

Latest Bernese advances in Lunar geodesy

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Outline

Lunar Geodesy

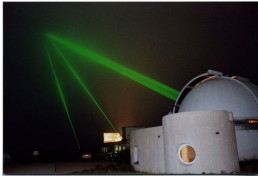
GRAIL @ AIUB

- Observables and modeling
- Orbit recovery
- Gravity field determination
- GRAIL+LLR

Conclusions



Lunar Geodesy



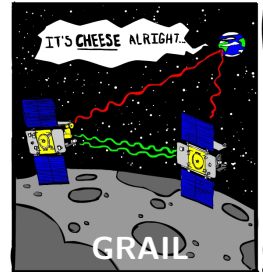
LLR

rotation, librations,
distance



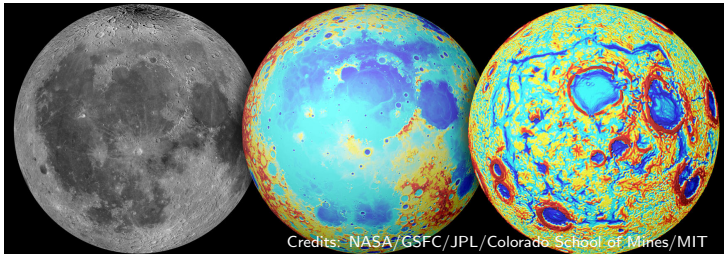
LRO

topography, rotation



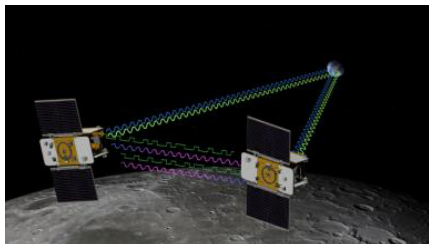
GRAIL

gravity, tides



Credits: NASA/GSFC/JPL/Colorado School of Mines/MIT

The GRAIL mission



GRAIL

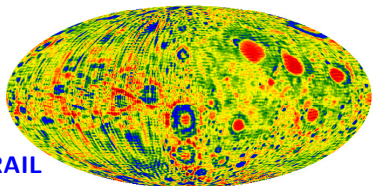
(Gravity Recovery and Interior Laboratory)

M.T. Zuber et al, Science, 2013

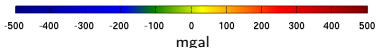
March - December 2012

Polar orbit, altitude 25-50 km

- Understand the internal structure and history of the Moon
- Homogeneous coverage of the far side (GRACE heritage)



pre-GRAIL

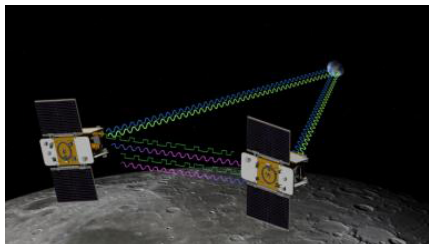


pre-GRAIL solutions:

LP165A (Lunar Prospector)

SGM150J (Selene)

The GRAIL mission



GRAIL

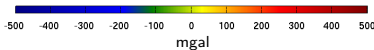
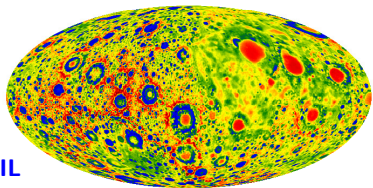
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- Understand the internal structure and history of the Moon
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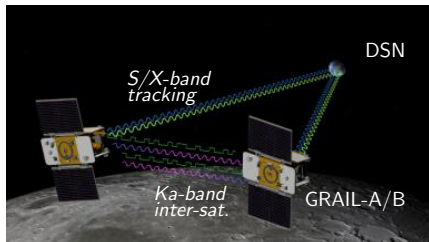


Latest NASA solutions:

GL1500E (JPL)

GRGM1200A (GSFC)

The GRAIL mission: Satellite signals



- S-band two-way link (2.3 GHz)
- X-band one-way link (8.4 GHz)

One-way X-band Doppler (nominal 0.08 mm/s):

- emission/reception by different clocks
- smaller onboard antenna

Two-way S-band Doppler (nominal 0.3 mm/s):

- emission/reception by the same clock (DSN)
- larger onboard antenna

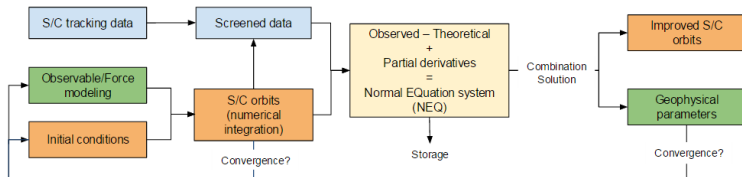
Ka-Band Range Rate (KBRR) (nominal $0.03\mu\text{m/s}$):

- Derived from Lunar Gravity Ranging System one-way phases

The Celestial Mechanics Approach (CMA)

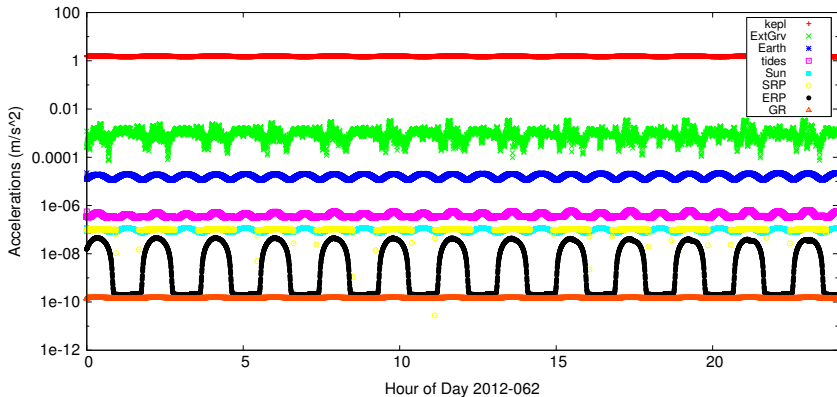
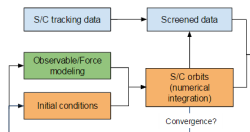
Within the Bernese GNSS Software (BSW):

- Numerical integration (with a priori parameters) of equations of motion and variational equations.
- Set up of normal equations (NEQs) **for each observation type** (Doppler, KBRR, positions, ...) on a daily basis.
- Combination of the NEQs with appropriate weighting.
- NEQ manipulation (e.g., preelimination of parameters and accumulation to weekly, monthly, etc... NEQs)
- NEQ inversion \rightarrow simultaneous solution for the improved parameters (orbit, gravity field coefficients, etc...)



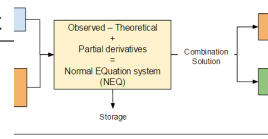
Orbit propagation

- Daily arcs, initial conditions from GNI1B science orbits
- Force model (SGM150J and GRGM900C up to d/o 600 a priori)



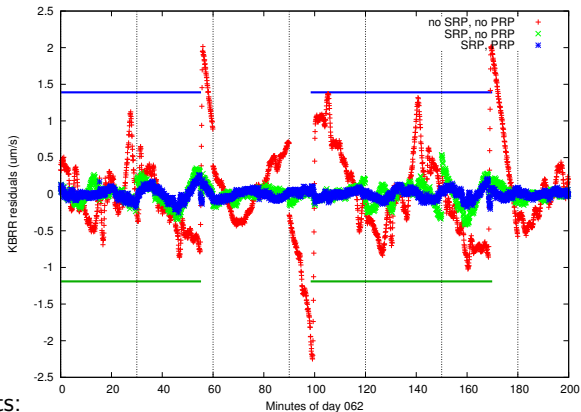
Parameter estimation

Observation	nObs	error	weight
2-way Doppler	416746	0.3 mm/s	1
1-way Doppler	334181	0.08 mm/s	0.1
KBRR	1261440	0.03 $\mu\text{m/s}$	10^8



Parameter		R	S	W
Arc-specific				
x_0, v_0	6			
emp. accel.	opr	×		
pulses	30'	0	1 $\mu\text{m/s}$	1 $\mu\text{m/s}$
Global				
Gravity field coeff.	×			
Love number k_2	×			

Orbit determination: KBRR residuals

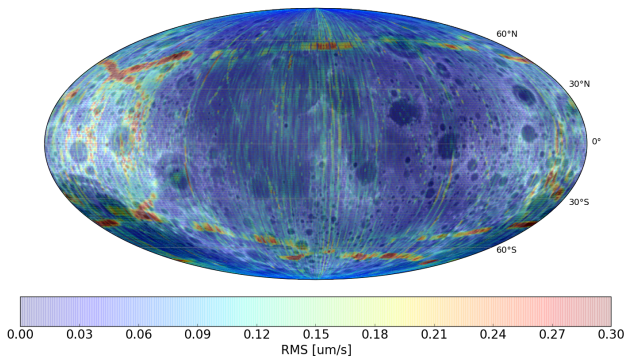


Visible effects:

- impact of the pseudo-stochastic pulses (every 30');
- solar radiation pressure at light/shadow transitions.

Based on GRGM900C, d/o 600

Orbit determination: KBRR residuals



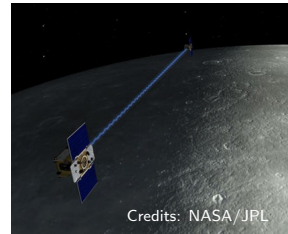
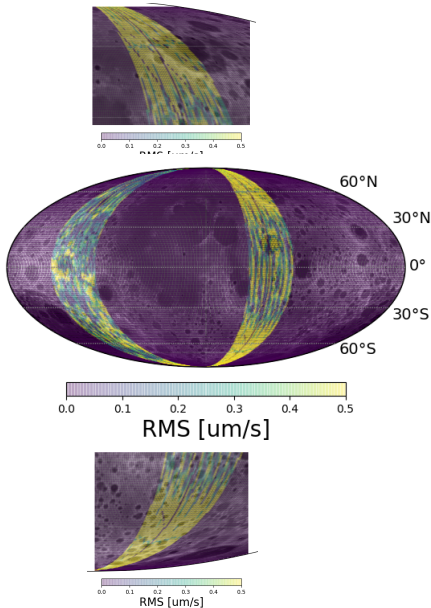
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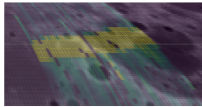
Huge improvement from additional SRP and PRP modeling!!

Orbit determination: improved eclipses

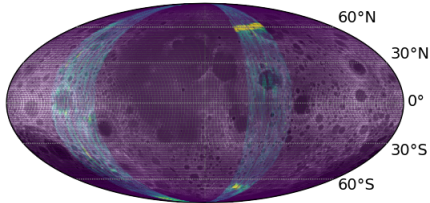
No SRP, ERP
(pulses + empirical only)



Orbit determination: improved eclipses

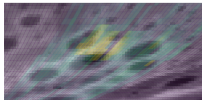


RMS [$\mu\text{m/s}$]



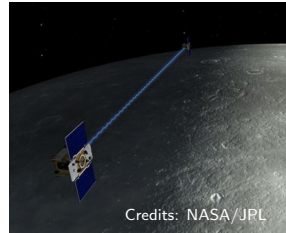
RMS [$\mu\text{m/s}$]

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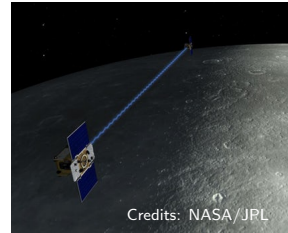
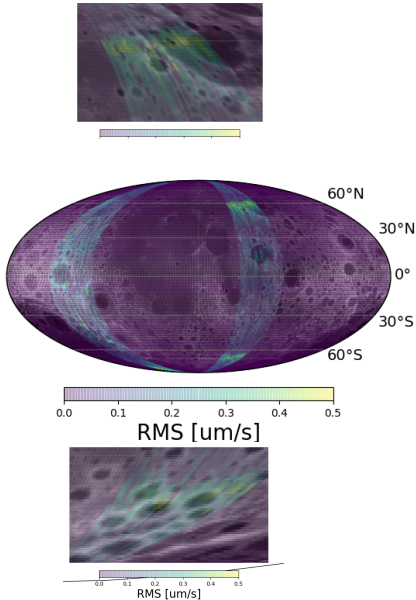
RMS [$\mu\text{m/s}$]

SRP + ERP



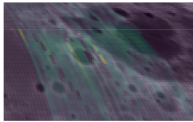
Orbit determination: improved eclipses

Solar Panel Current based

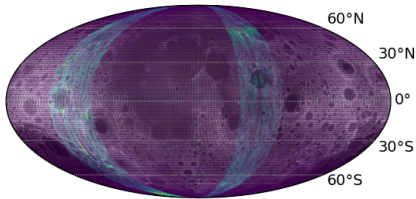


Orbit determination: improved eclipses

Solar Panel + Time Shift

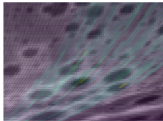


0.0 0.1 0.2 0.3 0.4 0.5

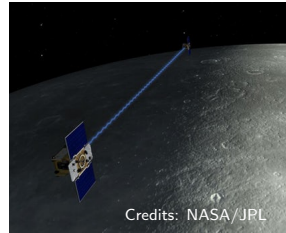


0.0 0.1 0.2 0.3 0.4 0.5

RMS [$\mu\text{m/s}$]



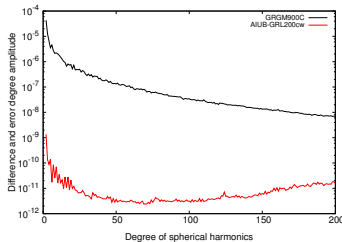
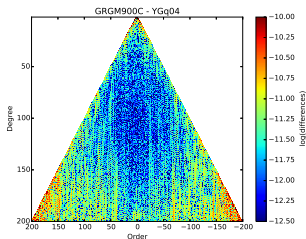
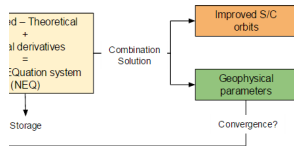
0.0 0.1 0.2 0.3 0.4 0.5
RMS [$\mu\text{m/s}$]



Credits: NASA/JPL

Gravity field determination

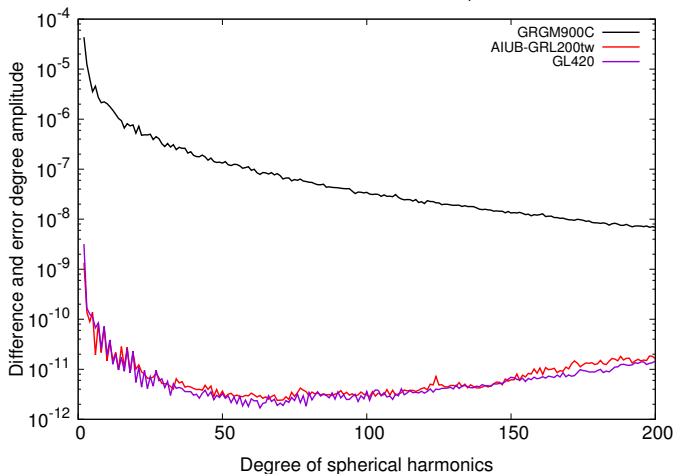
- **A priori orbit: fit of Doppler and KBRR observations with appropriate parametrization**
- Combination with KBRR daily NEQs
- NEQs stacking up to the whole mission (pre-elimination of orbit parameters)
- NEQs inversion and solution



$$V(r, \lambda, \phi) = \frac{GM_M}{r} \sum_{l=1}^{l_{\max}} \left(\frac{R_M}{r} \right)^l \sum_{m=0}^l \bar{P}_{lm}(\sin \phi) (\bar{C}_{lm} \cos m\lambda + \bar{S}_{lm} \sin m\lambda)$$

Gravity field determination: GRGM900C

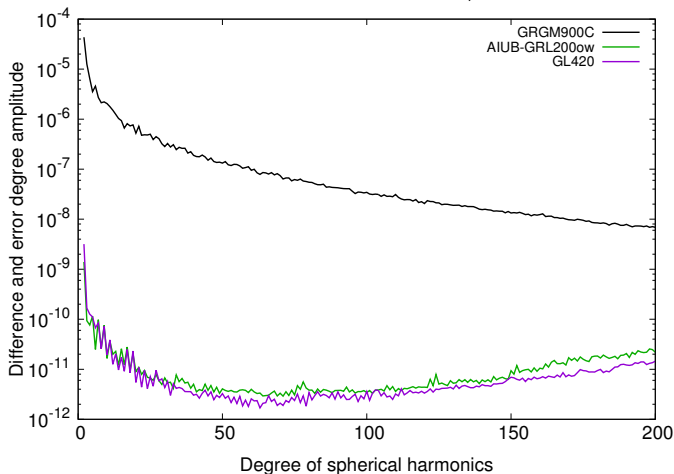
Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1} \sum_{m=0}^l (\Delta \bar{C}_{lm}^2 + \Delta \bar{S}_{lm}^2)}$



a priori GRGM900C
(d/o 660): 2-way
Doppler + KBRR

Gravity field determination: GRGM900C

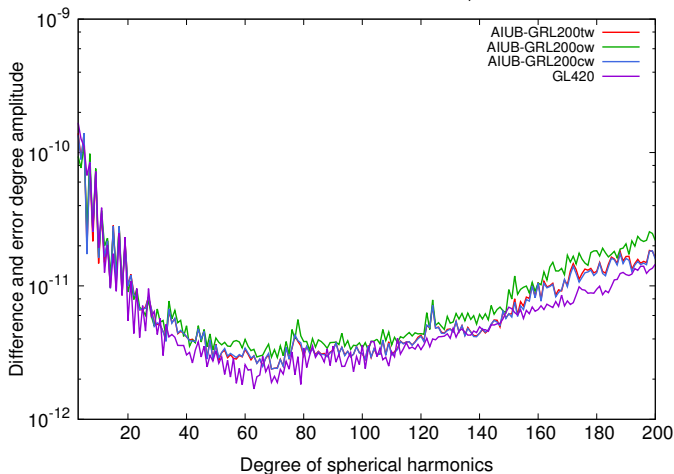
Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1} \sum_{m=0}^l (\Delta \bar{C}_{lm}^2 + \Delta \bar{S}_{lm}^2)}$



a priori GRGM900C
(d/o 660): 1-way
Doppler + KBRR

Gravity field determination: GRGM900C

Difference degree amplitudes : $\Delta_l = \sqrt{\frac{1}{2l+1} \sum_{m=0}^l (\Delta \bar{C}_{lm}^2 + \Delta \bar{S}_{lm}^2)}$

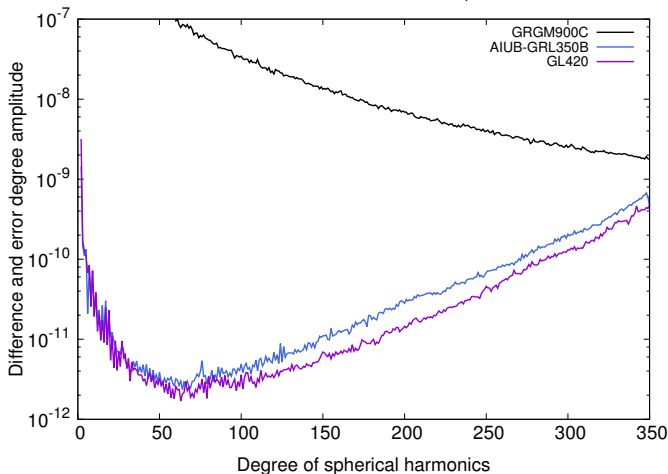


NEQ Combination:

$0.1 \times 1\text{-way} +$
 $1 \times 2\text{-way} +$
 $10^8 \times \text{KBRR}$

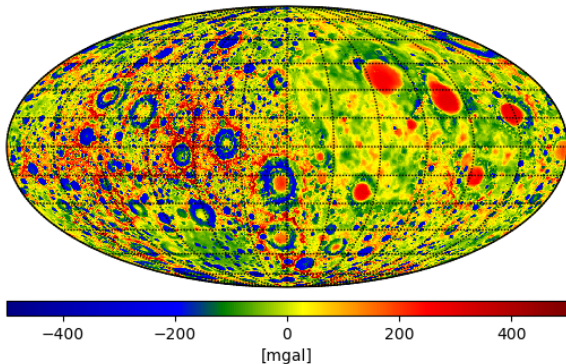
Gravity field determination: GRGM900C

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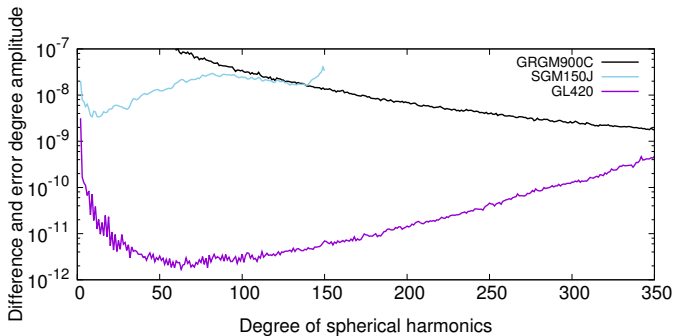
Gravity field determination: GRGM900C

Gravity field anomalies AIUB-GRL350B

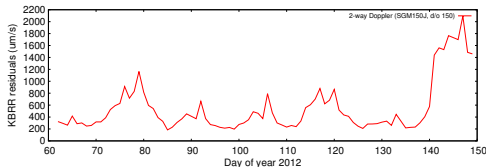
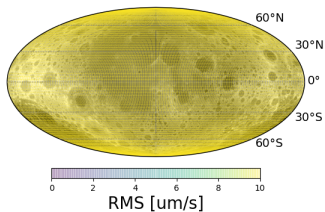


Solution	$k_2 \pm \sigma$
AIUB-GRL350B	0.024147 ± 0.000069
GRGM900C	0.024116 ± 0.000108

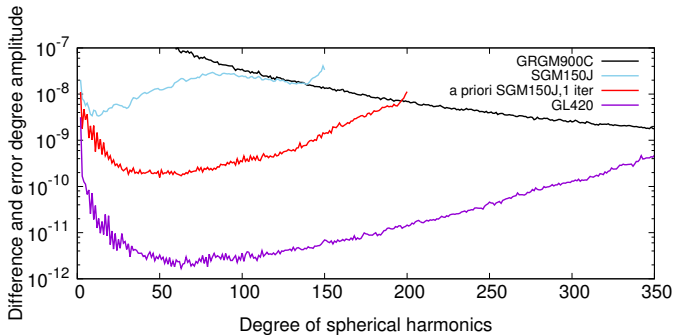
Gravity field determination: SGM150J



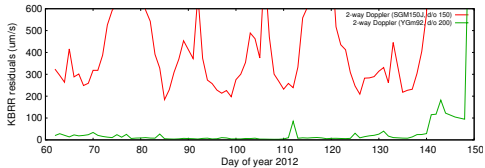
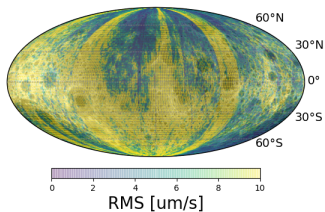
a priori SGM150J



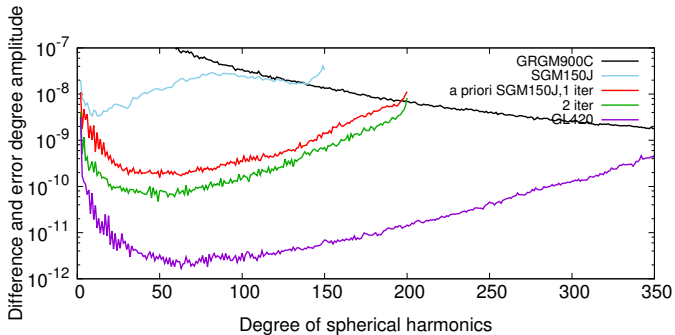
Gravity field determination: SGM150J



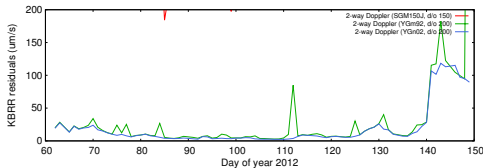
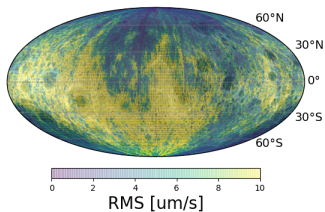
a priori SGM150J
1 iteration: April



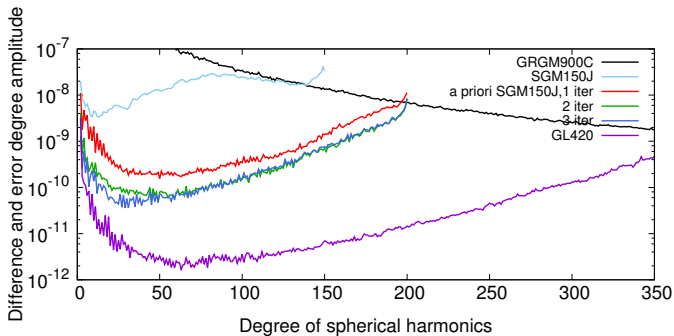
Gravity field determination: SGM150J



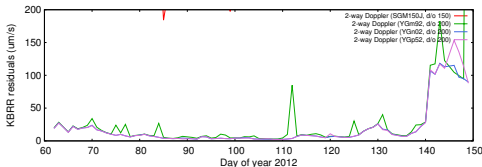
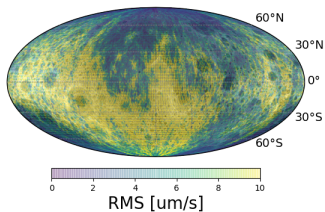
a priori SGM150J
1 iteration: April
2 iteration: 62-140



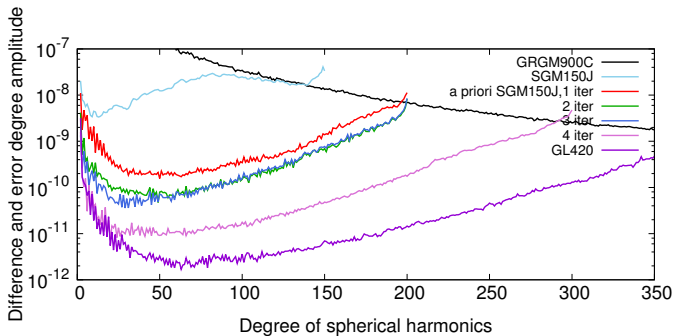
Gravity field determination: SGM150J



a priori SGM150J
1 iteration: April
2 iteration: 62-140
3 iteration:
SRP+PRP modeling



Gravity field determination: SGM150J



a priori SGM150J

1 iteration: April

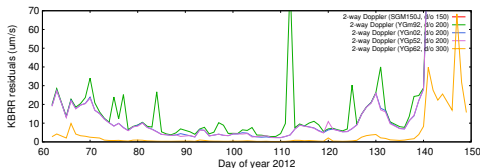
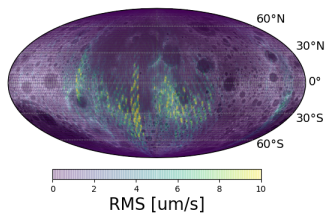
2 iteration: 62-140

3 iteration:

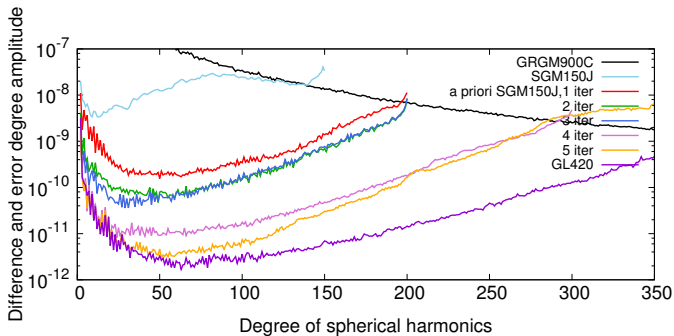
SRP+PRP modeling

4 iteration:

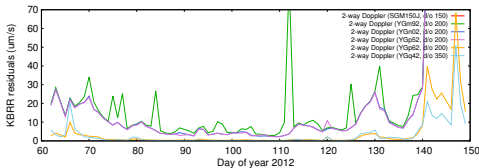
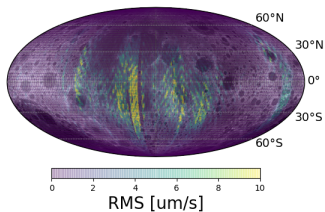
larger param. space



Gravity field determination: SGM150J



- a priori SGM150J
- 1 iteration: April
- 2 iteration: 62-140
- 3 iteration:
- SRP+PRP modeling
- 4 iteration:
- 5 iteration: 62-149
- larger param. space

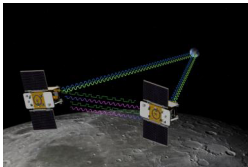


GRAIL + Lunar Laser Ranging

Combination of techniques \Rightarrow Optimal solutions for geophysics

- GRAIL (AIUB) + LLR (POLAC@SYRTE)

Collaboration with A. Bourgoïn



Gravity field, tides, rotation



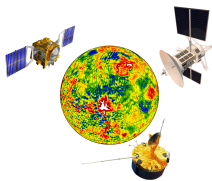
Low degrees gravity field, tides, rotation, Earth/Moon distance

- Combination on NEQ level (full covariance information)
- Different geometries \Rightarrow different sensitivity
- Similar principle as GRACE + SLR on Earth
- **Current status:** combined gravity + k_2

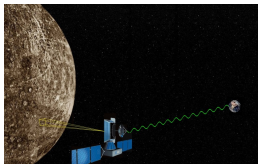
Conclusions

- Bernese GNSS Software capable of 1-way and 2-way DSN Doppler data → **inhouse** processing of planetary mission data
- Parallelized MKL/Lapack environment for large solutions
- Final Moon gravity field (and tides) solution on track
- Collaborations and ongoing projects in planetary geodesy @ AIUB

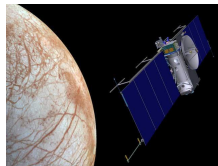
Venus



Mercury



Europa





Credits: JAXA (Selene)

Thanks for your attention!
Questions?

LAPACK/INTEL MKL

- High resolution Moon gravity fields = high computational needs
- Parallel code for gravity NEQ setup (NEQSYS2) + inversion (NEQSOLVE)

d/o	n. of parameters	standard	MKL
200	40397	≈ 1 week	≈ 1 day (20' Y)
300	90527	≈ 2.5 week	≈ 3 days (1.5 h Y)
350	123000	-	≈ 1 week (3.5 h Y)



UBELIX

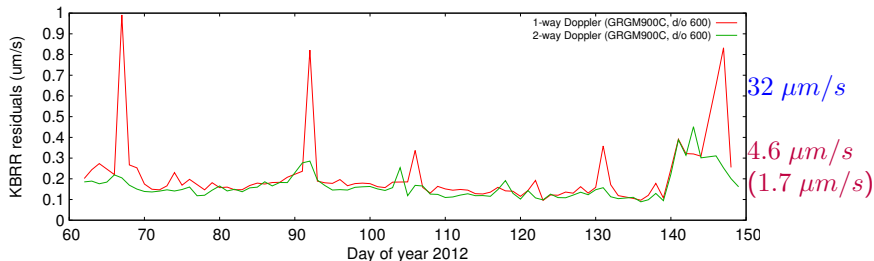
+



Parallel Intel MKL/LAPACK libraries for optimal use of parallel UniBE HPC Cluster (UBELIX) environment

Combined orbit: KBRR residuals

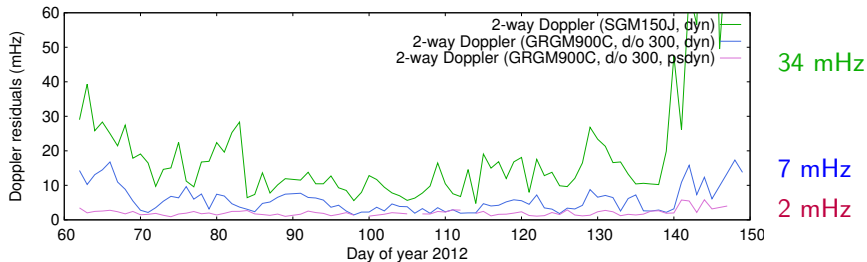
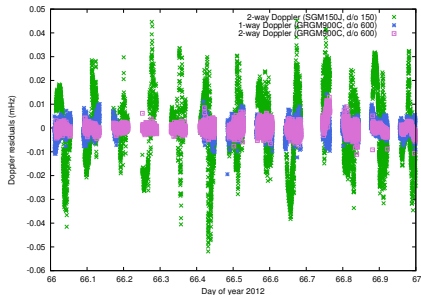
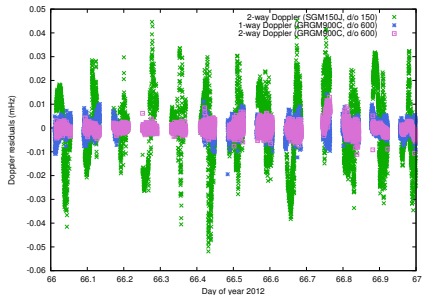
~~0.68 mm/s~~



Daily RMS values of KBRR residuals for GRAIL-A (PM), using different gravity field models and parametrizations.

- Days 140 – 150 at lower altitude → larger residuals

Observed vs computed : Doppler residuals



Non-gravitational forces: setup

- Solar Radiation Pressure (28-plates macromodel, Fahnestock 2012)

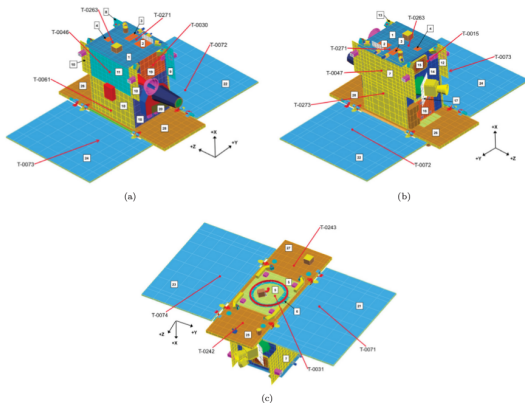
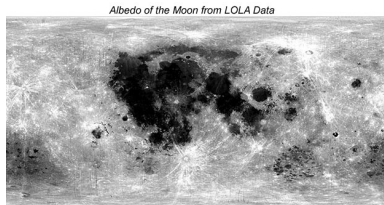
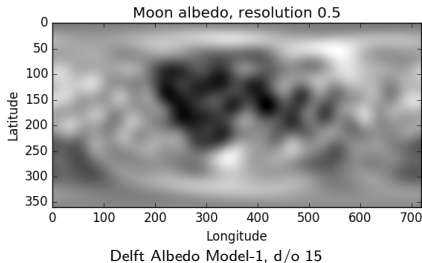


Figure 1. Placement of surfaces on GRAIL-B in highest fidelity model.

Non-gravitational forces: setup

- Solar Radiation Pressure (28-plates macromodel, Fahnestock 2012)
- Moon Albedo (Delft Albedo Model-1, d/o 15)



- Moon IR (black body)

