. of points = 2329
Residual_with_orbit (second)
Residual_w/o_orbit (second)
Time of Day (hr)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
5
4
3
2
1
0
-1
-2
-3
-4
-5
22.9
23
23.1
23.2
23.3
23.4
23.5
23.6

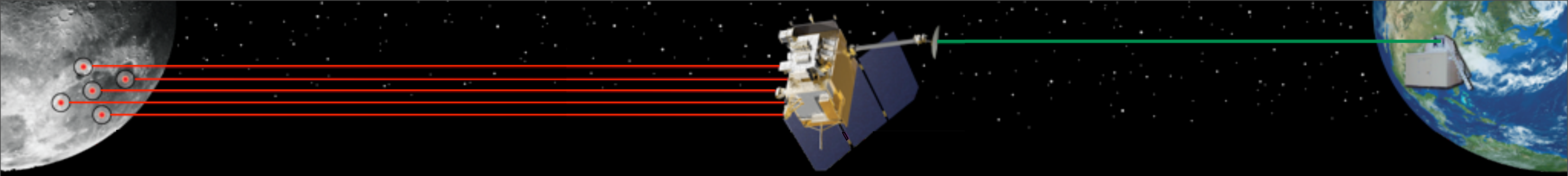


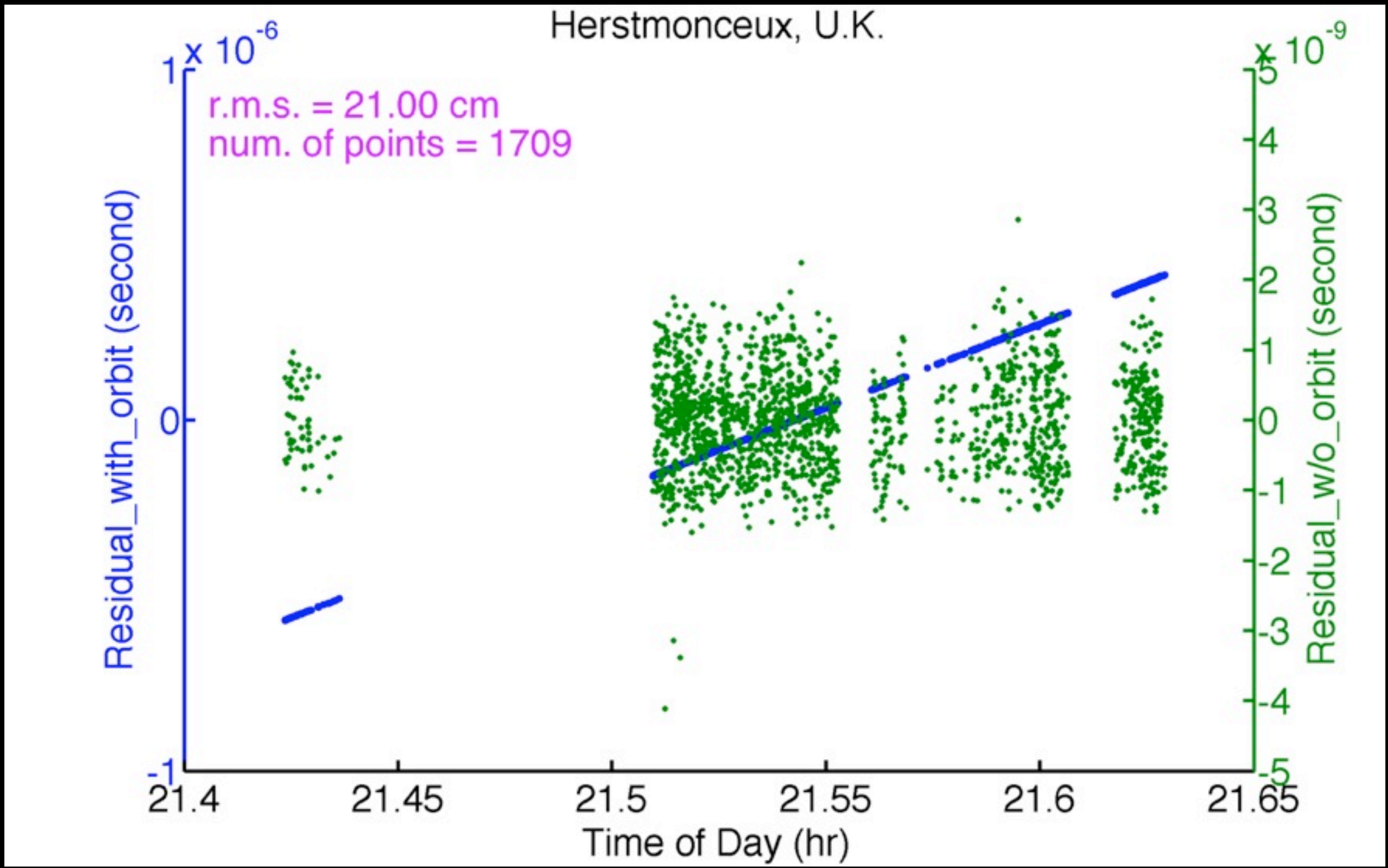

Hartebeesthoek, South Africa
x 10^-6
x 10^-9
r.m.s. = 17.95 cm
num. of points = 2410
Residual_with_orbit (second)
Residual_w/o_orbit (second)
Time of Day (hr)
1
0.5
0
-0.5
-1
5
4
3
2
1
0
-1
-2
-3
-4
-5
2.7
2.8
2.9
3
3.1



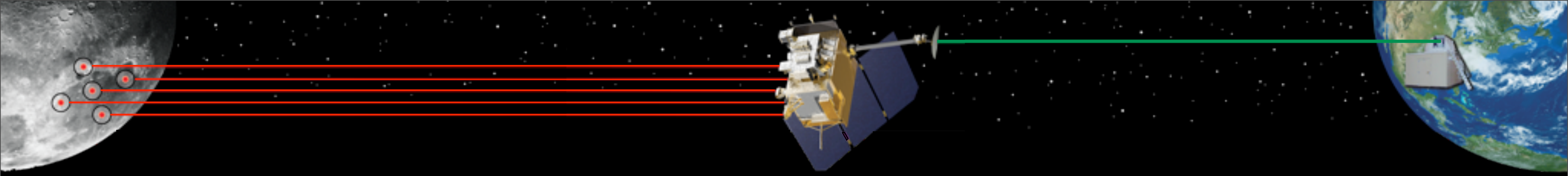


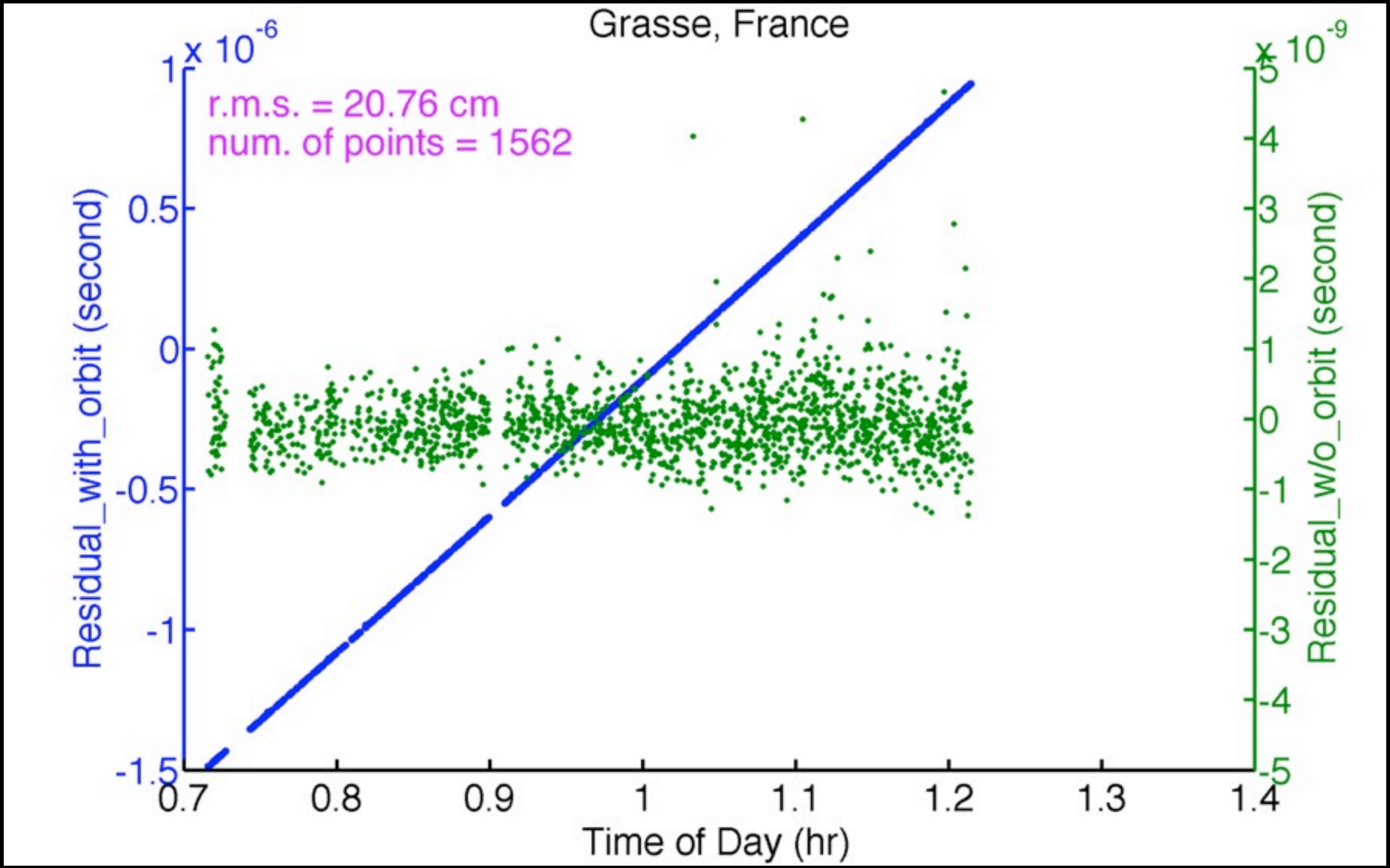
Tuesday, May 24, 2011



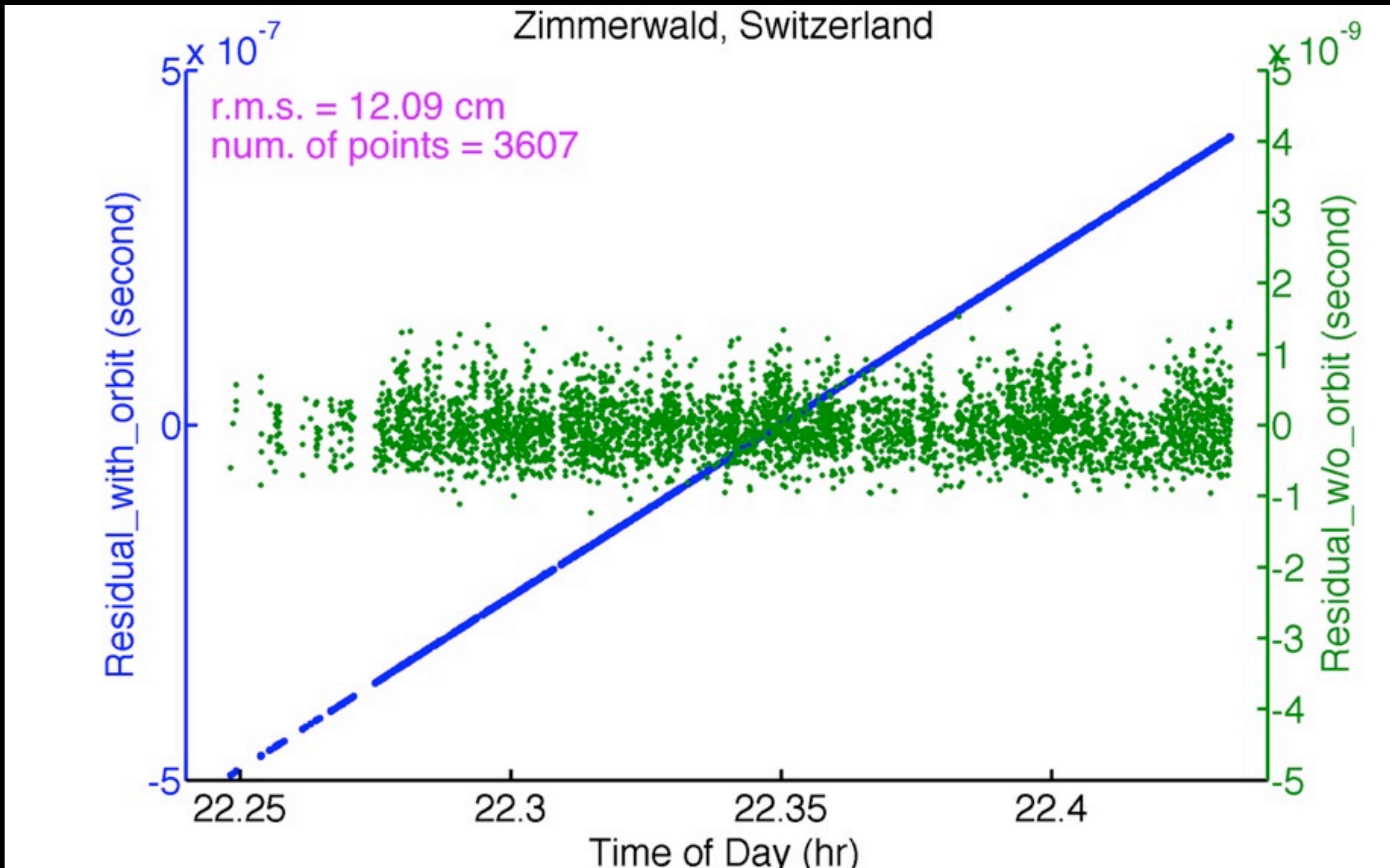


Tuesday, May 24, 2011

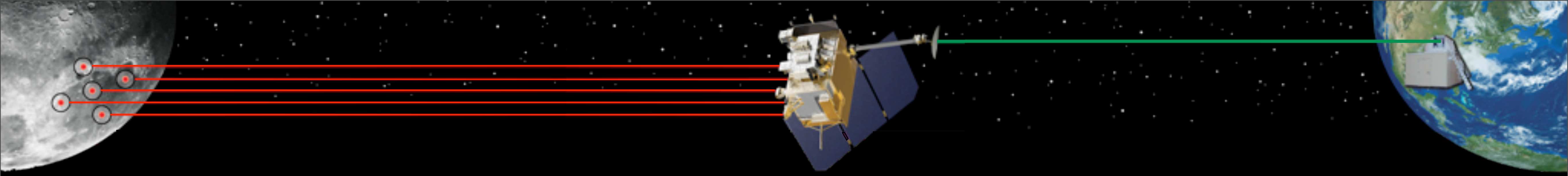


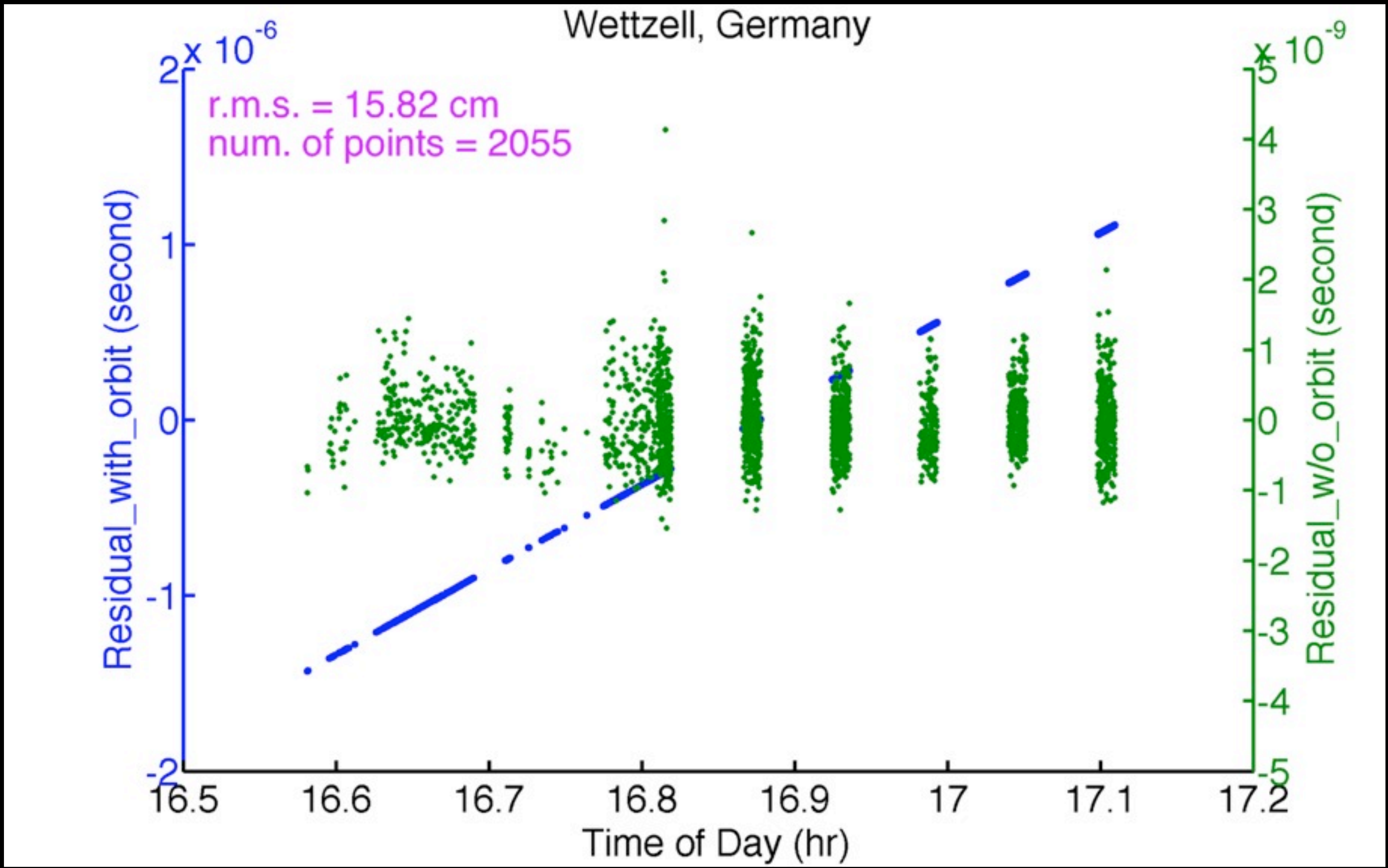


Grasse, France
x 10^-6
r.m.s. = 20.76 cm
num. of points = 1562
Residual_with_orbit (second)
1
0.5
0
-0.5
-1
-1.5
x 10^-9
5
4
3
2
1
0
-1
-2
-3
-4
-5
Residual_w/o_orbit (second)
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
Time of Day (hr)



Tuesday, May 24, 2011





Wettzell, Germany
x 10^-6
r.m.s. = 15.82 cm
num. of points = 2055
Residual_with_orbit (second)
Residual_w/o_orbit (second)
x 10^-9
2
1
0
-1
-2
5
4
3
2
1
0
-1
-2
-3
-4
-5
16.5
16.6
16.7
16.8
16.9
17
17.1
17.2
Time of Day (hr)

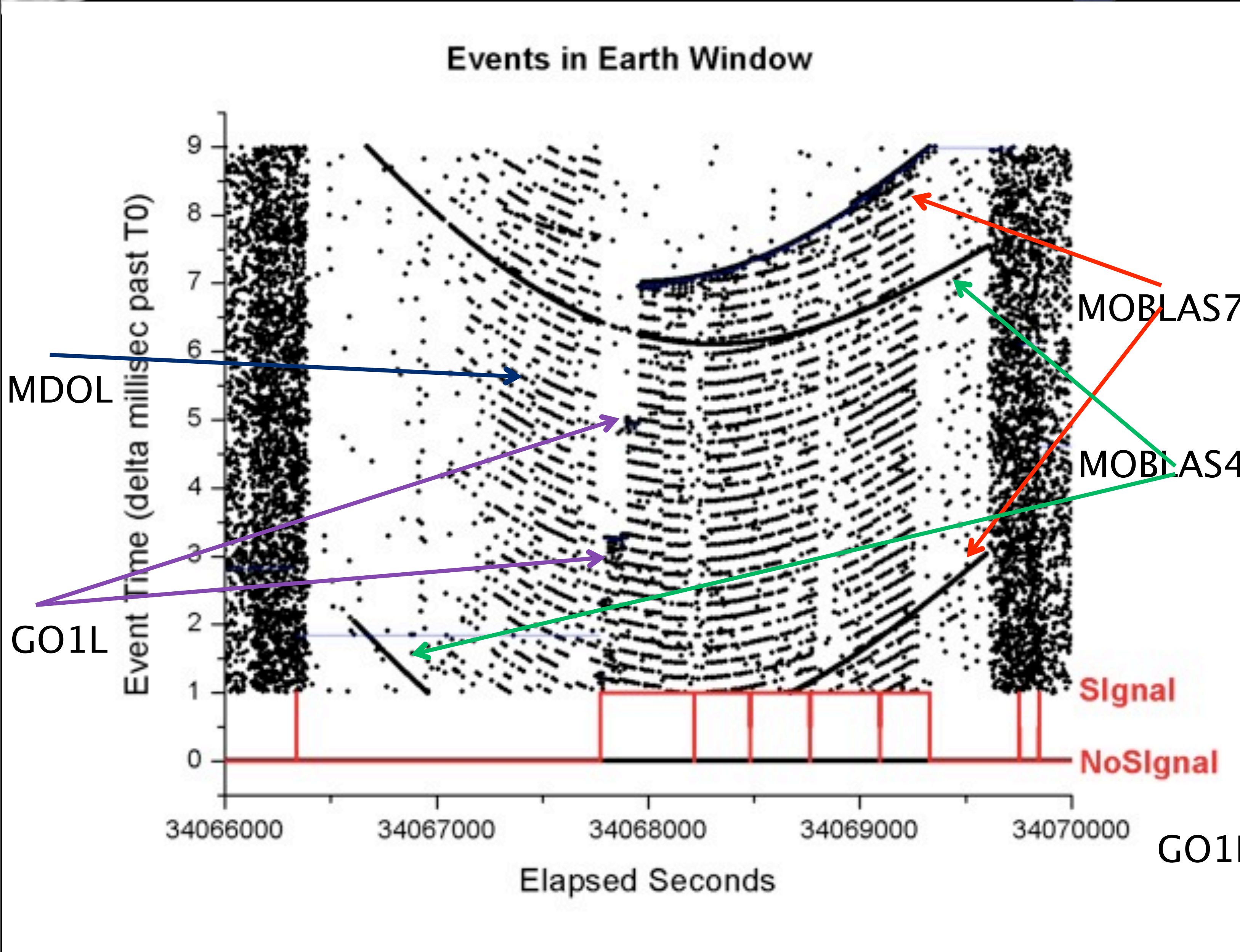
LRO clock recovery

- One-way range measurement: clocks at the ground station & LRO clock

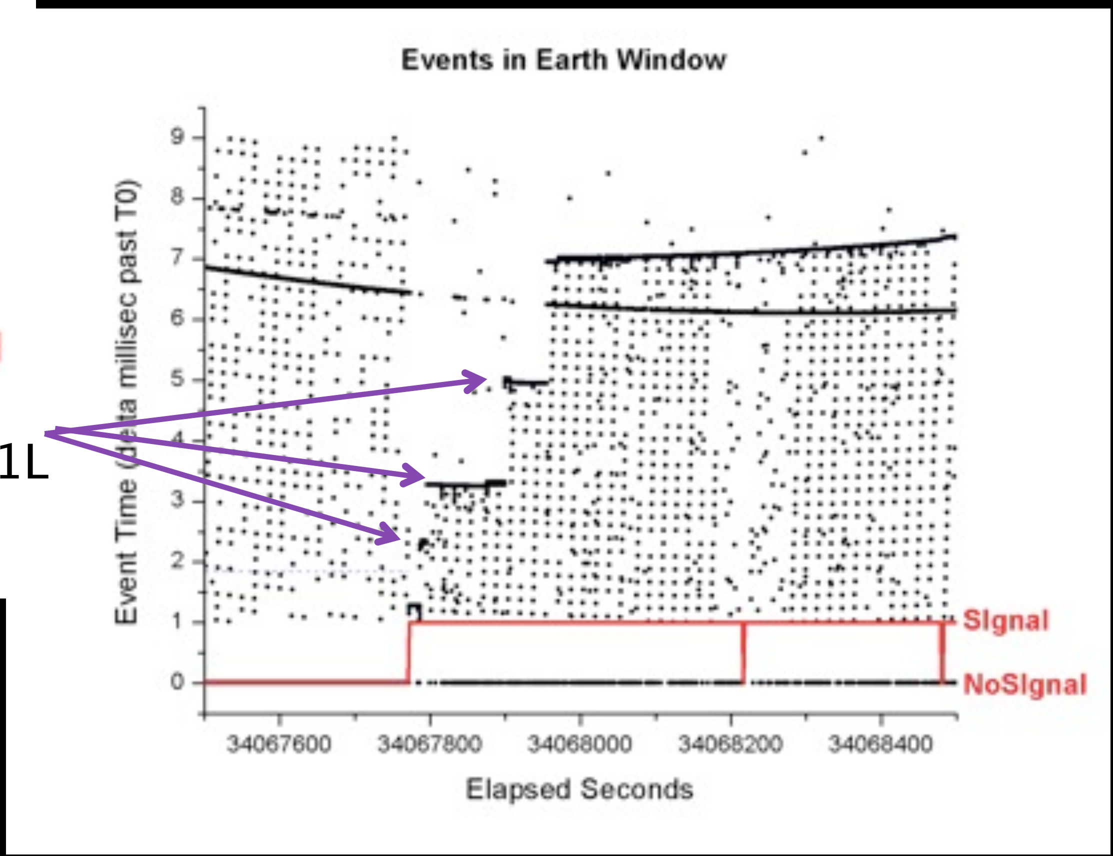
- LRO power off: extra offset between LRO clock time and UTC introduced

  - sun-safe mode power off: 02/23/2011 - 02/25/2011
    -> offset_LR = 0.850 s
    -> offset_LRO = 0.8508 s

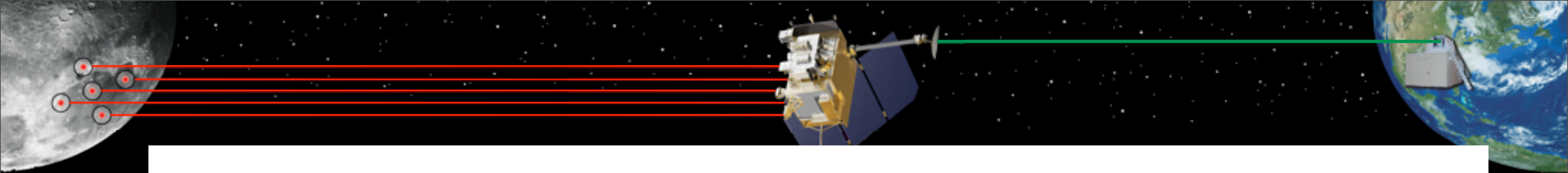
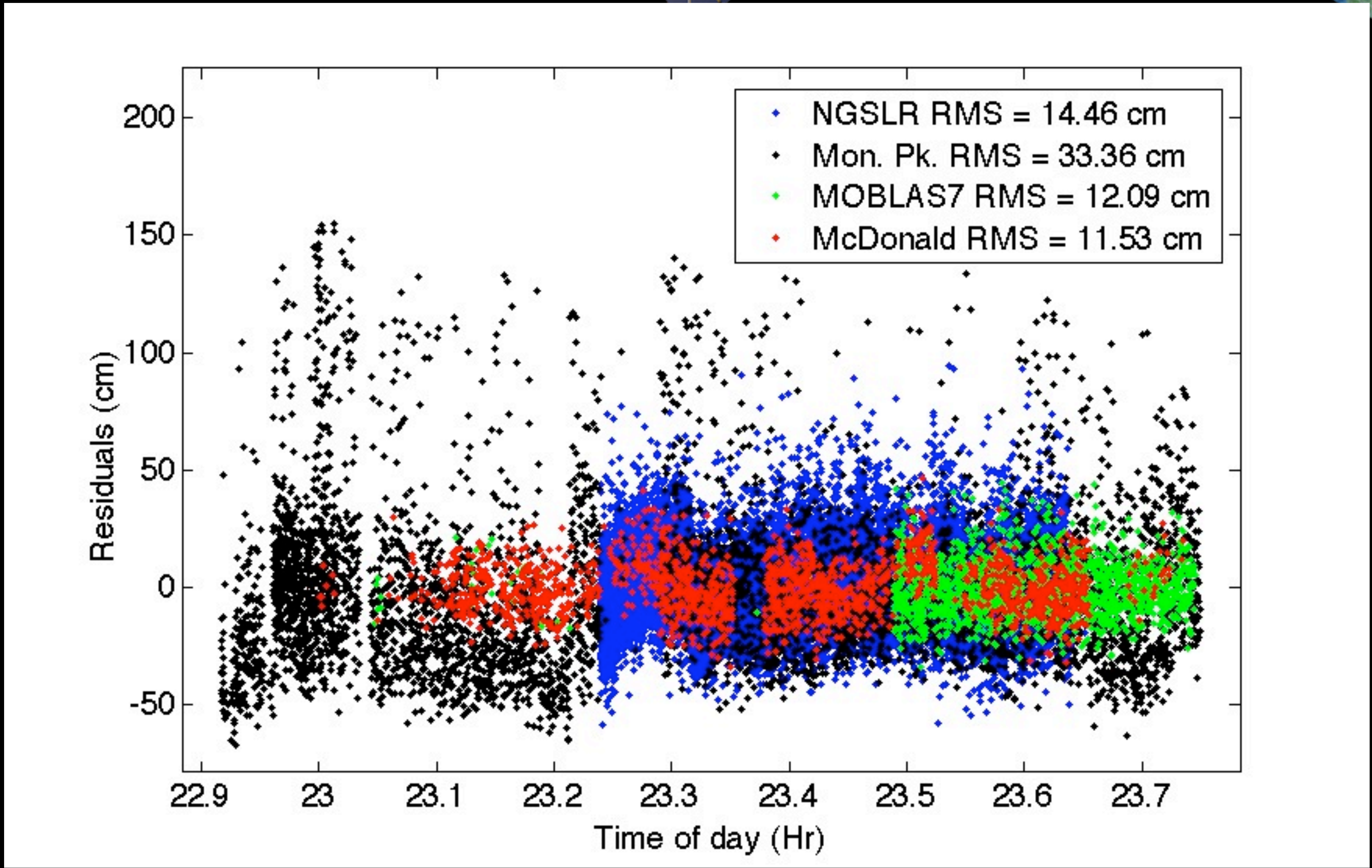
Simultaneous Ranging



First 4-way simultaneous ranging to LRO: March 11, 2011 at 22:50Z
Stations are: MONL, MDOL, GODL and GO1L

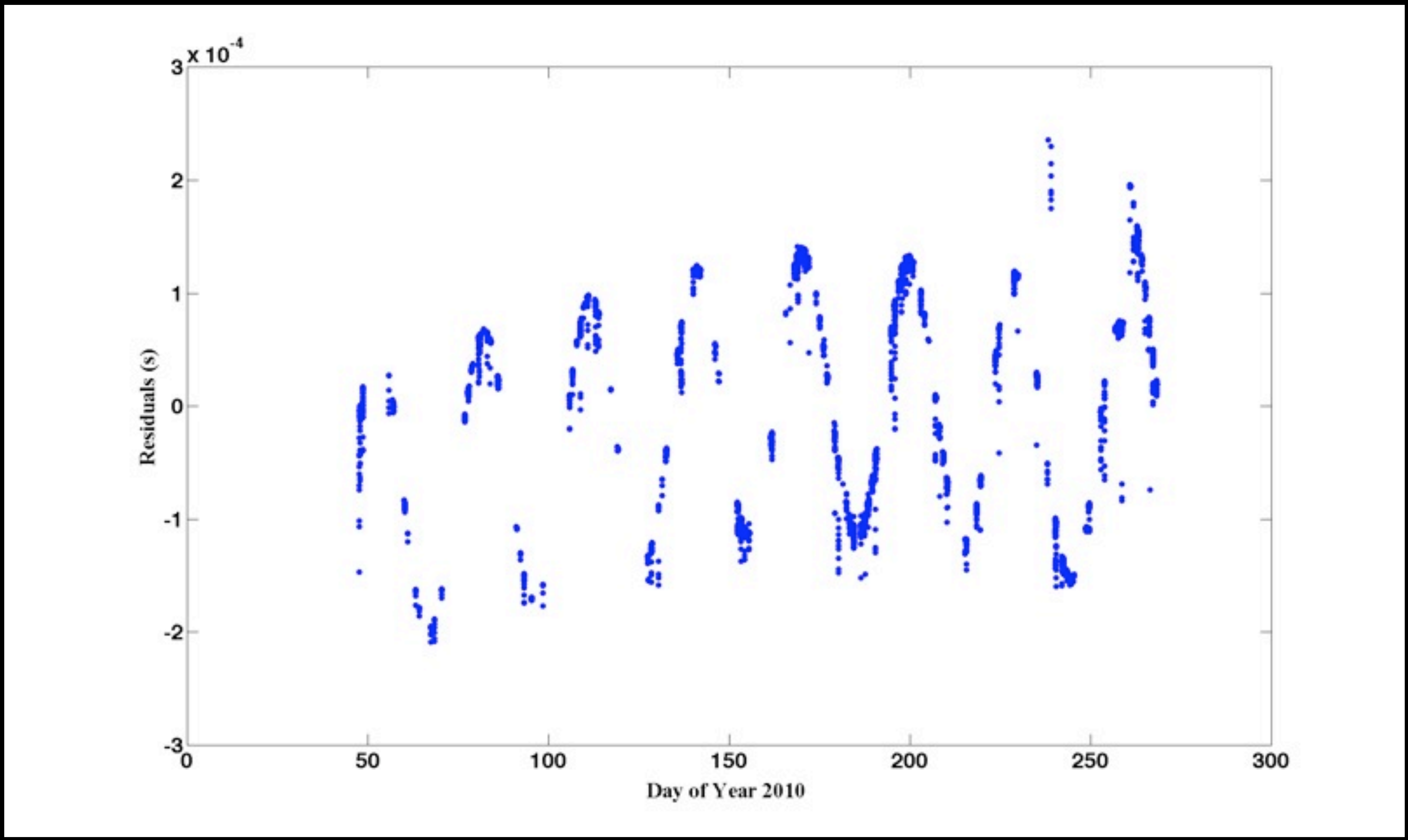


LOLA receive data vs. LRO time



NGSLR RMS = 14.46 cm
Mon. Pk. RMS = 33.36 cm
MOBLAS7 RMS = 12.09 cm
McDonald RMS = 11.53 cm
Residuals (cm)
200
150
100
50
0
-50
22.9
23
23.1
23.2
23.3
23.4
23.5
23.6
23.7
Time of day (Hr)

LRO clock long term stability

Residual = LRO MET – NGSLR UTC – Light Time – offset_drift_aging



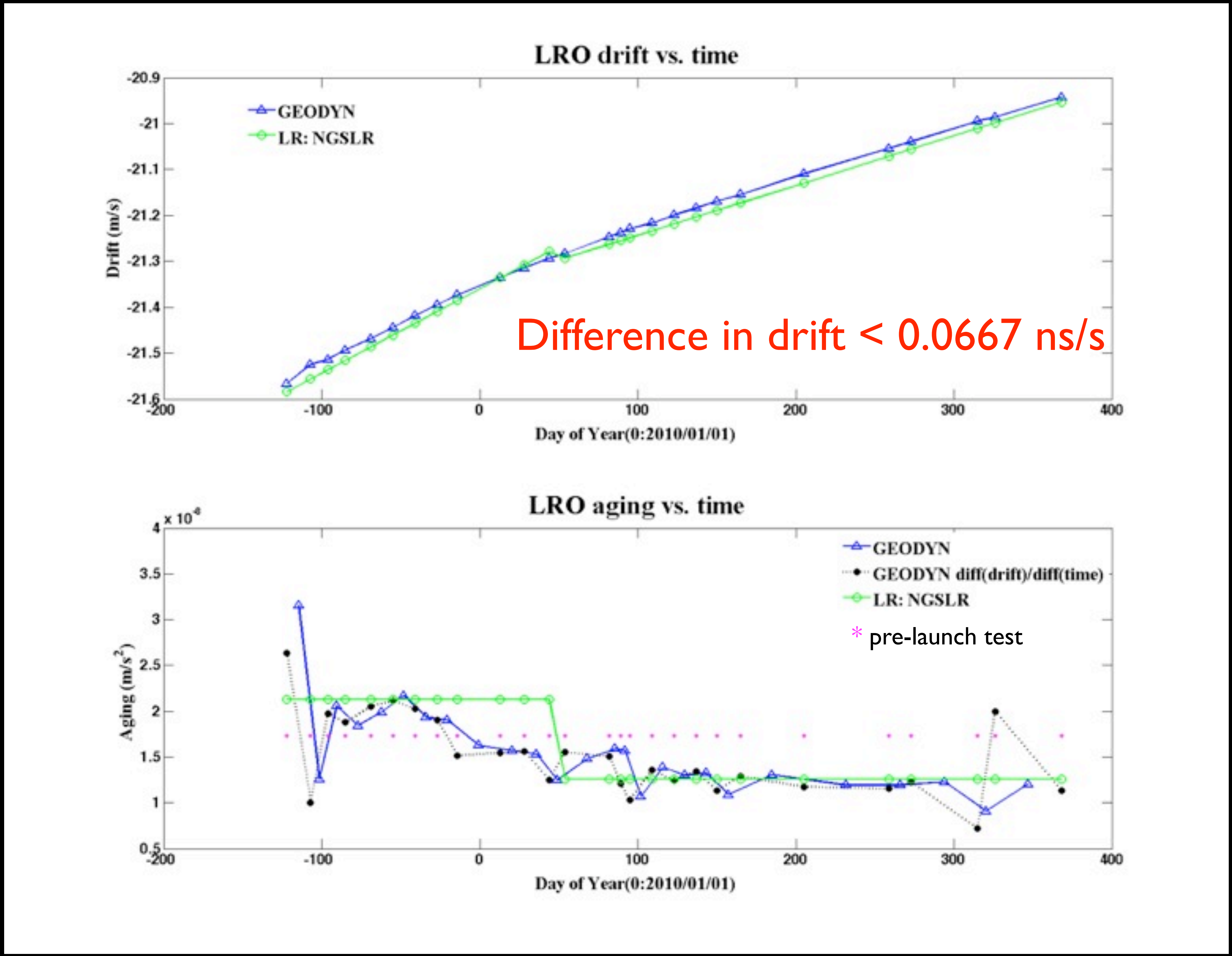
Timing: LRO MET vs. UTC

- The clock offset of LR and LOLA can be predicted much more easily just using the drift and aging, obviating the need for using LRO SCLK to calculate LOLA time offsets

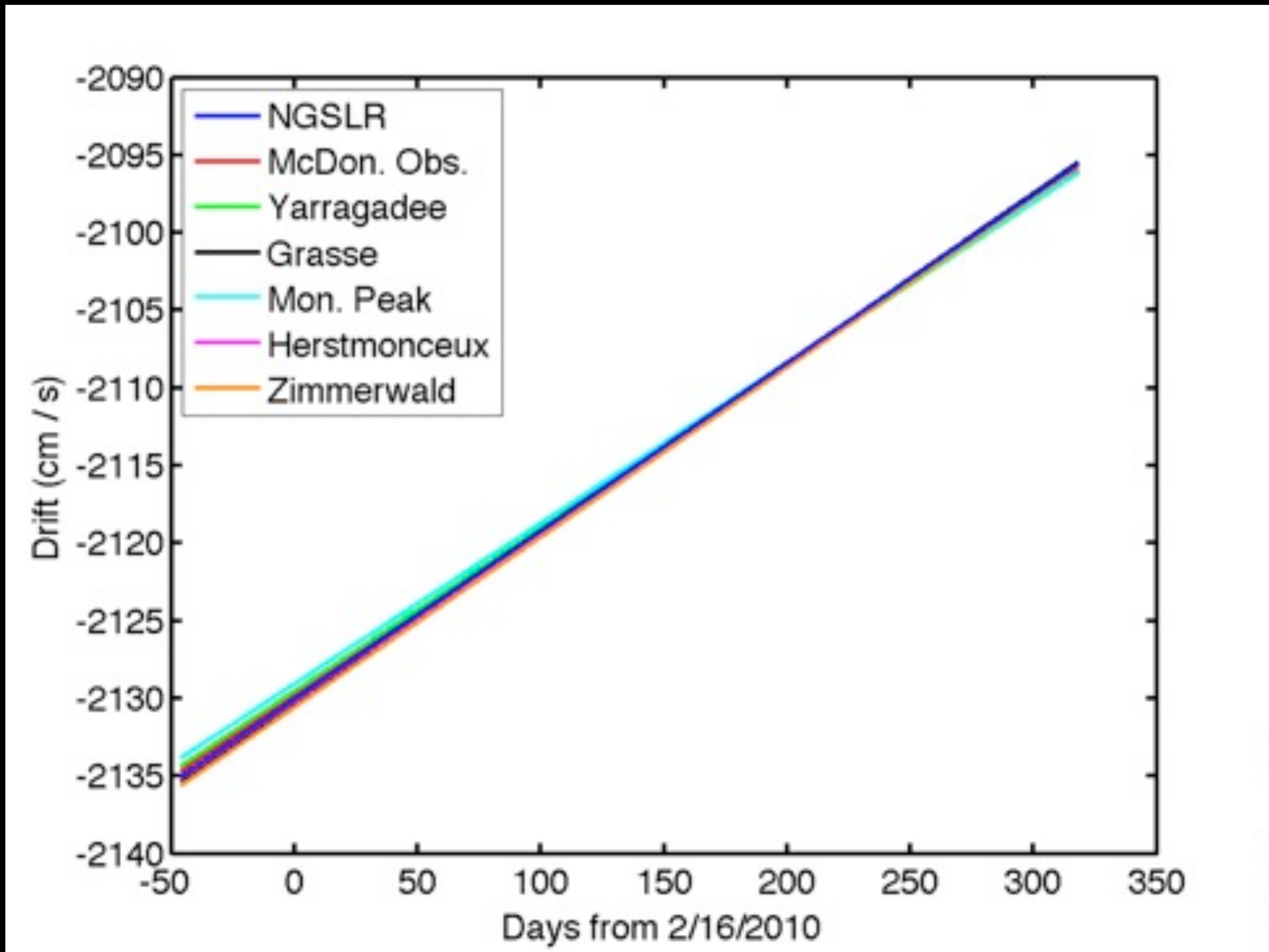
- SCLK precise only to 3ms (as required), updated weekly

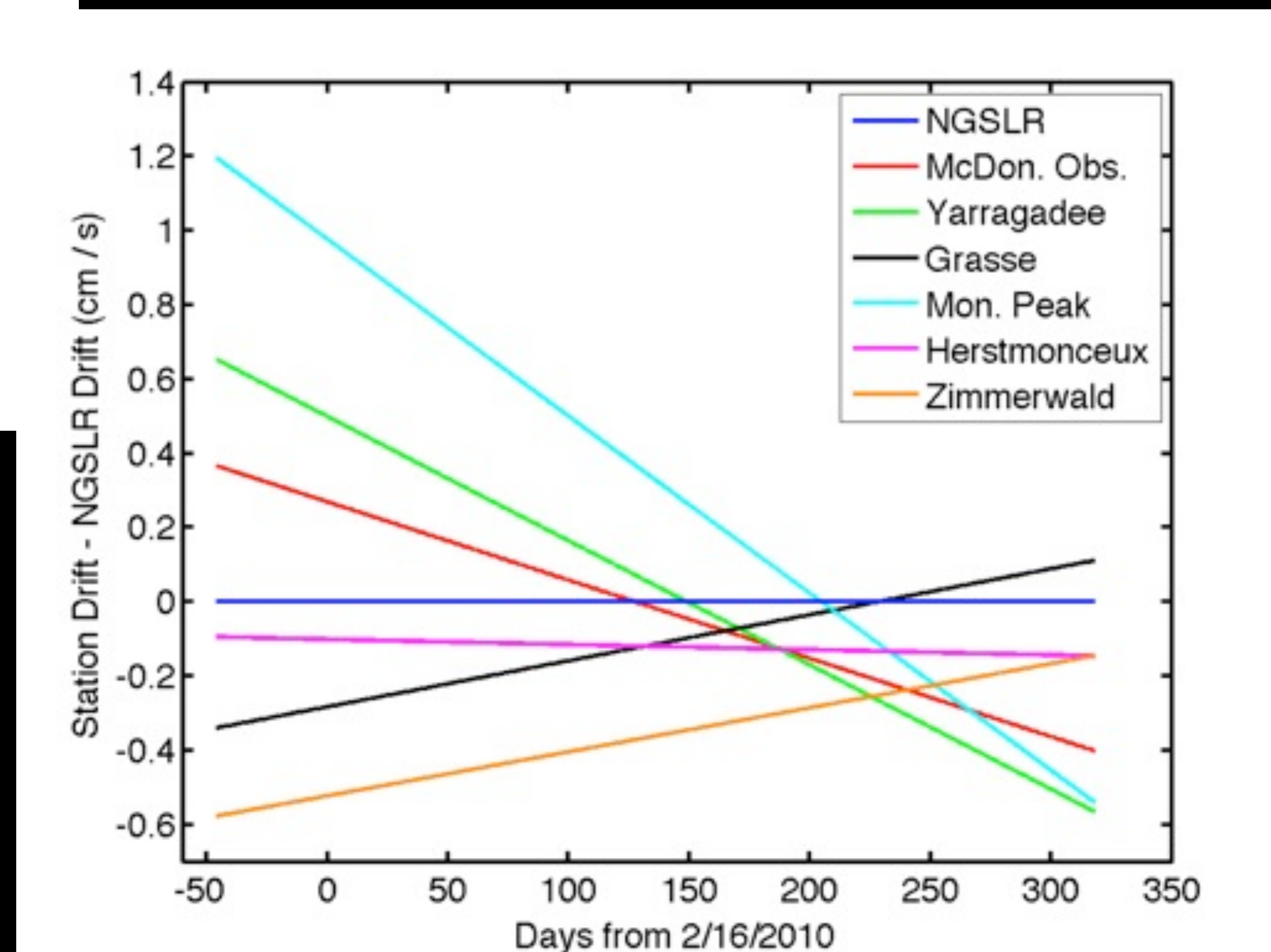
	Prelaunch measurement	LR estimation (NGSLR/GO1L)		
	2009	11/05/2009	02/16/2010	02/25/2011
drift (s/s)	**7.659E-08**	**7.159E-08**	**7.105E-08**	**6.959E-08**
aging (s/s^2)	**2.8935E-17**	**3.5536E-17**	**2.0925E-17**	**0.1631E-17**

LRO clock long term stability



Ground Station Clocks





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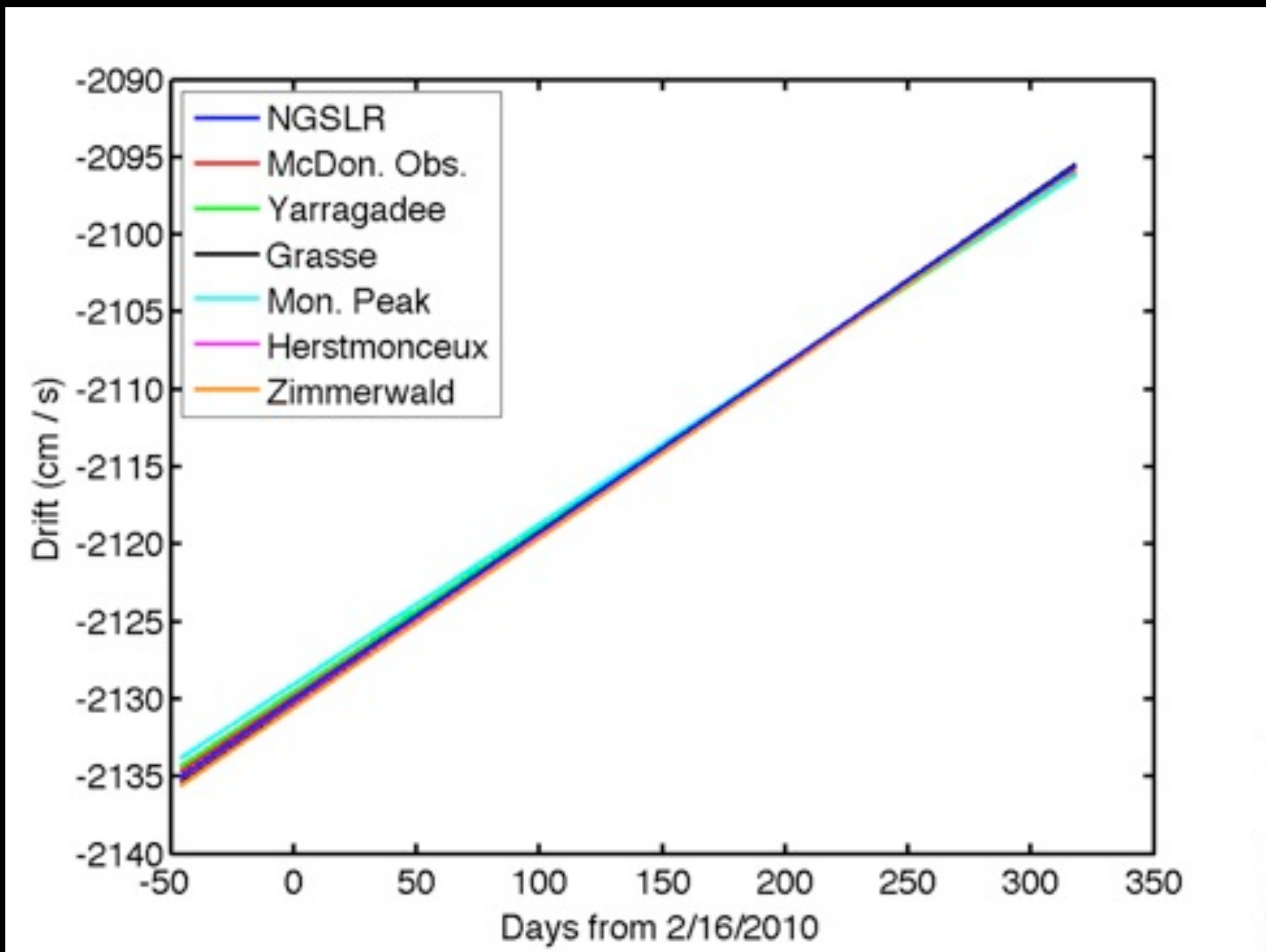
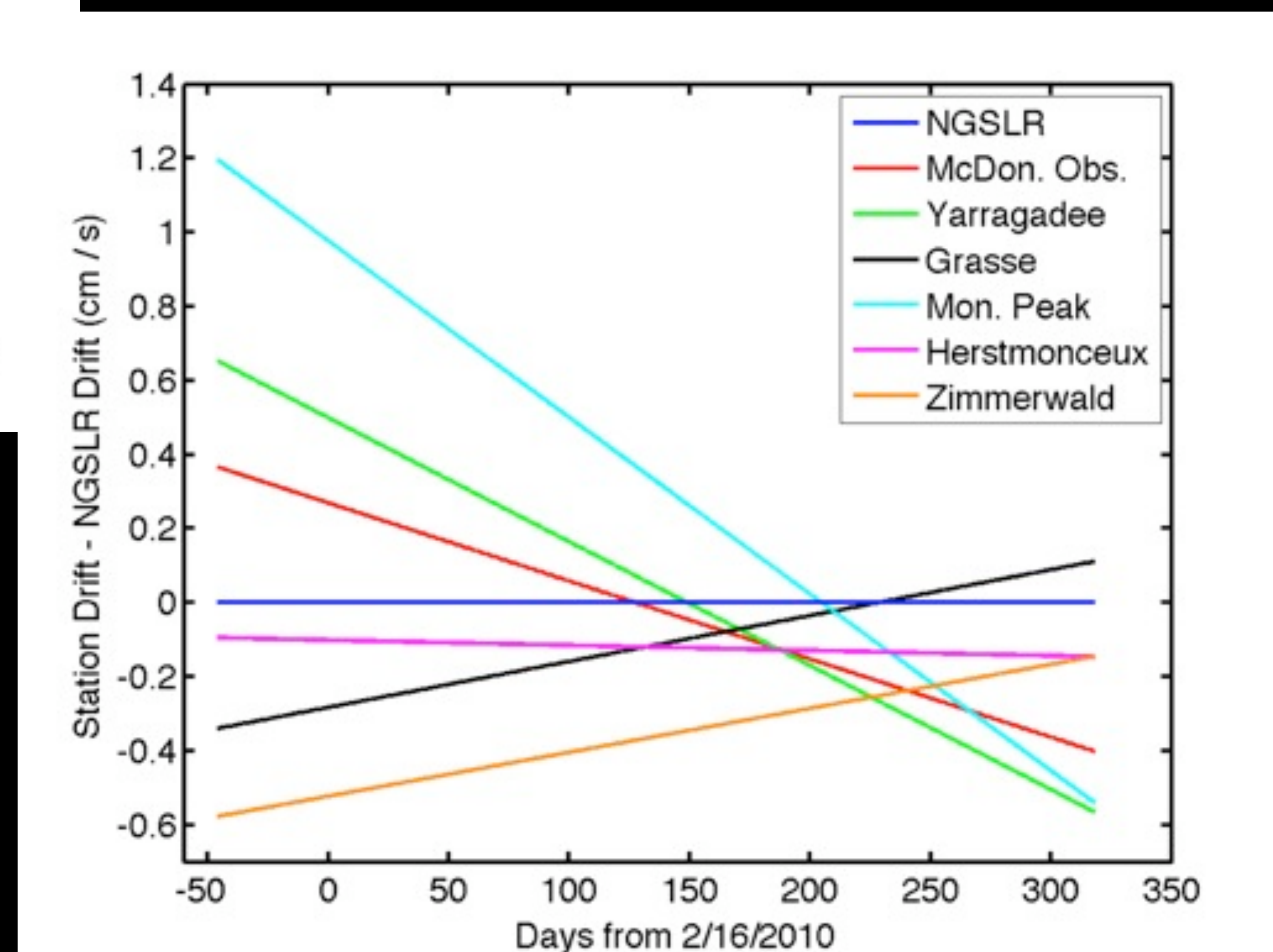




aging difference (NGSLR - Mon. Peak)
= 9.2 E-19 s/s^2

Precision Orbit Determination
Description

- GEODYN: Integrate spacecraft trajectory over 2 weeks

  → iteratively adjust parameters to achieve best fit between tracking observations and computed values

- Tracking LRO: two types of range measurements

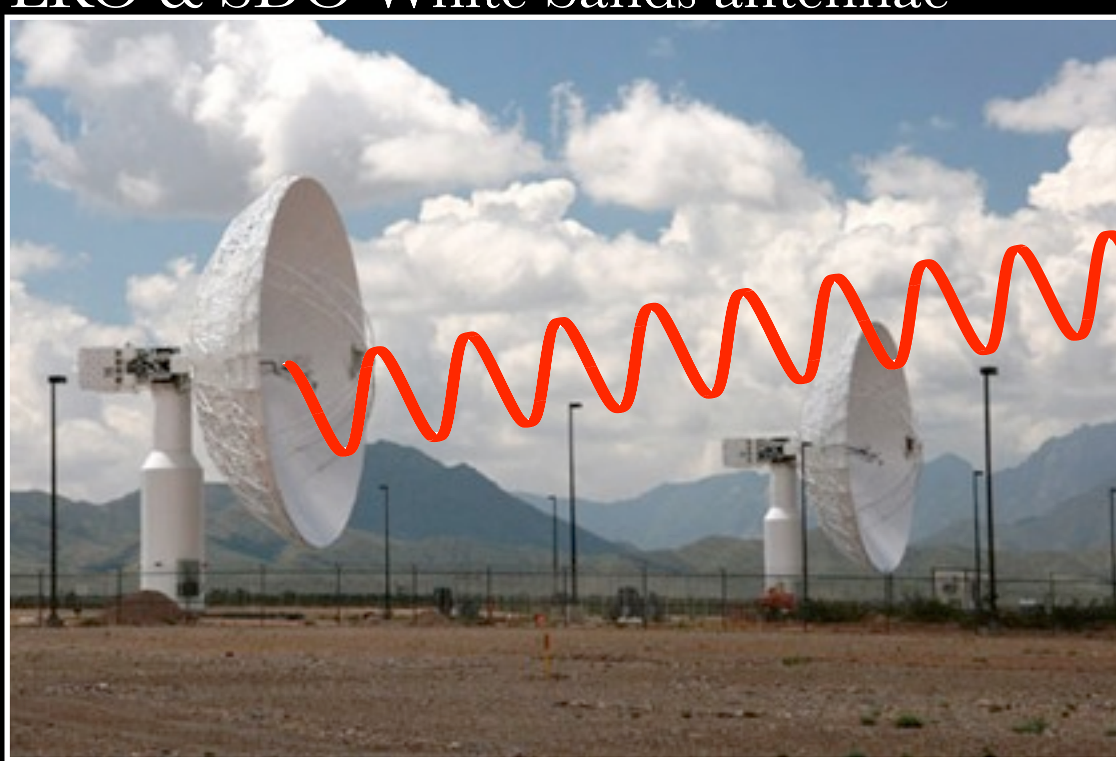
  → LR
  → commercial tracking network (USN) supplements NASA dedicated station (WS)

Radiometric Tracking Data

- S-band telecom system for radiometric tracking
  - line-of-sight measurements
  - 2-way Doppler observations (~0.5-1mm/s)
  - Range observations (~0.5-1m)

- NASA White Sands station supported by USN network

LRO & SDO White Sands antennae



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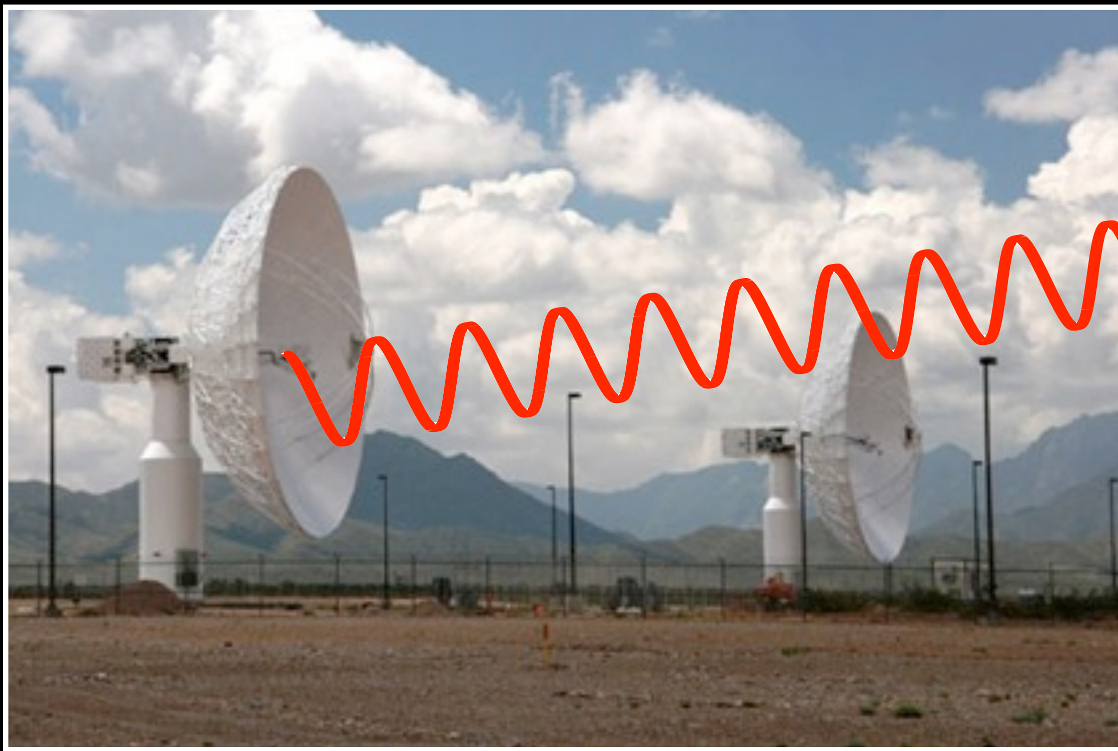
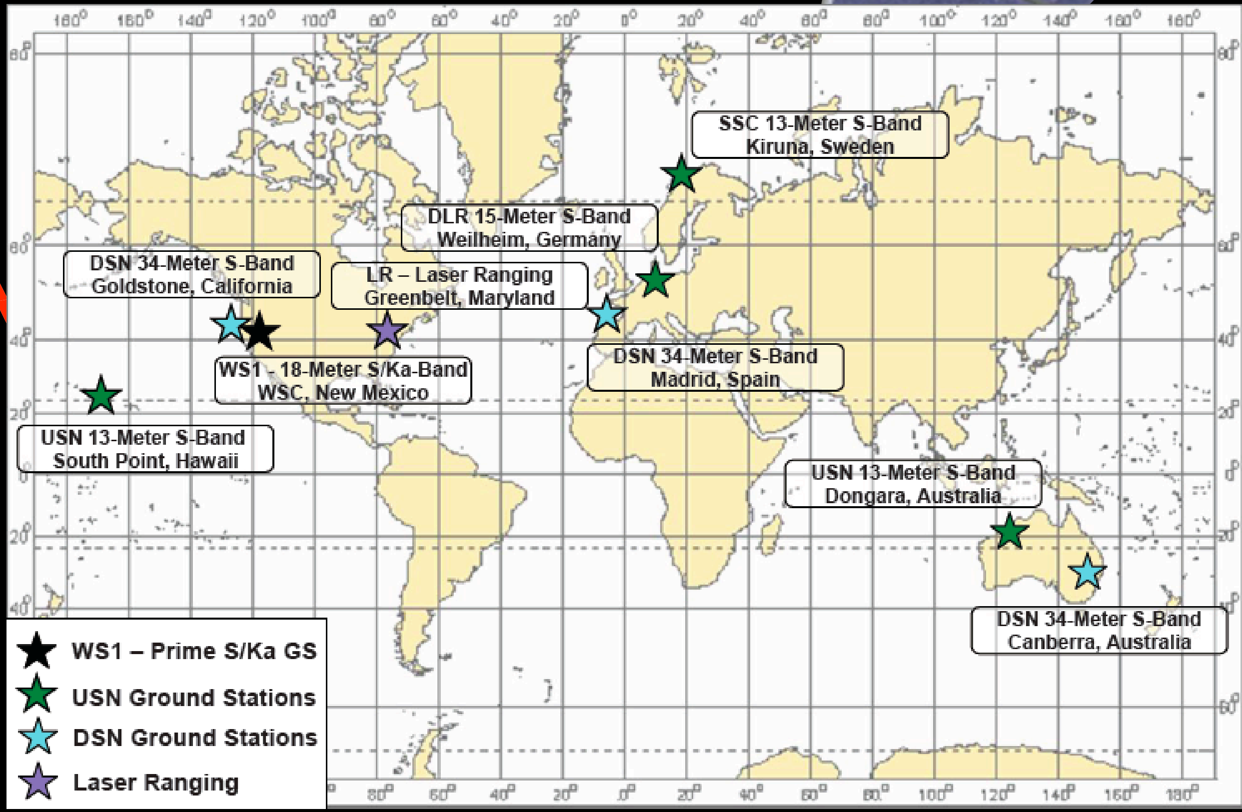
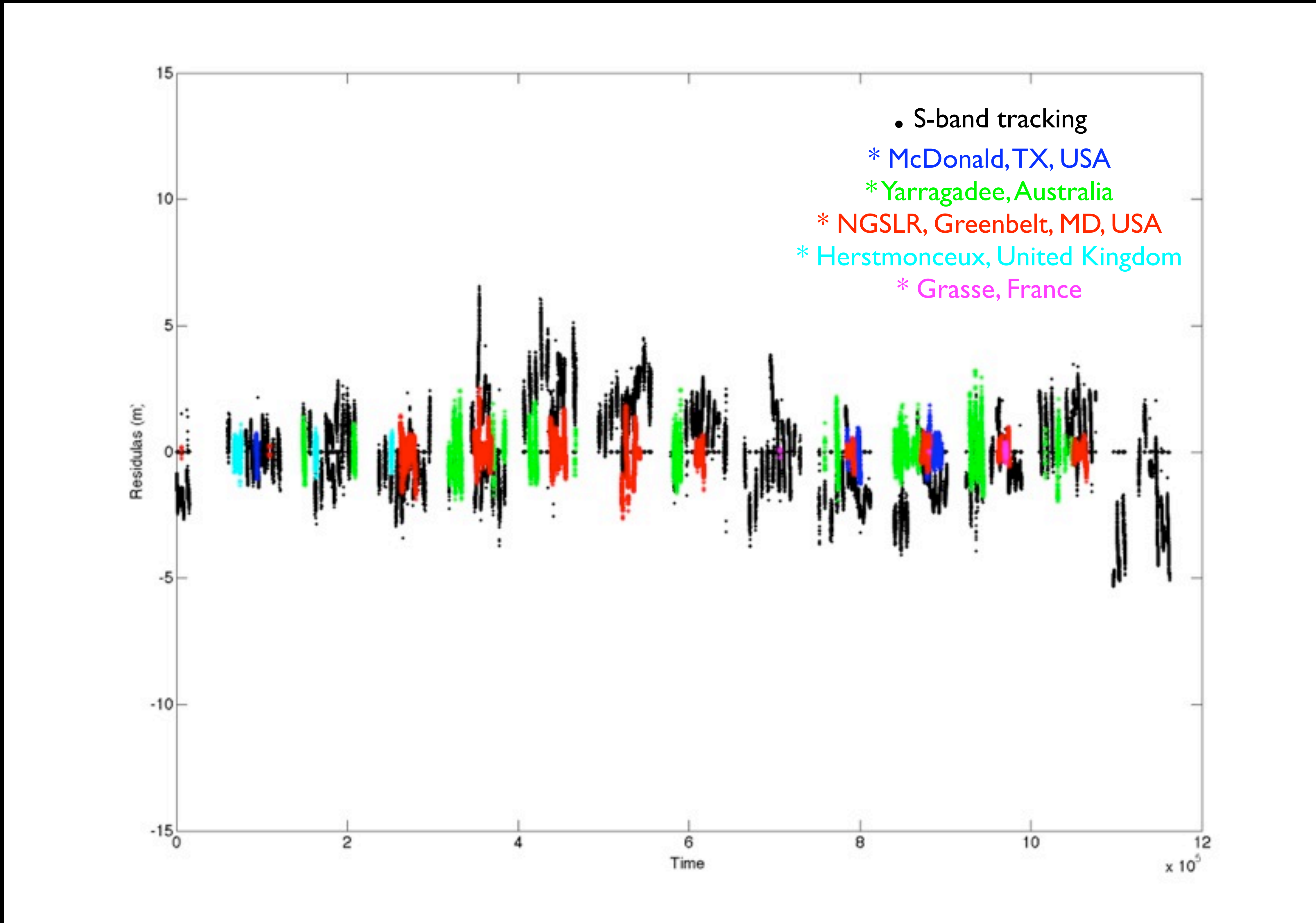
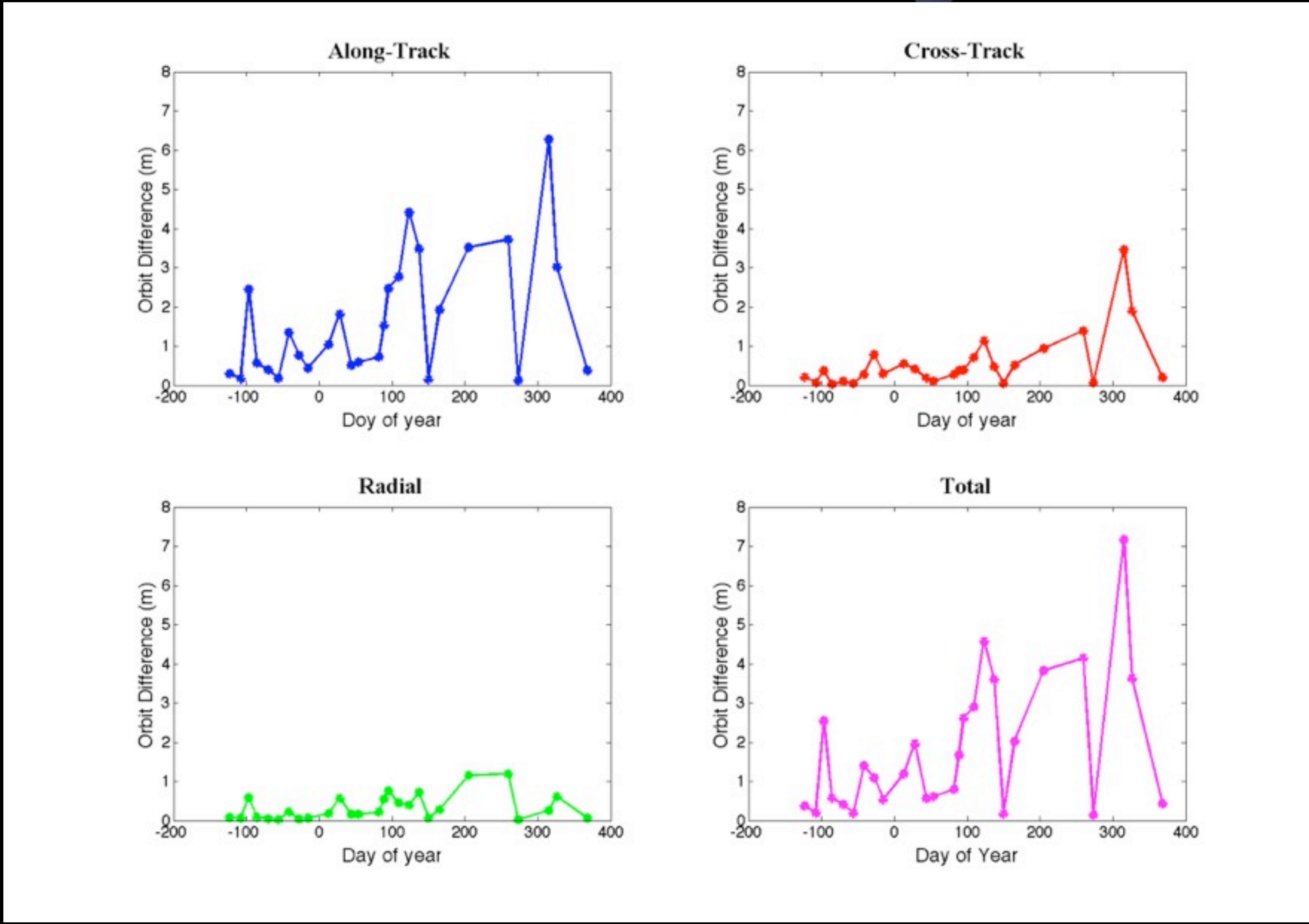




Range Residuals: LR vs. S-band



Orbit difference: LR vs.S-band



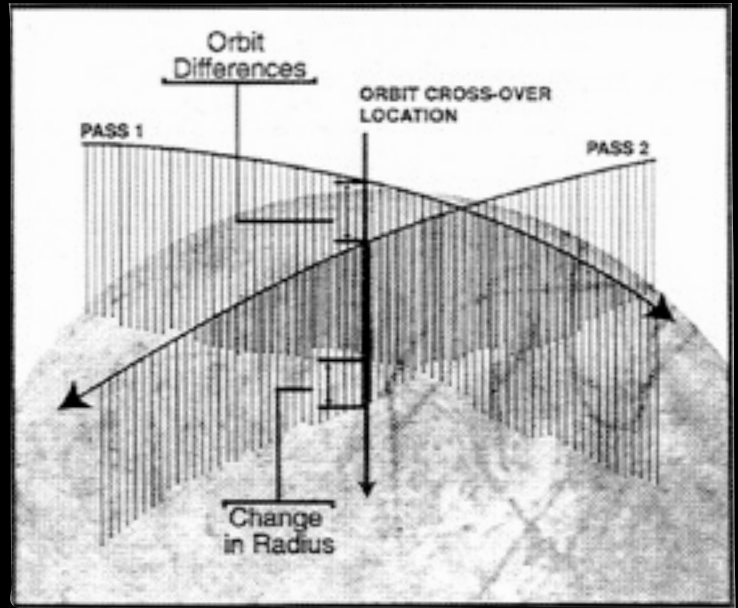
LOLA Altimetric Crossovers

• Altimeter data can be used to constrain the spacecraft orbit
  • not line-of-sight
  • accounting for surface height changes, the derived elevations should equal

• The strength of those constraints is commensurate with the altimeter precision (~10 cm)

• from LOLA's five-spot pattern, 25 single-beam crossover constraints can be derived

• polar orbit convergence and the Moon's slow rotation induce lead to extreme density at both poles



Neumann et al. [2001]

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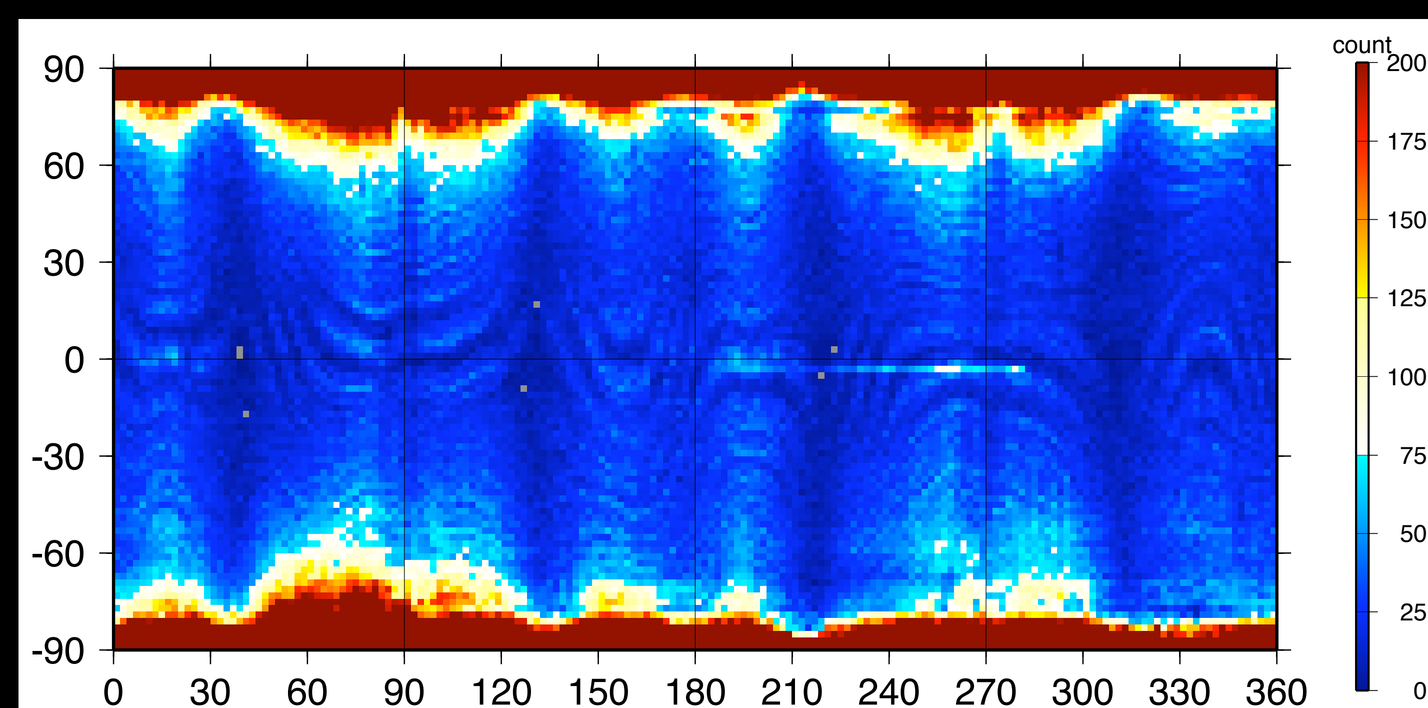

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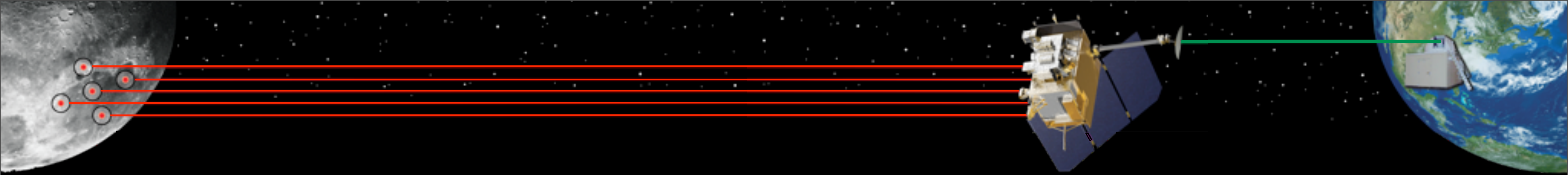
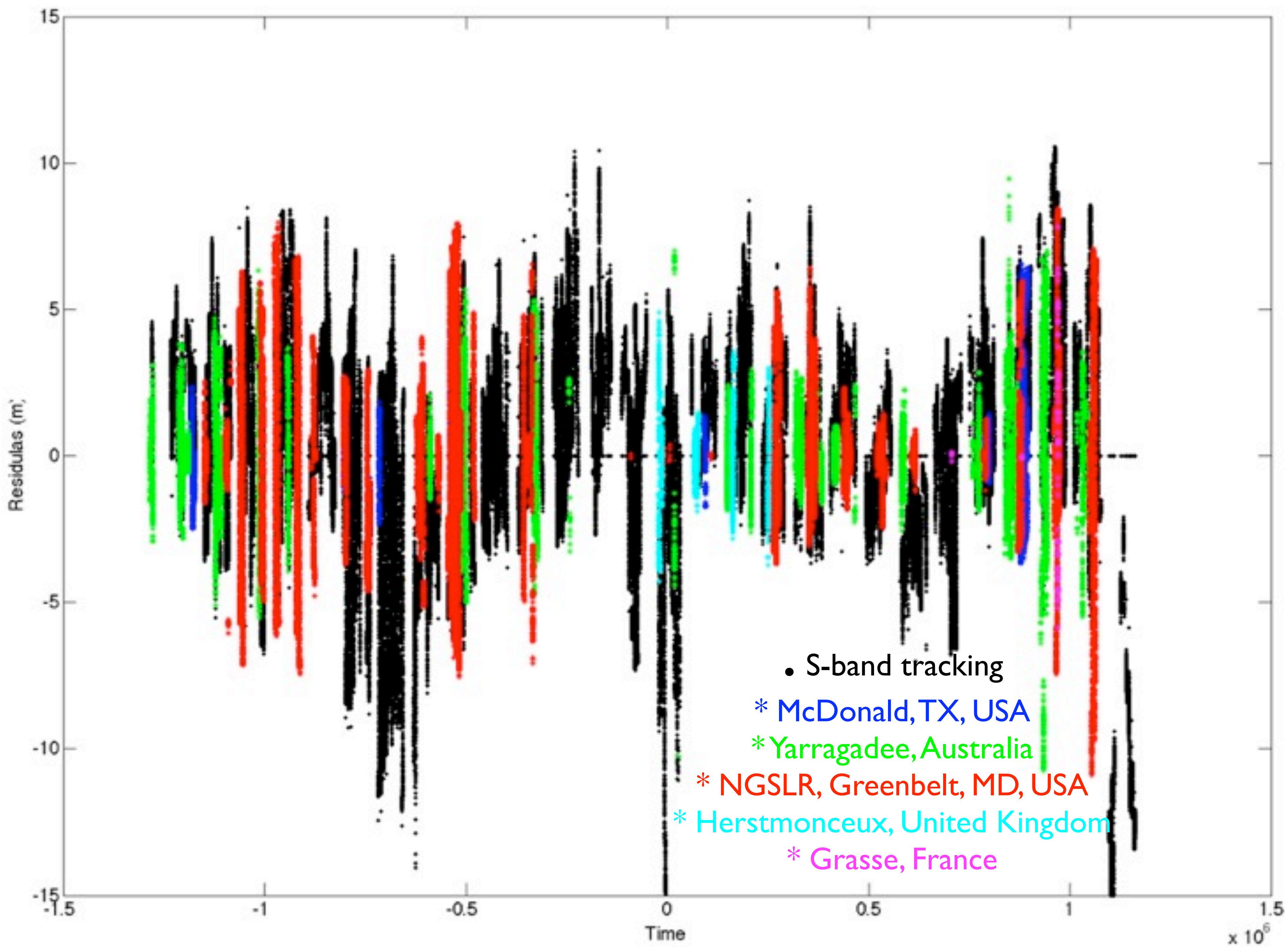
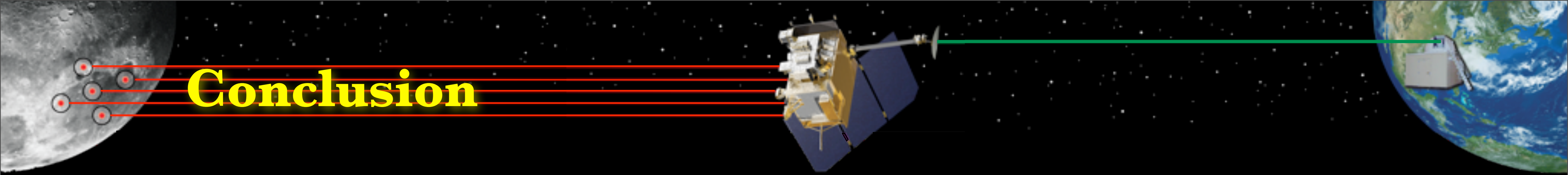




15
10
5
0
-5
-10
-15
-1.5
-1
-0.5
0
0.5
1
1.5
Residulas (m)
Time
x 10^6
• S-band tracking
* McDonald, TX, USA
* Yarragadee, Australia
* NGSLR, Greenbelt, MD, USA
* Herstmonceux, United Kingdom
* Grasse, France



Conclusion

- Time analysis:
  - ability to accurately relate spacecraft time to ground time
  - ability to monitor spacecraft long term behavior
  - ability to monitor relative ground station clock behavior

- Orbit determination:
  - LR precision comparable to S-band tracking
  - LR + S-band + Altimetry