# Terrestrial and lunar gravity field recovery from ground-based tracking data

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# Subject of my talk

- Terrestrial and lunar gravity field recovery
  - through orbit perturbations using tracking data
    $\Rightarrow$ long wavelengths
  - Earth:
    usage of Satellite Laser Ranging (SLR) measurements to geodetic satellites
  - Moon:
    usage of laser ranges and Doppler range-rates to the Lunar Reconnaissance Orbiter (LRO)

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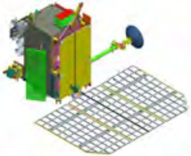
    usage of Satellite Laser Ranging (SLR) measurements to geodetic satellites
  - Moon:
    usage of laser ranges and Doppler range-rates to the Lunar Reconnaissance Orbiter (LRO)
  - parameter estimation based on least squares adjustment
  - using the NASA/GSFC software tools GEODYN II/SOLVE

# Perturbing forces

- gravitational forces
  - potential of the central body
  - third bodies
  - general relativistic effects
- non-gravitational forces
  - atmospheric drag
  - solar radiation pressure
  - planetary radiation (albedo and infrared radiation)
- empirical forces

# Satellite shape



- spherical shape (geodetic satellites) vs. complex shape (LRO)
- LRO is approximated by a macromodel
  - main spacecraft bus (6 plates)
  - solar array (2 plates)
  - high gain antenna (2 plates)

⇒ non-gravitational force modeling is more complicated for LRO!

# Satellite laser ranging

- 2-way runtime measurement
- precision of normal point: $1 - 2\,\mathrm{mm}$


- Station network:

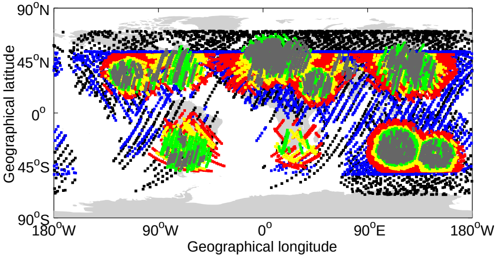
- Geodetic satellites
  - LAGEOS 1 and 2
  - Ajisai
  - Stella/Starlette
  - Etalon 1 and 2
  - LARES
  - Larets
  - ...

# SLR data set

- satellites taken into account:

| | LAGEOS 1\|2 | Ajisai | Starlette\|Stella | Larets |
|---|---|---|---|---|
| Launch date | 1976\|1992 | 1986 | 1975\|1993 | 2003 |
| A/M [$cm^2/kg$] | 7.0 | 53.0 | 9.4 | 19.7 |
| Inclination [°] | 110\|53 | 50 | 50\|99 | 98.2 |
| Altitude [km] | 5 850\|5 625 | 1 485 | 800\|815 | 691 |

- spatial coverage for January 2007:




- time span: Jan 2000 to Oct 2013 (≈ 14 years)

# Approach

- subdivision of $\approx$14 yrs into weeks $\rightarrow$ 1 arc = 1 week
- about 3500 NPs per arc

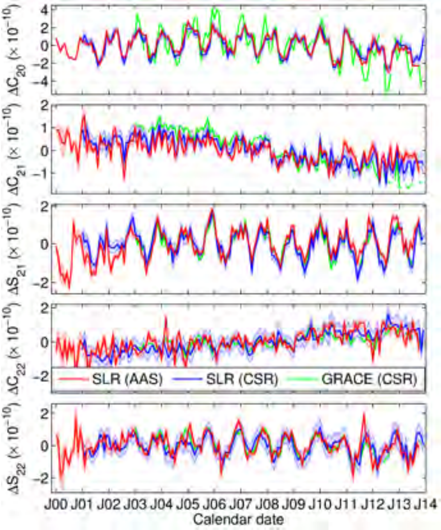
- estimated arc parameters:
  - state vector
  - solar radiation pressure coefficient
  - empirical parameters
  - measurement biases

| Satellite | RMS of residuals [cm] |
|---|---|
| LAGEOS 2 | 1.60 |
| LAGEOS 1 | 1.63 |
| Ajisai | 11.46 |
| Starlette | 11.91 |
| Stella | 16.56 |
| Larets | 20.27 |

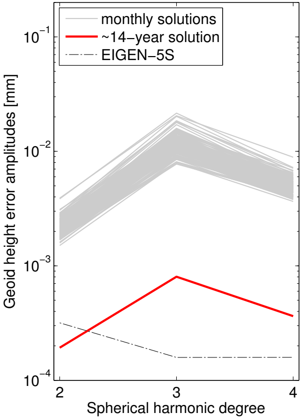
- estimated global parameters:
  - gravity field coefficients up to degree and order 4
  - station coordinates

# Recovered gravity field information

- monthly variations of degree-2 coefficients




- static gravity field



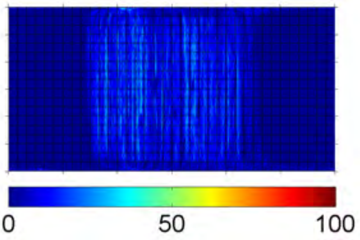
# The Lunar Reconnaissance Orbiter

- mission objectives:
  - identify potential lunar resources
  - gather detailed maps of the lunar surface (e.g. imagery, topography, radiation)
  - ...
- launched in June 2009
- still operational
- orbital characteristics (polar mission phase):
  - polar orbit
  - orbital period of 117 minutes
  - near-circular orbit
  - altitude: 50 km

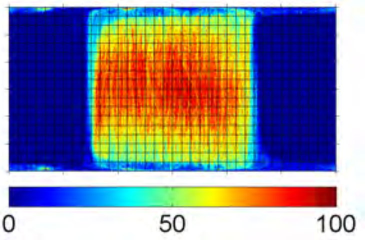
Credit: NASA/GSFC

# Optical laser ranges vs. Doppler

- Laser ranges
  - 1-way measurement
  - bin size of normal point: 5 s
  - precision: 10 cm
  - number of stations: 10
  - 40 000 obs. per month
  - # observations over 1 year on top of the lunar surface:




- Range-rates
  - 2-way measurement
  - integration interval: 5 s
  - precision: 1 mm/s
  - number of stations: 5
  - 200 000 obs. per month
  - # observations over 1 year on top of the lunar surface:



# Overlap analysis tests

Overlap tests using 100 days of Doppler data to find the optimal parametrization w.r.t.

- arc length
  - short (1.25 days, 6 hours overlap)
  - medium (2.5 days, 12 hours overlap)
  - long (4.5 days, 36 hours overlap)
- empirical parameters
  - along track constant
  - along track 1-cpr
  
  ⋮

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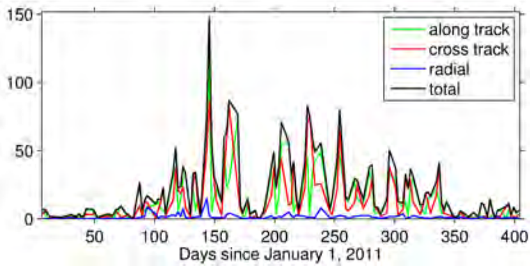
| RMS of orbit overlaps [m] | | | |
|---|---|---|---|
| Along track | Cross track | Radial | Total |
| 2.4 | 2.2 | 0.2 | 3.6 |

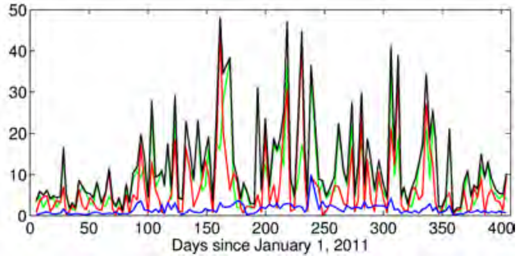
- 14 months of Doppler data were processed with these optimum paramters

# POD results

- orbital precision:
  - RMS of orbit overlaps




- external orbit validation:
  - RMS of orbit differences between estimated orbit and SPICE orbit

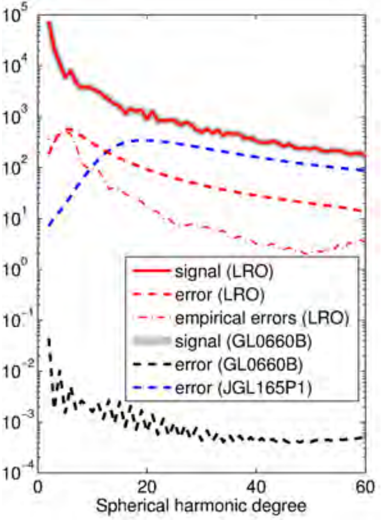


# Extracting gravity field information

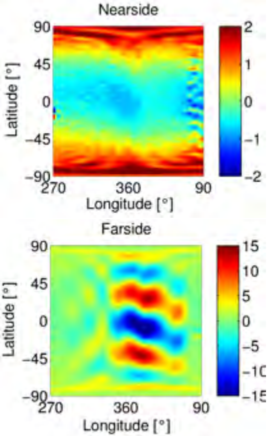
- processing without overlapping periods
- 14 months of Doppler range-rates ($\approx$2 millions observations)
- gravity field coefficients were estimated up to degree and order (d/o) 60 (GRAIL model served as a priori information)
- farside data gap makes regularization indispensable
  - Tikhonov-Phillips regularization
  - regularization matrix: Kaula matrix
  - the optimum regularization parameter was found with the L-curve criterion
  - $\Rightarrow$ all coefficients of d/o$\geq$6 were regularized!

# Results

- Degree variances




- Difference in selenoid height [m] between the LRO-based solution and the a priori gravity field



# Lessons learnt

- Concept of POD and gravity field recovery are the same for the Earth and the Moon BUT differences due to
  - precision of tracking data
  - data coverage
  - dominant perturbing forces
  - non-gravitational force modeling
- orbits based on Doppler range-rates AND optical laser ranges are less precise than Doppler-only orbits