NEROGRAV

New Refined Observations of Climate Change from Spaceborne Gravity Missions

International Spring School
Neustadt an der Weinstraße, Germany, March 10-14, 2025

Special Aspects of GRACE-FO Level1 Instrument Data

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OVERVIEW

GRACE-FO Instruments

From Level0 to Level1b Overview

Error types in time-series data (Spectral densities, Tone Errors)

Spectral content of accelerometer and ranging data

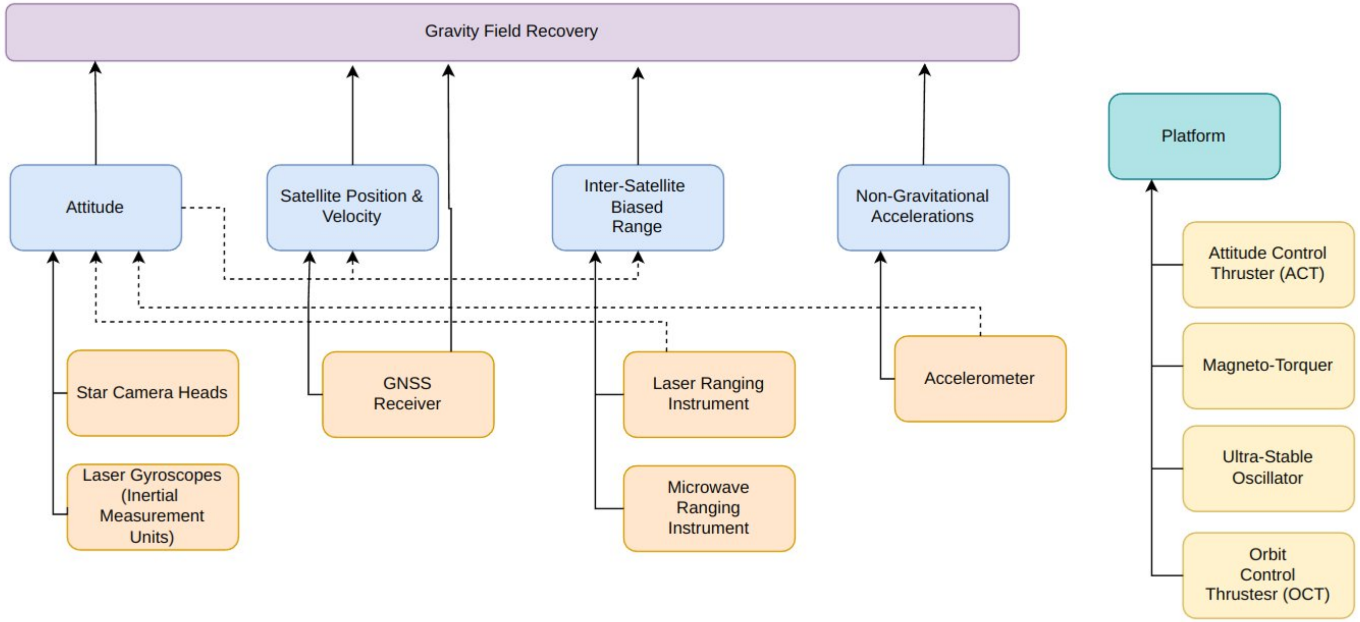
Accelerometer & Processing

Laser Ranging Instrument Data

- LRI working principle
- Level1B processing corrections
- Comparison of LRI and KBR data
- Complete chain from Level1a to Level1b
- [Special Events in LRI data]

GRACE-FO INSTRUMENTS

MAX PLANCK GESELLSCHAFT



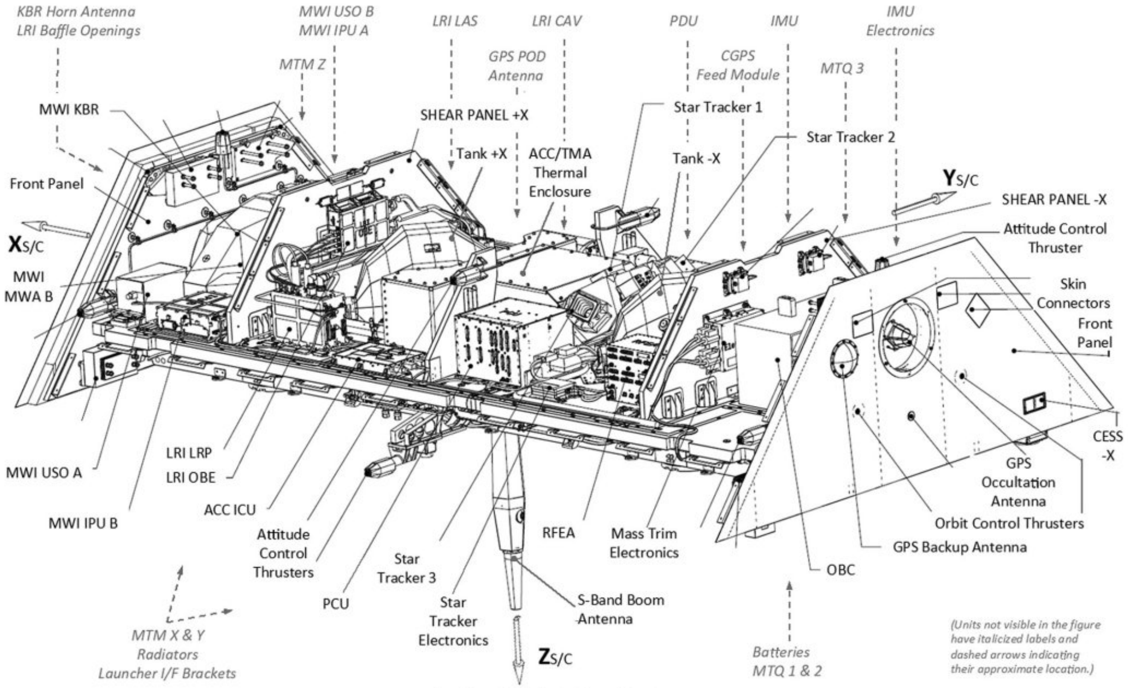


Fig. 11 **GRACE-FO satellite layout.**

[Kornfeldt, 2019]

Inter-satellite range is modulated by

- Earth's gravitational field & its variations
- non-gravitational forces

Simplified Model:

$$\text{Gravity Signal} \approx \ddot{\rho} - a_{\text{ng,LOS,SC1}} - a_{\text{ng,LOS,SC2}}$$

DATA PROCESSING LEVELS

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Level0 Raw Telemetry

- Binary data in Packet Utilization Standard (PUS) Format
- Data often organized in files obtained during downlink of ground-station passes
- Science and Housekeeping channels
- Can include diagnostic data files
- Science Tlm typically: 10 Hz

→ Non-destructive / reversible re-formating
Concatenate, remove duplicates

Level1A Readable Telemetry

- Human-readable science and housekeeping telemetry
- Engineering units (volt, ampere, degC) or raw digital counts
- Diagnostic data often removed
- Local instrument time-system, local instrument coordinate system
- Organized in daily data files
- Same data rate as level0

→ Filter & Decimate, Transform

Level1B Physical Units

- Telemetry interpolated onto compatible common time-grids (GPS time)
- Common „Science Reference Frame“
- Filtered & Decimated from high rate (e.g. 10 Hz) to 0.1/0.2/0.5 Hz
- Corrections applied
- Physical units: m, m/s², rad
- „Ready for gravity field recovery“

→

Level2 Spherical Harmonics

LEVEL 1 DATA PRODUCTS

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Level-1A

ACC1A	ACC measurements
ACT1A	Corrected ACC measurements
AHK1A	ACC housekeeping data
GNV1A	GPS navigation measurements
GPS1A	GPS measurements
HRT1A	High Resolution Temperature measurements
IHK1A	IPU housekeeping data
ILG1A	IPU log messages
IMU1A	IMU measurements
KBR1A	KBR phase measurements
LHK1A	LRI housekeeping data
LLG1A	LRI log messages
LLT1A	LRI states and light times
LRI1A	LRI phase measurements
LSM1A	LRI steering mirror measurements
MAG1A	Magnetometer and magnetorquer measurement
MAS1A	Spacecraft and fuel mass
PCI1A	Antenna offset corrections to KBR range
PLT1A	Satellite states and signal travel times from PO
SCA1A	SCA measurements
THR1A	Thruster activation data
TNK1A	Gas tank sensor data

Level-1B

ACC1B	Linear and angular accelerations (GRACE only)
ACT1B	Corrected linear and angular accelerations
AHK1B	ACC housekeeping data
CLK1B	Clock offsets for conversion from Receiver to GPS Time
GNI1B	Trajectory states in Inertial Frame
GNV1B	Trajectory states in Earth-Fixed Frame
GPS1B	GPS flight data
HRT1B	High Resolution Temperature data
IHK1B	IPU housekeeping data
IMU1B	IMU data
KBR1B	KBR ranging data
LHK1B	LRI housekeeping data
LLK1B	Clock offsets for conversion from LRI to GPS Time
LRI1B	LRI ranging data
LSM1B	LRI steering mirror data
MAG1B	Magnetometer and magnetorquer data
MAS1B	Spacecraft and fuel mass
QCP1B	Rotation from SCA "pilot" frame to KBR pointing frame
QSA1B	Rotation from SCFs into SRF
SCA1B	Processed SCA data
THR1B	Thruster activation data
TIM1B	Clock mapping from OBC to Receiver Time
TNK1B	Gas tank sensor data
USO1B	USO and K-Band frequency data
VCM1B	Vector offset for satellite center of mass
VGB1B	Vector offset for GPS backup navigation antenna
VGN1B	Vector offset for GPS main antenna
VGO1B	Vector offset for GPS occultation antenna
VKB1B	Vector offset for KBR antenna
VSL1B	Vector offset for SLR corner cube reflector

Gravity Recovery and Climate Experiment Follow-On (GRACE-FO)
Level-1 Data Product User Handbook

JPL D-56935 (URS270772)
NASA Jet Propulsion Laboratory
California Institute of Technology

Hui Ying Wen, Gerhard Kruizinga, Meegyeong Paik, Felix Landerer, William Bertiger, Carly Sakumura, Tamara Bandikova, Christopher Mccullough

September 11, 2019

LEVEL 1 EXAMPLARY FILES

gracefo_1B_2025-02-13_RL04.ascii.LRI.tgz

gracefo_1B_2025-02-13_RL04.ascii.noLRI.tgz

Level1A and Level1B can be downloaded from

- https://podaac.jpl.nasa.gov/
- https://isdc.gfz.de/grace-fo-isdc/


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    publisher_url: http://podaac.jpl.nasa.gov
    references: https://podaac.jpl.nasa.gov/gravity/gracefo-documentation
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    summary: 1-Hz trajectory states from POD in Inertial Frame
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ERRORS IN TIME-SERIES DATA

Physical measurements like

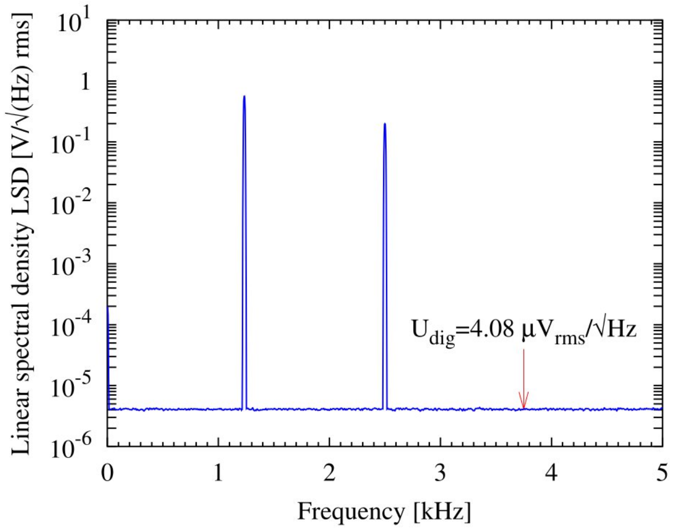
- Inter-satellite range
- Non-gravitational accelerations

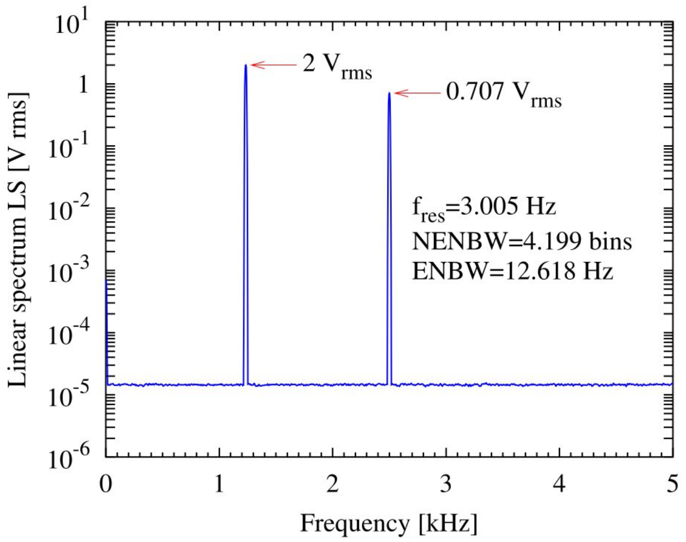
are recorded as voltage by an analog-to-digital converter in terms of digital raw counts (value 0... 1023).

Conversion from raw counts to physical units via calibration factors

Measurements or conversions have different types of errors:

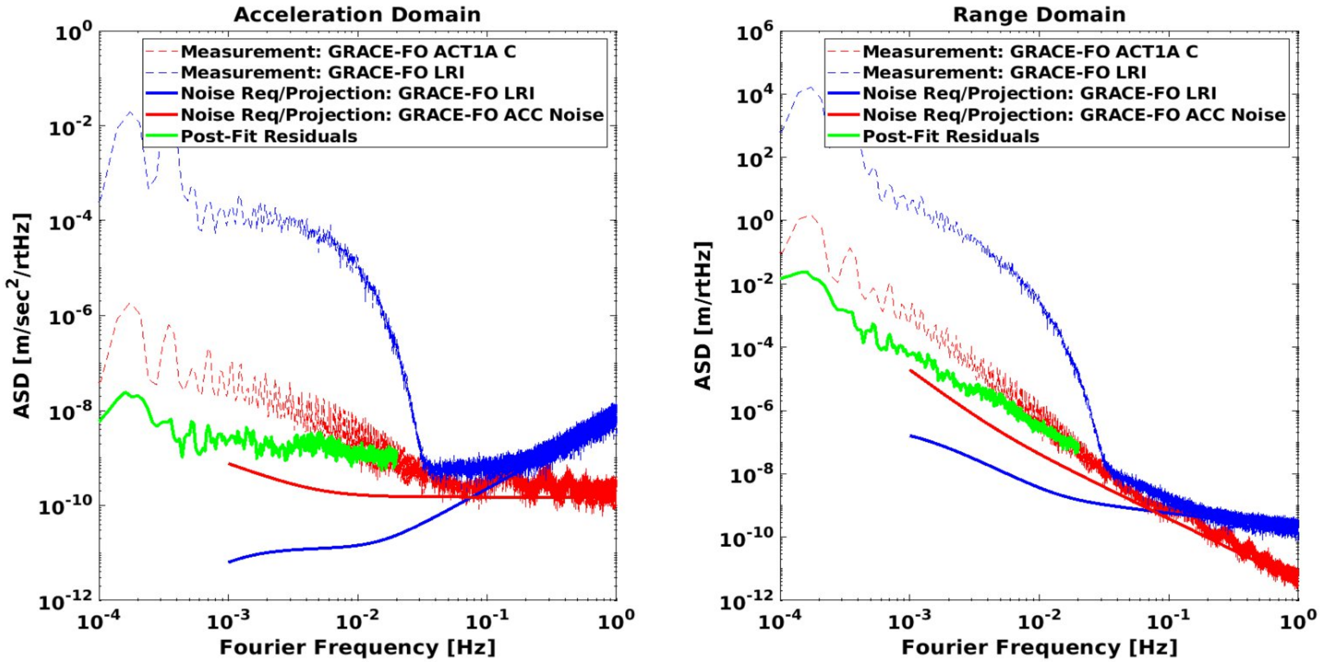
- Stochastic / random noise
  - Correctly described by a spectral density over frequency
    - Amplitude (Linear) spectral density (ASD/LSD): e.g. m/rtHz
    - Power spectral density (PSD): e.g. m² / Hz
  - Averaging of data improves the signal-to-noise ratio
- Deterministic errors
  - Sinusoidal (tone) errors at particular frequencies
    - Correctly described by an amplitude spectrum (e.g. m(rms) at f)
  - Biases/offsets
  - Drifts
  - Scale errors





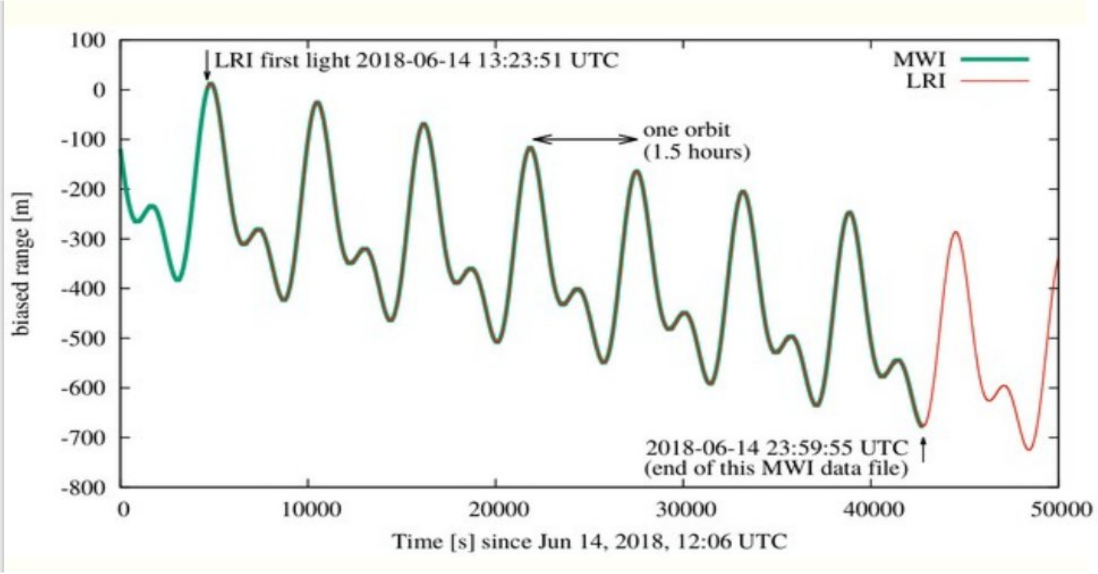
TYPICAL LRI AND ACC SIGNALS

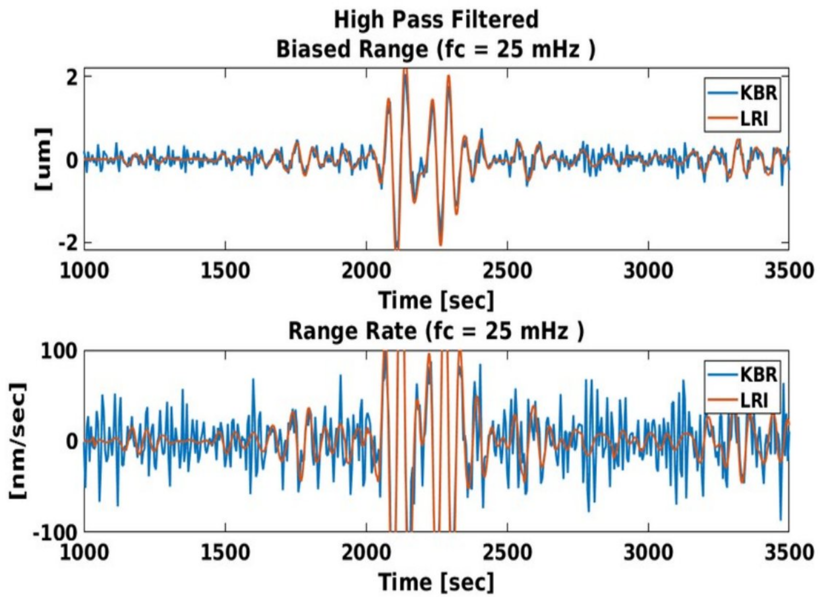
- **Instrument noise models / requirements close to actual measurements at high frequencies (above 0.1 Hz)**
  - measurement is noise dominated
- **LRI ranging data around 30..200 mHz dominated by non-gravitational signals (ACC)**
  - LRI data above predicted noise
- **Below 30 mHz, LRI and ACC are signal dominated**
- **LRI data exhibits 7..8 orders of magnitude between noise floor and signal**

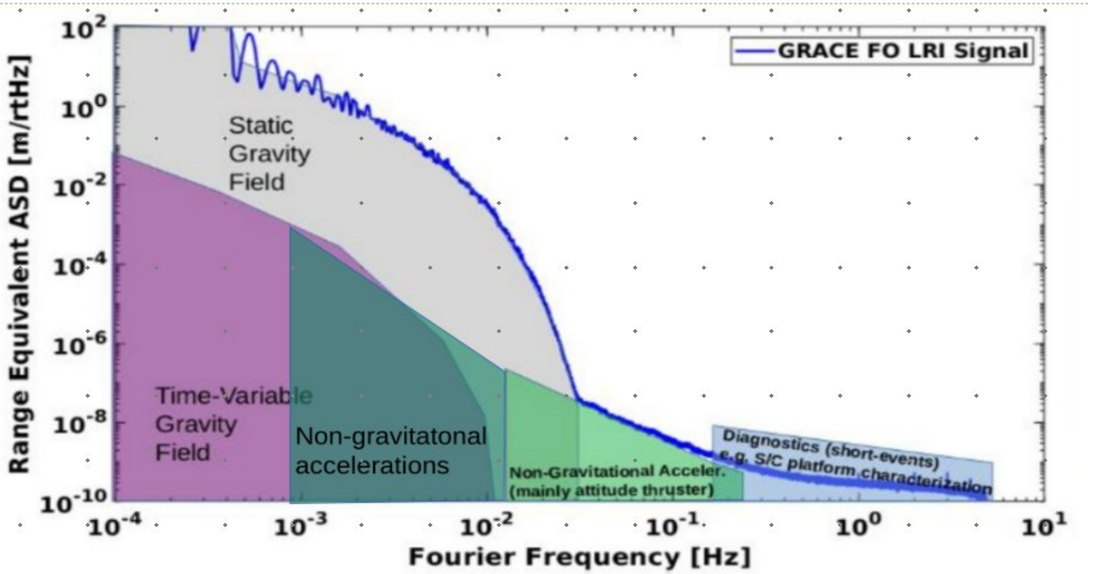


$$\text{Gravity Signal} \approx \ddot{\rho} - a_{\text{ng,LOS,SC1}} - a_{\text{ng,LOS,SC2}}$$

INTER-SATELLITE RANGING – SIGNAL CONTENT







ACCELEROMETER

Proof-mass re-centered by electro-static forces in housing

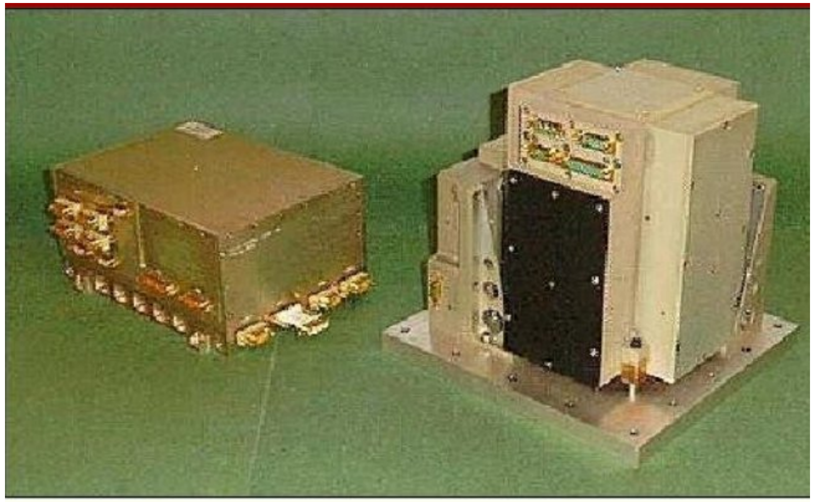
- Applied force ideally equal to non-gravitational accelerations acting on S/C
    - Atmospheric air drag
- Force applied between electrode plates and PM
    - common force along one PM face: linear force / acceleration
    - differential force between electrodes on one side: angular force/acc.

PM co-located with satellite center-of mass

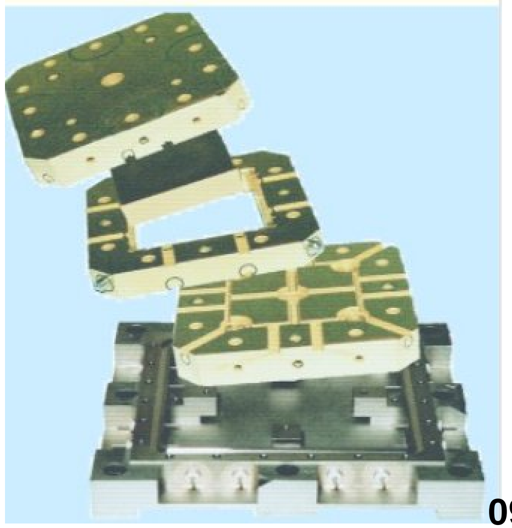
- co-location regularly measured using calibration maneuvers
- mass-trim mechanism activated to re-center S/C CoM to PM

Accelerometry is challenging

- ACC level1b data is highly low-pass filtered
- short-term disturbances/signals (e.g. from thruster) are not properly resolved in GRACE-FO
    - thruster events replaced by models
- GRACE-D ACC is malfunctioning
    - transplant ACC products available



SuperSTAR accelerometer with the sensor unit (right) and the ICU (left), image credit: ONERA; https://directory.eoportal.org/web/eoportal/satellite-missions/g/grace



ACCELEROMETER PERFORMANCE MODELS

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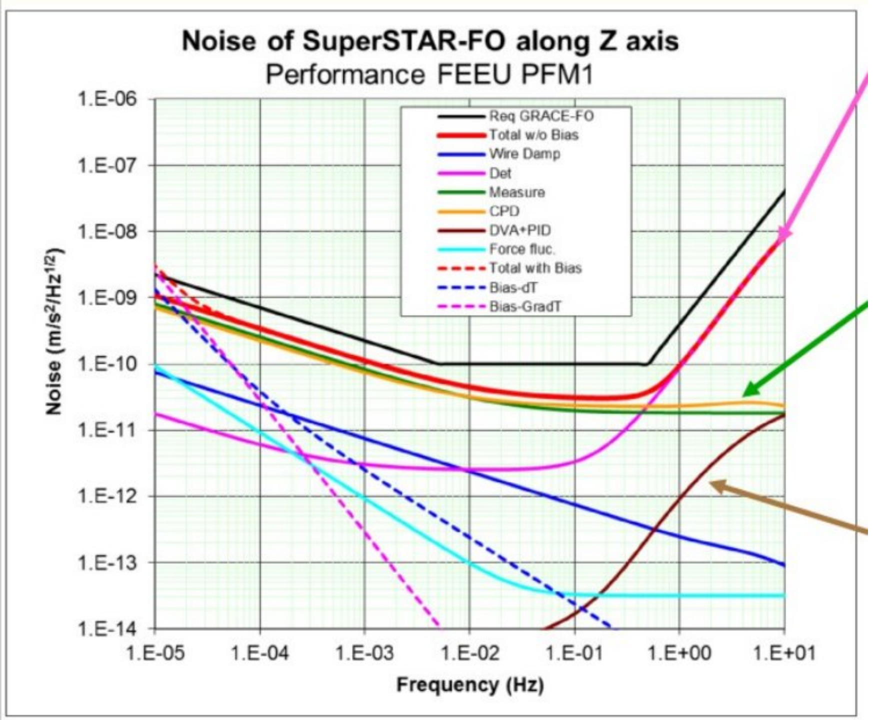

Christophe, Onera, Development status of GRACE Follow-On accelerometers, GSTM 2015

	Range	Resolution
x_{ARF}	$\pm 5 \cdot 10^{-4} \frac{m}{s^2}$	$10^{-9} \frac{(m/s^2)}{\sqrt{Hz}}$
y_{ARF}	$\pm 5 \cdot 10^{-5} \frac{m}{s^2}$	$10^{-10} \frac{(m/s^2)}{\sqrt{Hz}}$
z_{ARF}	$\pm 5 \cdot 10^{-5} \frac{m}{s^2}$	$10^{-10} \frac{(m/s^2)}{\sqrt{Hz}}$
φ(pitch)	$\pm 10^{-3} \frac{rad}{s^2}$	$2 \cdot 10^{-7} \frac{(rad/s^2)}{\sqrt{Hz}}$
θ (yaw)	$\pm 10^{-2} \frac{rad}{s^2}$	$5 \cdot 10^{-6} \frac{(rad/s^2)}{\sqrt{Hz}}$
ψ (roll)	$\pm 10^{-2} \frac{rad}{s^2}$	$5 \cdot 10^{-6} \frac{(rad/s^2)}{\sqrt{Hz}}$

Table 5.1: SuperSTAR range and resolution performance.

Najda Peterseim, TWANGS – High-Frequency Disturbing Signals in 10 Hz Accelerometer Data of the GRACE Satellites

INTERFEROMETRY

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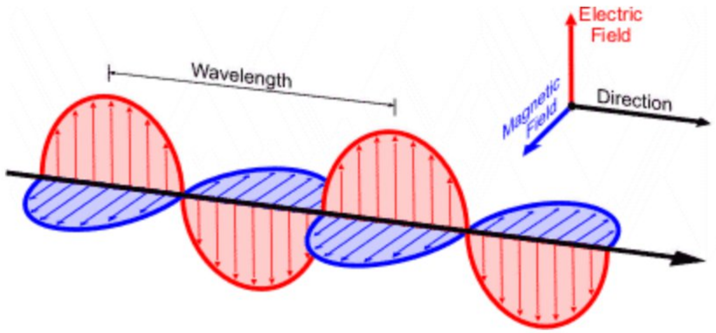
Electro-magnetic waves (light, radio or microwaves) are

- **exchanged between satellites**
- **produced by an oscillator**
  - Laser Ranging Instrument: laser source (resonator)
  - Microwave Ranging Instrument (KBR/MWI): ultra-stable oscillator clock at MHz, upconverted to 24/32 GHz
  - GNSS satellite: atomic clock transitions, upconverted to 1.1 .. 1.5 GHz (L1, L2, L5)



https://www.noaa.gov/jetstream/satellites/electromagnetic-waves

EM waves described by a field vector

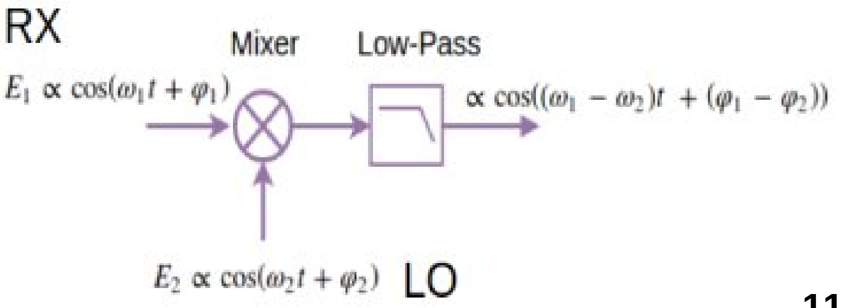
- amplitude $\mathrm{Re}[\vec{E}^c] \propto \mathrm{Re}[e^{i\omega t - ikr}] = \cos(\omega t - kr) = \cos(\omega \cdot t - \omega \cdot \Delta t) \propto \vec{E}$
- phase and frequency $\omega = 2\pi f = \frac{\mathrm{d}}{\mathrm{d}t}\varphi(t)$

Received phase is proportional to time and propagation delay (distance)

Phase can be measured by beating/interfering received (RX) waves with local field/oscillator (LO)

Phase tracking/measurement used in

- GNSS / GPS receiver
- Microwave Ranging
- Laser Ranging



LRI MEASUREMENT PRINCIPLE

Role of Reference and Transponder interchangeable

- Both S/C almost identically equipped
- Both S/C emit light at 1064 nm wavelength (281 THz) with 25 mW optical power

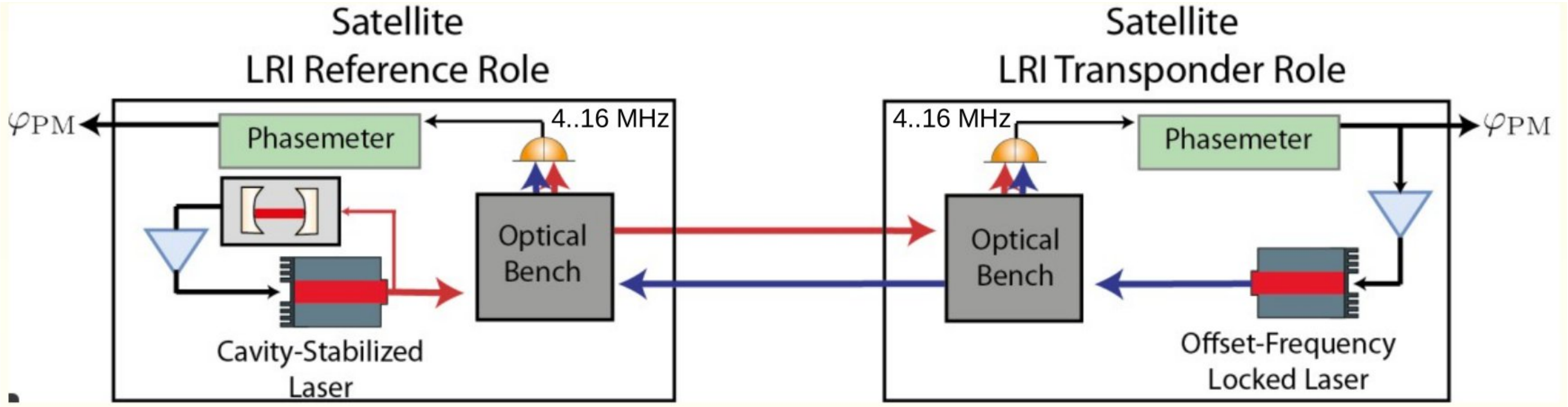
Transponder S/C: high-gain frequency locked loop (FLL)

- ensures that measured phase is a phase ramp with 10 MHz slope
- transponder laser has 10 MHz offset w.r.t. received light

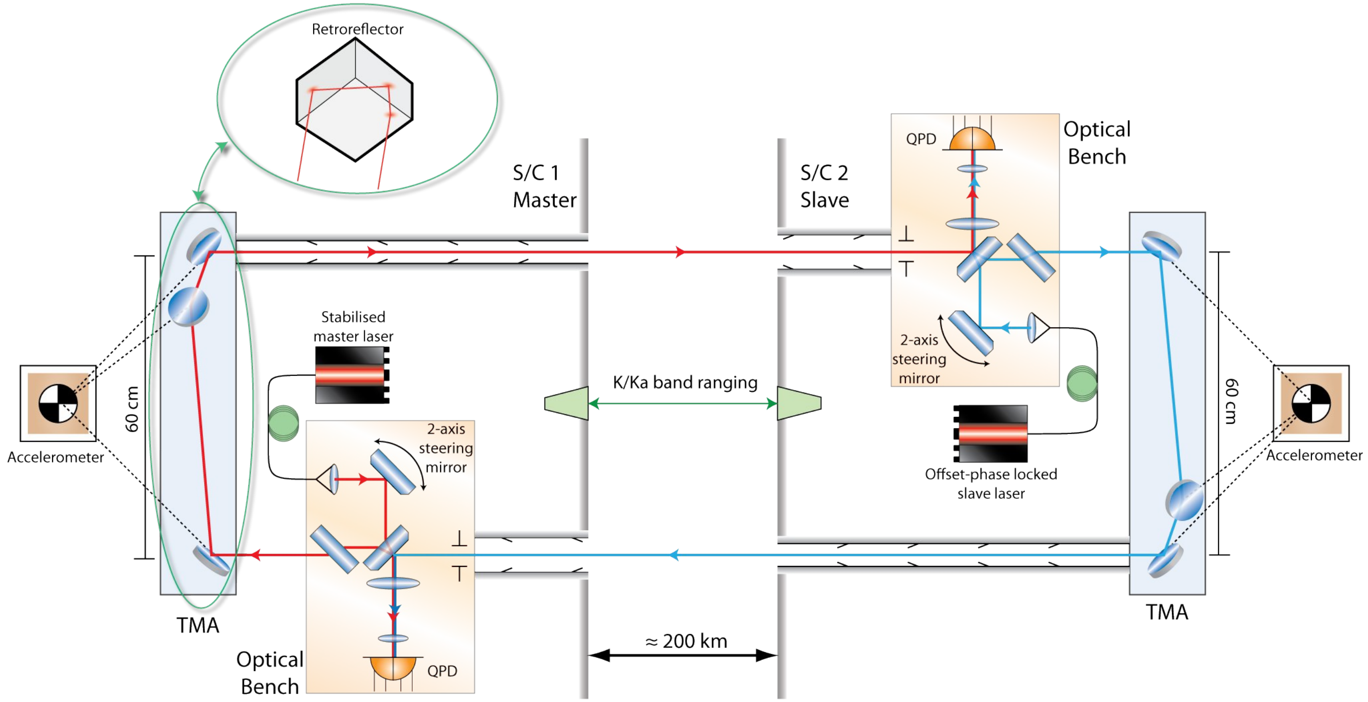
Reference S/C:

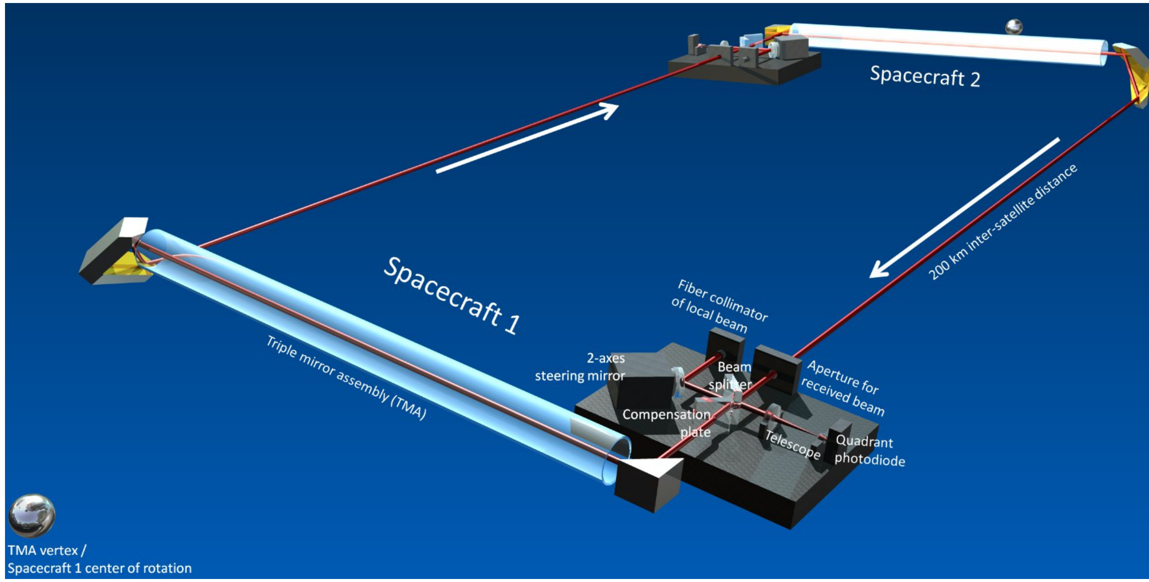
- Active laser frequency stabilization
- Measured frequency: 2x Doppler + frequency offset
- Phase:

$$\varphi_{\mathrm{PM,R}}(t) = 10\,\mathrm{MHz}\cdot t + \Phi_{\mathrm{Las,R}}(t) - \Phi_{\mathrm{Las,R}}(t-\Delta t_{\mathrm{RTR}}) + \mathrm{const.}$$
$$\approx 10\,\mathrm{MHz}\cdot t + \dot{\Phi}_{\mathrm{Las,R}}\cdot\Delta t_{\mathrm{RTR}} + \mathrm{const.}$$



LRI OPTICAL LAYOUT





Triple Mirror Assembly (TMA)

- produces 60 cm lateral beam offset
- guides beams around cold-gas tanks and KBR system
- „Reference points“ at TMA vertex,
  i.e. close to S/C center-of-mass

KBR (& LRI) LRI1B DATA FORMAT

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LRI re-uses KBR data format

Instantaneous (Corrected) biased range formed by

- biased ranged (includes the ionospheric correction)
- light time correction
- antenna offset correction

Parameter	Definition
gps_time	Seconds past 12:00:00 noon of January 1, 2000 in GPS Time
biased_range	CRN-filtered biased inter-satellite range. If KBR1B, contains ionospheric correction. See usage notes below table.
range_rate	First time derivative of biased_range
range_accl	Second time derivative of biased_range
iono_corr LRI scale	If KBR1B: biased ionospheric correction for biased_range, for Ka frequency. If LRI1B: estimated scale correction epsilon for biased_range, range_rate, and range_accl due to unknown onboard LRI frequency (scale correction = 1 + epsilon)
lighttime_corr	Light time correction for biased_range
lighttime_rate	Light time correction for range_rate
lighttime_accl	Light time correction for range_accl
ant_centr_corr	If KBR1B: antenna phase center offset correction for biased_range. If LRI1B: not defined
ant_centr_rate	If KBR1B: antenna phase center offset correction for range_rate. If LRI1B: not defined
ant_centr_accl	If KBR1B: antenna phase center offset correction for range_accl. If LRI1B: not defined

K_A_SNR CNR S/C_C	If KBR1B: SNR of K band for GRACE-FO C (or GRACE A) satellite (units of 0.1 db-Hz). If LRI1B: CNR of laser ranging for GRACE-FO C (or GRACE A) satellite (db-Hz)
Ka_A_SNR N/A	If KBR1B: SNR of Ka band for GRACE-FO C (or GRACE A) satellite (units of 0.1 db-Hz). If LRI1B: not defined
K_B_SNR CNR S/C_D	If KBR1B: SNR of K band for GRACE-FO D (or GRACE B) satellite (units of 0.1 db-Hz). If LRI1B: CNR of laser ranging for GRACE-FO D (or GRACE B) satellite (db-Hz)
Ka_B_SNR N/A	If KBR1B: SNR of Ka band for GRACE-FO D (or GRACE B) satellite (units of 0.1 db-Hz). If LRI1B: not defined
qualflg	Quality flag. Meanings of individual integers, from position 0 at right to position 7 at left, are as follows: 0: Phase break 1: If KBR1B: unreliable PCI1A data for ant_centr_corr. If LRI1B: not defined 2: If KBR1B: interpolated PCI1A data for ant_centr_corr. If LRI1B: not defined 3-4: Not defined 5: If KBR1B: data corrected for time tag bias in either K or Ka phase. If LRI1B: not defined 6: Interpolated data point (due to gap) exists $>$ 5 s from center of CRN filter window 7: Interpolated data point (due to gap) exists $<=$ 5 s from center of CRN filter window

Correcting Biased Range Before using the **biased_range**, **range_rate**, and **range_accl** values, the light time and antenna offset corrections must be added as follows:

Corrected biased range = **biased_range** + **lighttime_corr** (+ **ant_centr_corr** if KBR1B)

Corrected range rate = **range_rate** + **lighttime_rate** (+ **ant_centr_rate** if KBR1B)

Corrected range acceleration = **range_accl** + **lighttime_accl** (+ **ant_centr_accl** if KBR1B)

LIGHT TIME CORRECTION

MAX PLANCK GESELLSCHAFT

- Measured range differs from the instantaneous Euclidean separation

  $$|\vec{r_1}(t) - \vec{r_2}(t)|$$

  due to finite speed of light
  - instantaneous range needed for gravity field recovery
- Special relativistic effects
  - depend on velocity (and acceleration) of satellites
- General relativistic effects depend on
  - Earth‘s gravity field
  - Earth‘s Rotation (spin)
- Light time correction computed from GNSS derived orbit states
- LTC has a magnitude of up to
  - 200 km / c * 1 m/s = 660 µm

Journal of Geodesy (2021) 95:48
https://doi.org/10.1007/s00190-021-01498-5

ORIGINAL ARTICLE

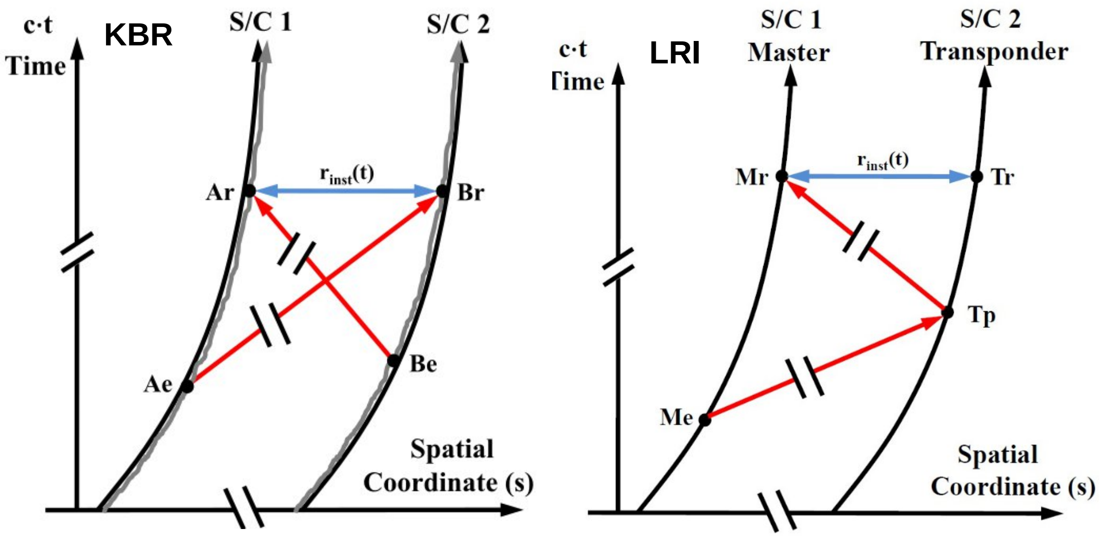
Check for updates

Revisiting the light time correction in gravimetric missions like GRACE and GRACE follow-on

Yihao Yan[1,2] · Vitali Müller[3] · Gerhard Heinzel[3] · Min Zhong[2,4]

Received: 19 May 2020 / Accepted: 4 March 2021 / Published online: 7 April 2021

$$\varphi_{\mathrm{PM,R}}(t) = 10\,\mathrm{MHz}\cdot t + \Phi_{\mathrm{Las,R}}(t) - \Phi_{\mathrm{Las,R}}(t - \Delta t_{\mathrm{RTR}}) + \mathrm{const.}$$
$$\approx 10\,\mathrm{MHz}\cdot t + \dot{\Phi}_{\mathrm{Las,R}}\cdot \Delta t_{\mathrm{RTR}} + \mathrm{const.}$$



It is noteworthy that the leading term in the TWR light-time correction

$$c_0 \widehat{\mathcal{T}}_{\mathrm{TWR}} = c_0 \frac{\mathcal{T}_{\mathrm{MeTp}} + \mathcal{T}_{\mathrm{TpMr}}}{2} = -\frac{|\mathbf{r}_B - \mathbf{r}_A| \cdot \dot{\rho}_{\mathrm{inst,OD}}}{c_0} + \mathrm{const.} + \ldots \quad (71)$$

differs by a factor of two compared to the DOWR correction (cf. Eq. (52)), whereby the static part has a similar magnitude (cf. Table 5).

ANTENNA OFFSET CORRECTION (TILT-TO-LENGTH)

Phase-tracking devices or ranging instruments like

- GPS (High-Low),
- KBR (Low-Low),
- LRI (Low-Low)

exhibit a cross-coupling between platform attitude and measured range (phase)

- center of rotation = S/C center-of-mass
- reference point for range/phase = antenna phase center or LRI TMA vertex point

Coupling Magnitude:

- Coupling factors LRI in yaw & pitch: ~100 µm/rad and ~1 mm/rad²
- Coupling factors KBR in yaw & pitch: ~100 µm/rad and **~1.4 m/rad²**

Satellite attitude variations/deadband

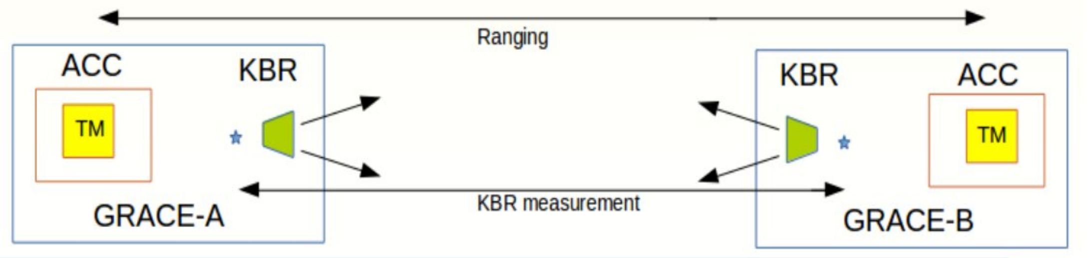
- ~300 µrad (peak)

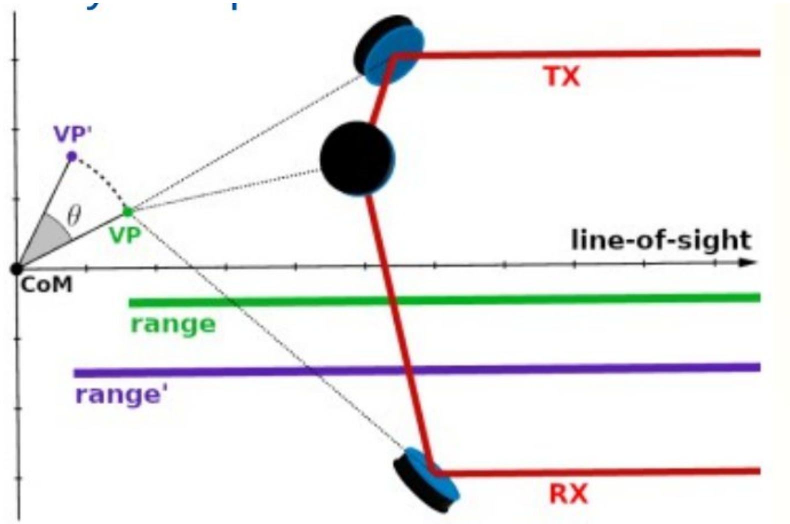
Official data products (RL04) consider only

- KBR antenna offset correction: static coupling factors

Alternative (AEI) data products (RL50)

- KBR & LRI antenna offset correction: dynamic coupling factors based on calibration maneuvers
- Available at: https://www.aei.mpg.de/grace-fo-ranging-datasets





[Wegener, https://doi.org/10.15488/11984]

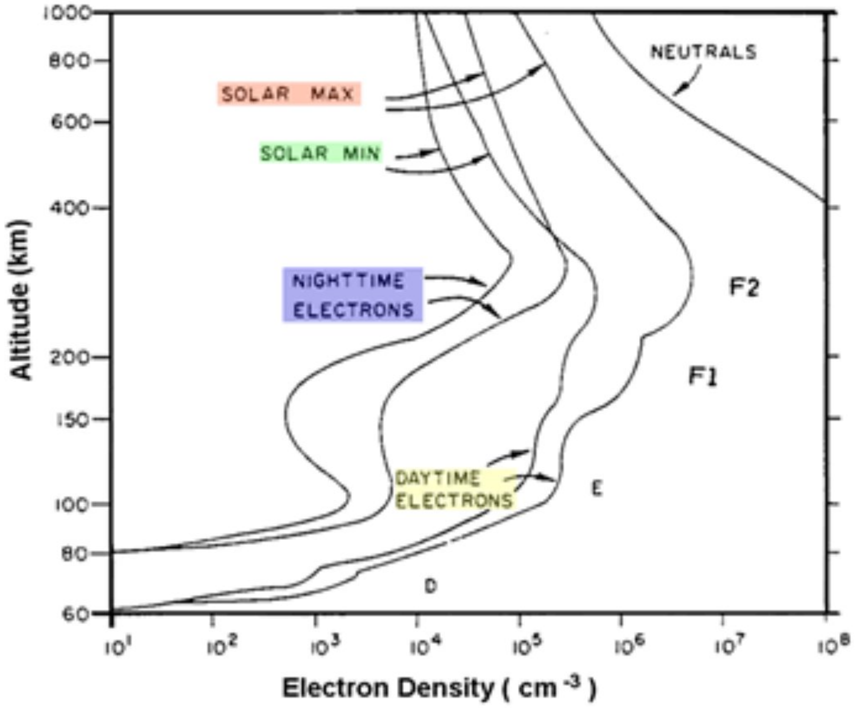
IONOSPHERIC CORRECTION

MAX PLANCK GESELLSCHAFT

- Free electrons in atmosphere change refractive index & propagation time
  - For KBR: total delay along one-way can be ~13 mm/c
- Static delays are uncritical, because phase tracking is always biased ranging
  - variations in delay / electron content are critical
- Effect is proportional to wavelength² ($1/f^2$)
  - highly relevant for KBR
  - negligible for LRI (10 ppb smaller than KBR)
- Microwave ranging instrument (MWI/KBR) and GPS perform dual-band measurements at different frequencies
  - variability in electron content can be measured
    - MWI/KBR: between satellites
    - GPS: between GRACE satellite and GNSS satellite
  - Ionosphere-free phase/range combination possible

$$\rho_{\mathrm{DOWR}}(t) := c_0 \cdot \frac{-9}{7} \cdot \frac{\varphi^{\mathrm{K}}_{\mathrm{DOWR}}(t)}{\nu^{\mathrm{K}}_{\mathrm{A}} + \nu^{K}_{\mathrm{B}}} + c_0 \cdot \frac{16}{7} \cdot \frac{\varphi^{\mathrm{Ka}}_{\mathrm{DOWR}}(t)}{\nu^{\mathrm{Ka}}_{\mathrm{A}} + \nu^{\mathrm{Ka}}_{\mathrm{B}}}$$

$$\begin{aligned}\Delta t_{\mathrm{media}} &= \frac{1}{c_0}\int_{\mathcal{P}} (n-1)\,\mathrm{d}s \approx -\frac{40.3\,\mathrm{Hz}^2/\mathrm{m}}{c_0 \cdot f_{\mathrm{em}}^2} \cdot \frac{\mathrm{TEC}}{1\,e^-/\mathrm{m}^2} \\ &= -\frac{40.3\,\mathrm{Hz}^2}{f_{\mathrm{em}}^2} \cdot \frac{\langle \eta \rangle}{1\,e^-/\mathrm{m}^3} \cdot \Delta t_{\mathrm{SR}}, \qquad (28)\end{aligned}$$



https://www.oc.nps.edu/NWDC_EM_Course/course_materials/module2_2.html

LASER VS MICROWAVE RANGING

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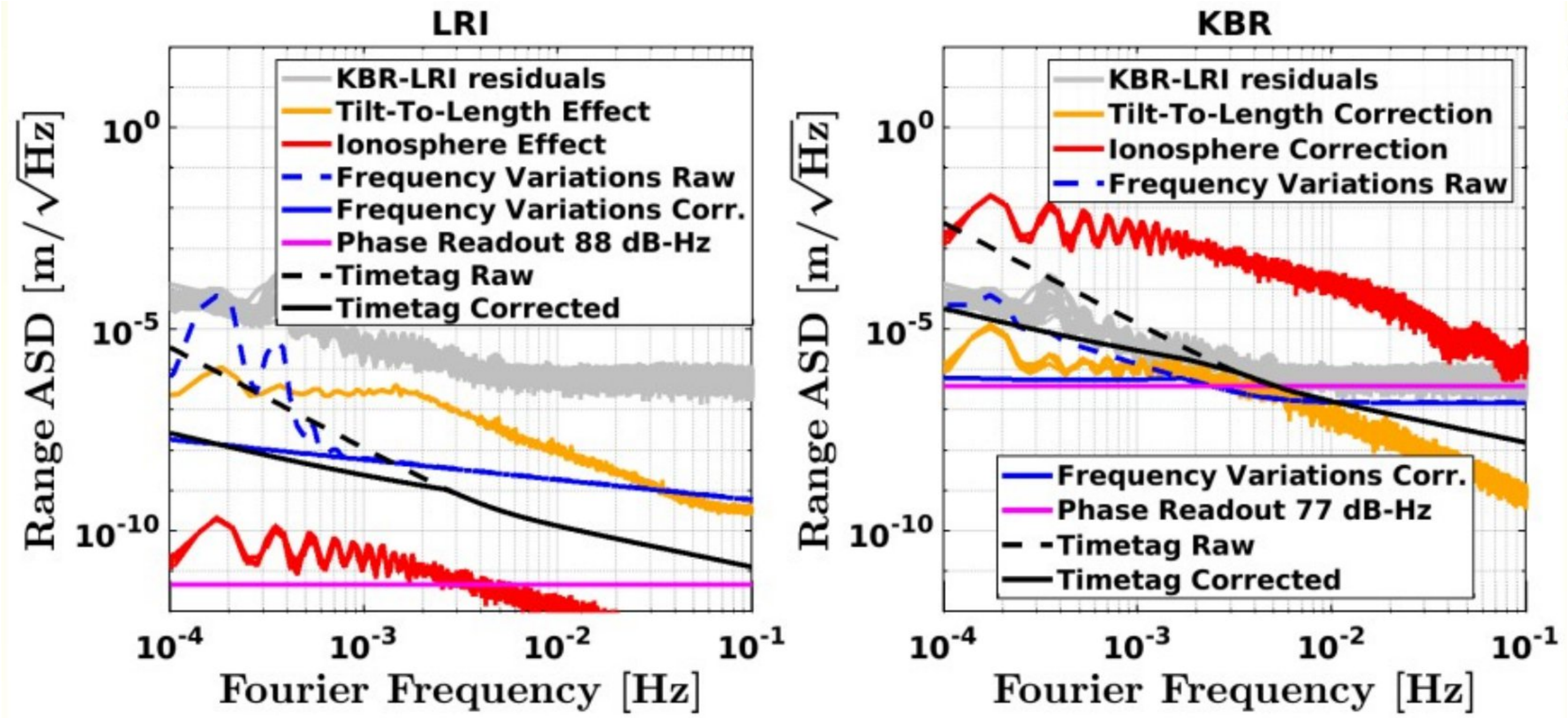

Comparing GRACE-FO KBR and LRI Ranging Data with Focus on Carrier Frequency Variations

by Vitali Müller [1,*], Markus Hauk [1,2,3], Malte Misfeldt [1], Laura Müller [1], Henry Wegener [1], Yihao Yan [1] and Gerhard Heinzel [1]

- Ionospheric effect significant (and is being corrected for)
- Microwave ranging limits (most-likely) KBR-LRI residuals
  - Time-tag accuracy after POD (black-solid trace)
- Frequency variations of microwaves (derived from USO) might impact as well
  - AEI applies carrier-frequency variations correction (FVC) in RL50

- High frequencies in KBR dominated by Phase-Readout noise

LRI LEVEL1A TO LEVEL1B PROCESSING

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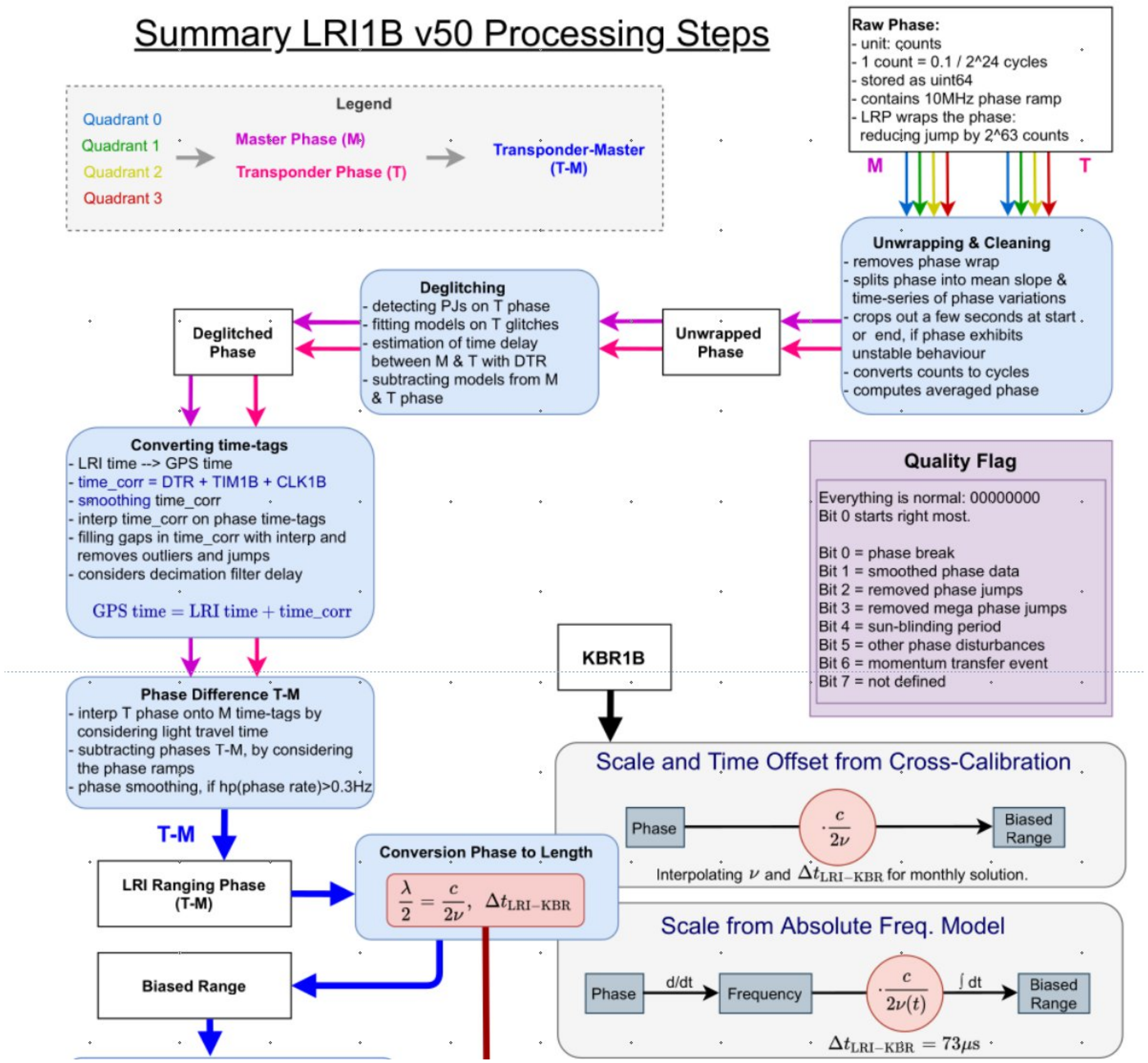
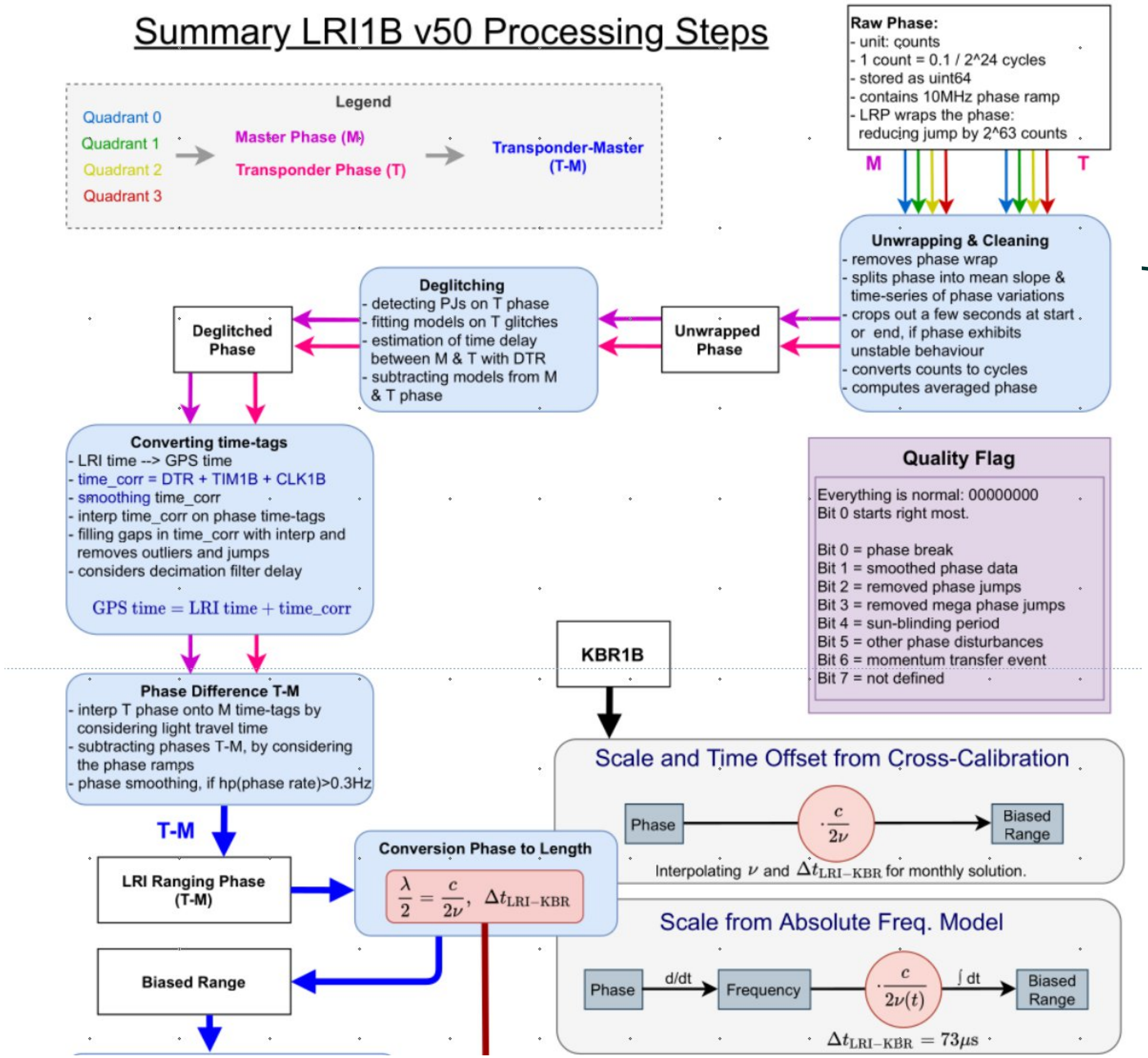
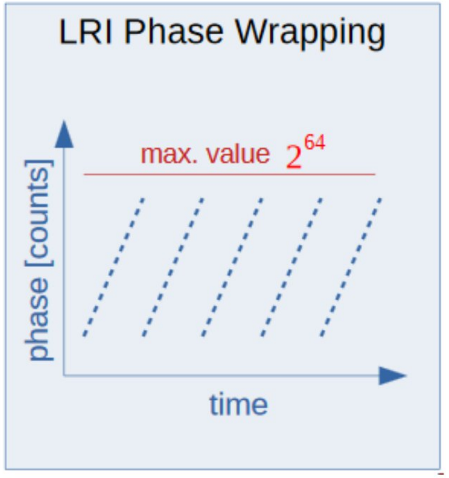


LRI LEVEL1A TO LEVEL1B PROCESSING

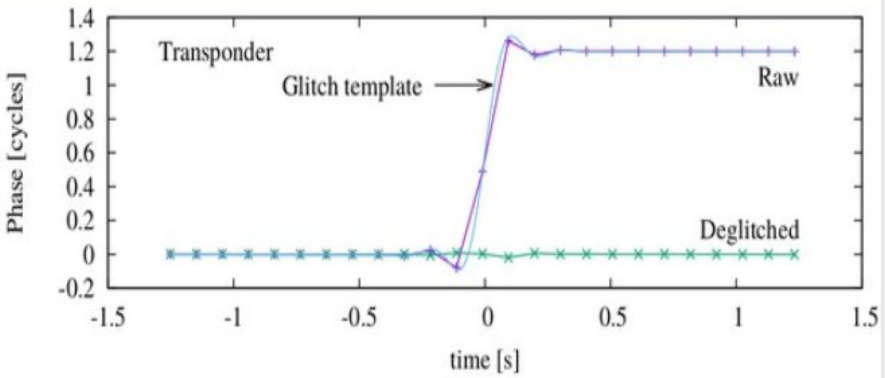


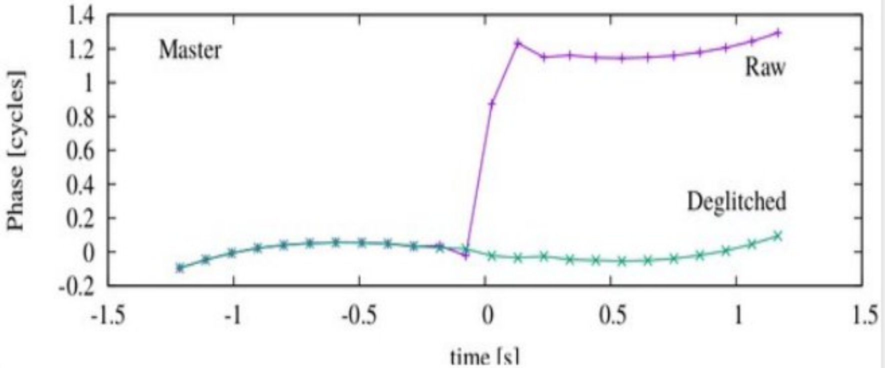


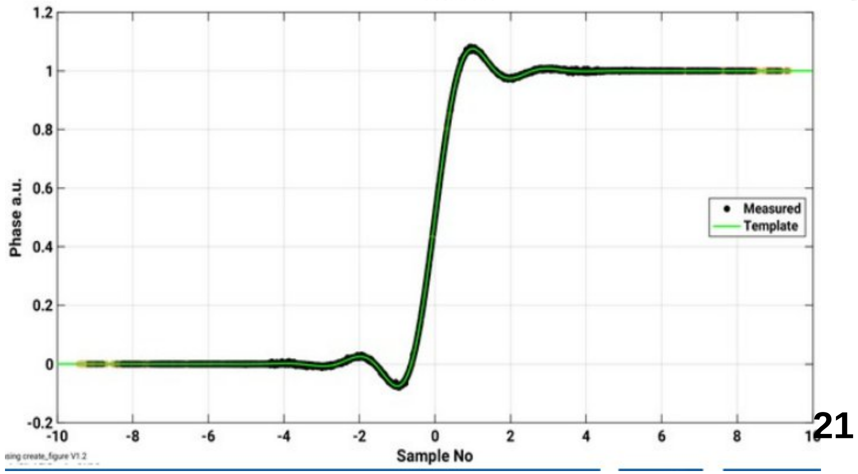
Constant Slope
+
Variations

DEGLITCHING

- LRI data showed „phase jumps“ when attitude control thrusters were fired
  - Laser crystal & laser frequency disturbed by micro-shocks
- Phase jump was present on both satellites (both data streams)
  - transponder data much cleaner as no ranging signal present
- Disturbances followed a pattern (template)
  - step response passing through on-board filter chains
  - each event samples template only sparsely and with undefined timing
- Transponder data was used to estimate scale and time of step/template
- Template was subtracted from reference (master) LRI data data
  - take into account propagation delay between satellites
- Flight-Software update changed configuration of the LRI
  - glitches removed/attenuated in-flight since September 2022
- Initial deglitching of LRI data on JPL side was not optimal until August 2020
  - use AEI data-sets: https://www.aei.mpg.de/grace-fo-ranging-datasets







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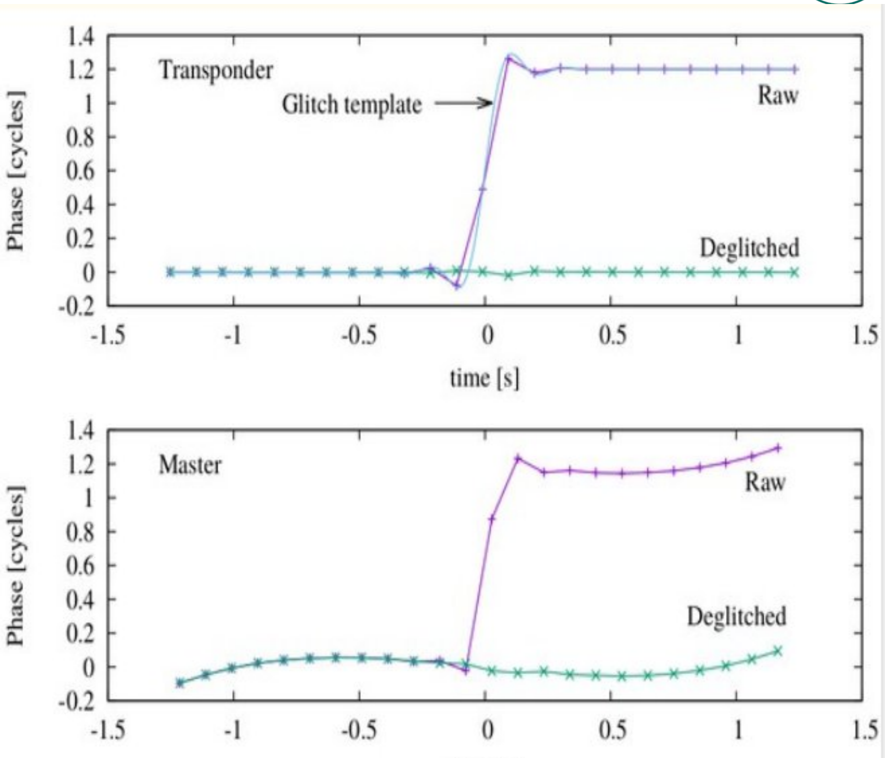

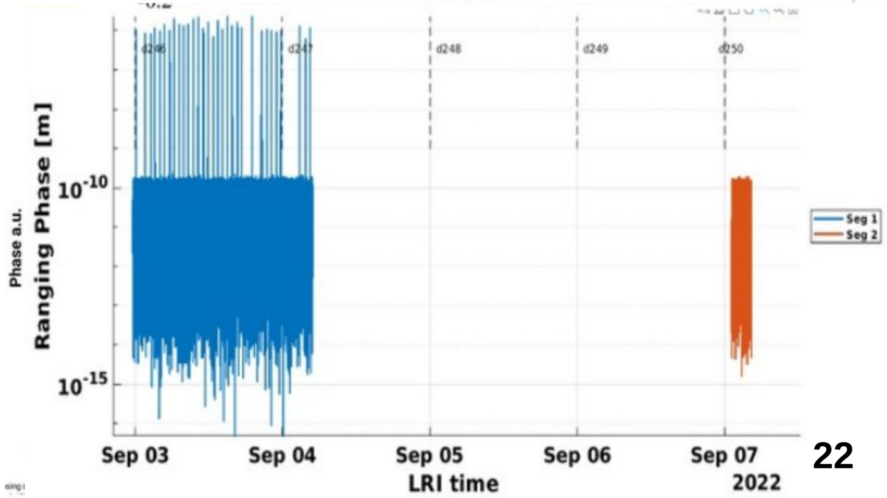

LRI LEVEL1A TO LEVEL1B PROCESSING

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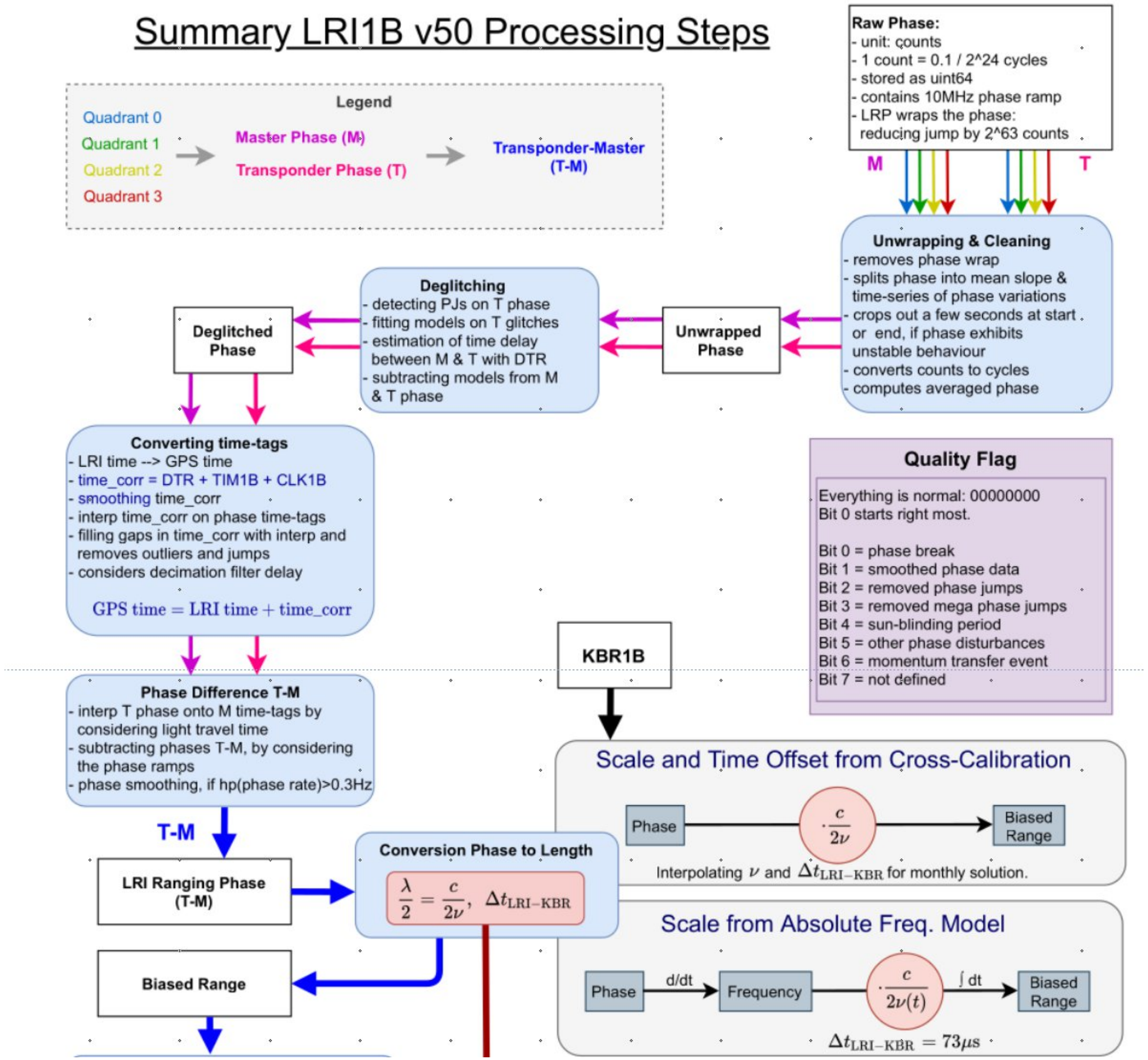


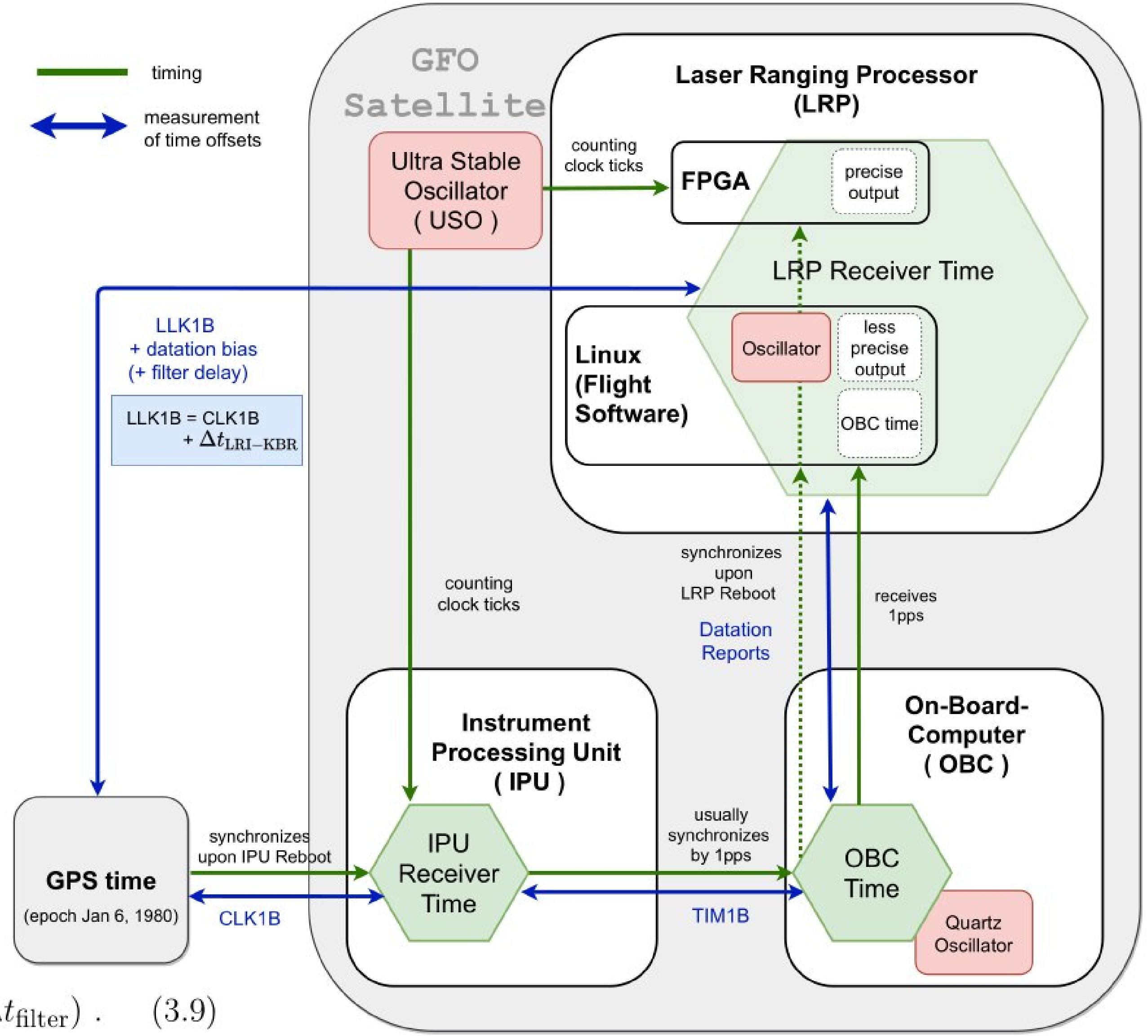
TIME-TAG CONVERSION

- GRACE-like missions require well-known timing relation between
  - GNSS/GPS observations
  - Inter-satellite ranging observations
  - Common clock required for both instruments
- Since GRACE-FO Instrument Processing Unit (IPU) contains
  - GNSS receiver
  - Microwave ranging system

timing is well known between GNSS and MWI.

- LRI time-tag conversion more elaborated due to different time systems
  - time-tag offsets change upon instrument reboots
  - on-board computer is in the loop and might introduced delays
- Conversion to GPS time requires precise orbit determination
  - on-board navigation solution not sufficient
- **Formula:**

$$\text{GPS time\_tag} = \text{LRI time\_tag} + \text{DTR}_{\text{offset}} + \text{TIM1B}_{\text{offset}} + \text{CLK1B}_{\text{offset}} \ (+\Delta t_{\text{filter}}) \ . \qquad (3.9)$$



[Master thesis, Laura Müller, 2021, AEI]

SCALE FACTOR FOR RANGING

- Ranging instrument exhibit high signal to noise ratio
  - 10^7 in SNR requires a scale error of 10^{-7}
- Conversion from phase to biased range/distance via wavelength (= c/frequency)
- Microwave Ranging Instrument scale factor well known
  - USO frequency and microwave frequencies (carrier) directly determined through precise orbit determination relative to GNSS
- LRI laser frequency depends on the laser and optical resonator
  - good stability, but poor accuracy
- GRACE-FO with tech-demo LRI:
  - Primary approach:
    - cross-correlate MWI ranging data with LRI ranging data
      - refine LRI scale factor
  - Alternative approaches (less precise)
    - rely on ground-calibrations or temperature models
- Future missions (GRACE-C, NGGM):
  - dedicated measurement technique to measure laser frequency
  - Scale Factor Unit / Scale Factor Measurement System

Simplified Formula:

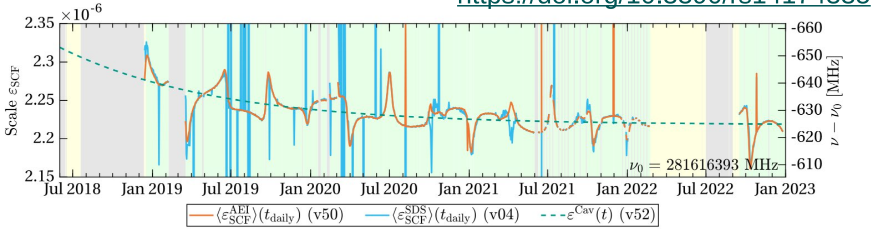
$$\Delta\rho = \frac{1}{2}\frac{c}{\nu}\cdot\Delta\varphi = \frac{1}{2}\lambda\cdot\Delta\varphi$$

Accurate approach:

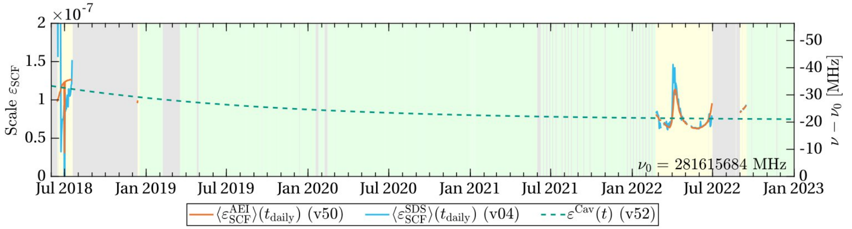
A handy approximation of the exact form in eq. (28) with all quantities being evaluated at the same time is given as

$$\rho_{\mathrm{TWR,2approx}} = c_0 \int_0^t \frac{\mathrm{d}\varphi_{\mathrm{TWR}}(t')/\mathrm{d}t'}{2\nu_{\mathrm{R}}(t')} - \left(1 - \frac{\mathrm{d}\Delta t_{\mathrm{RTR}}^{\mathrm{GPS}}}{\mathrm{d}t}\right)\cdot\frac{\dot{\nu}_{\mathrm{R}}(t')}{2\nu_{\mathrm{R}}(t')}\Delta t_{\mathrm{RTR}}^{\mathrm{GPS}}(t')\,\mathrm{d}t', \qquad (31)$$

https://doi.org/10.3390/rs14174335



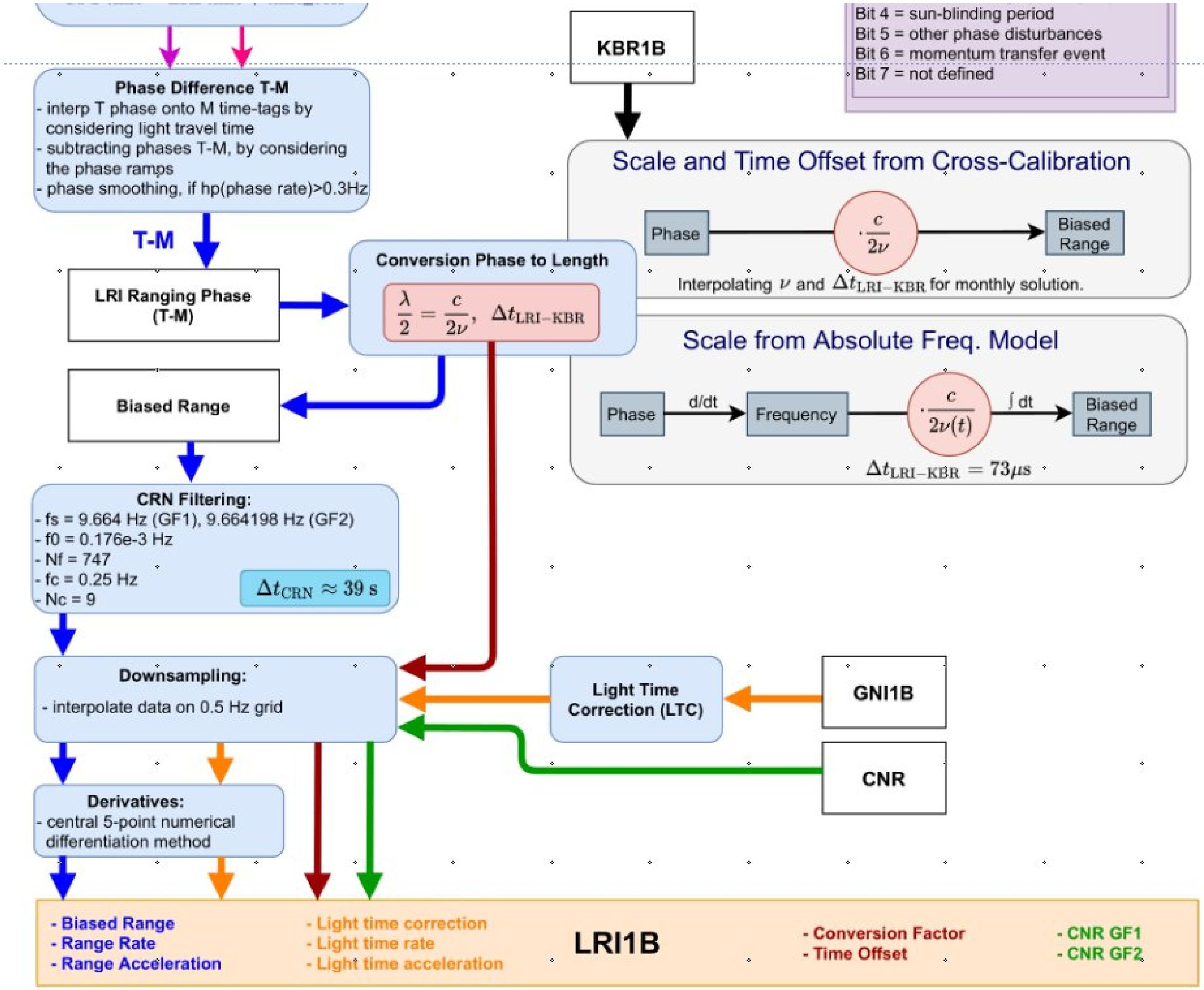
(a) Scale factor estimate of GF-1



(b) Scale factor estimate of GF-2

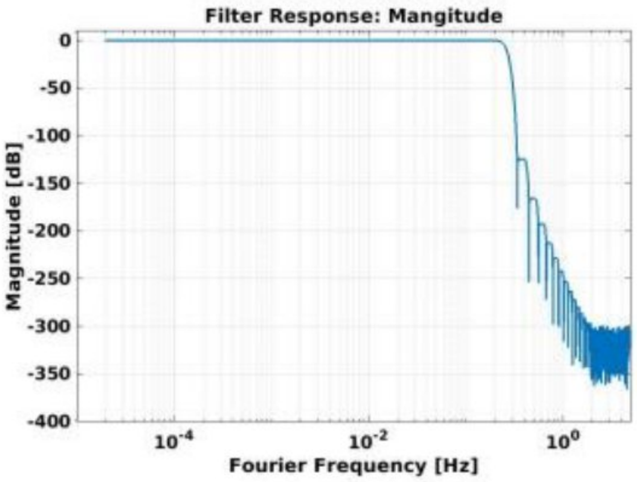
https://doi.org/10.15488/15152

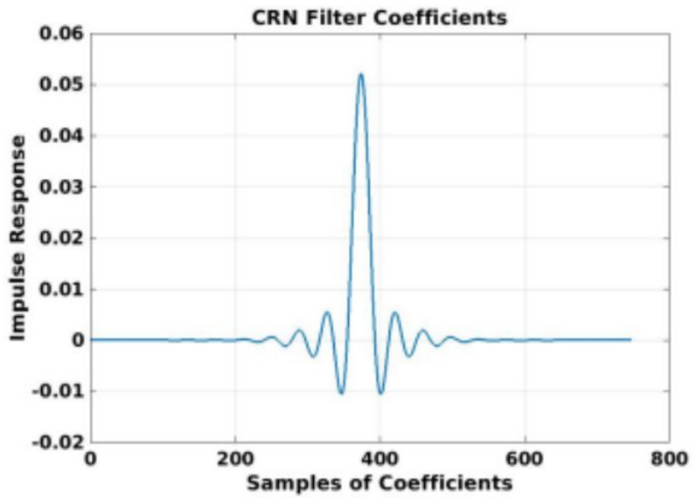
LRI LEVEL1A TO LEVEL1B PROCESSING



CRN FILTERING

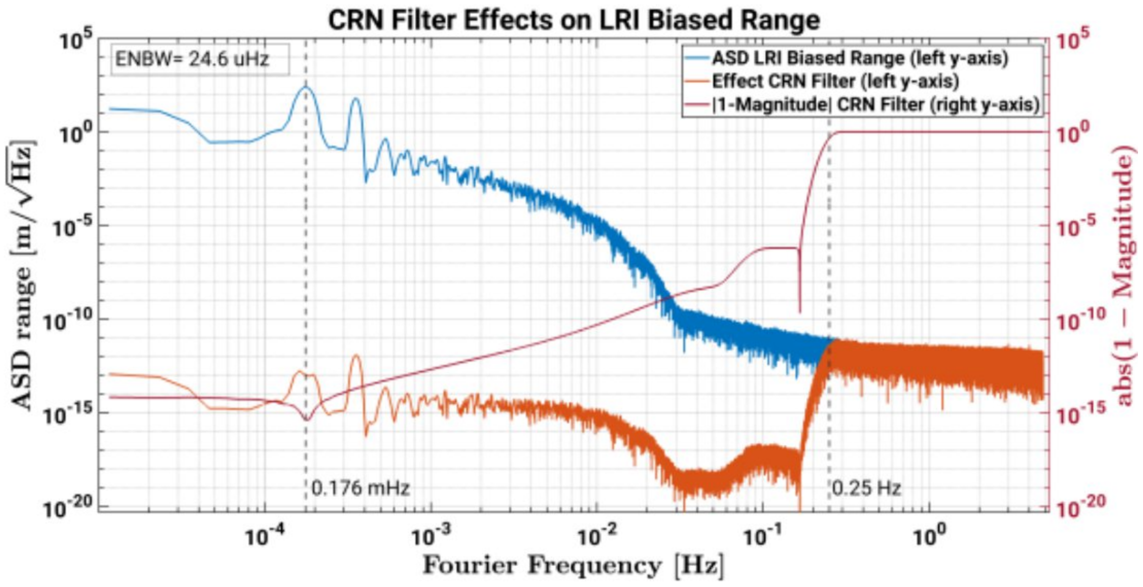
- Special (but simple) FIR filters used in GRACE-context
  - Convoluted Rectangle of order N (CRN)
- Filter ensures that
  - high frequencies are attenuated prior decimation
    - avoid aliasing noise
  - Low frequencies have unity gain
    - deviations smaller than 10^{-7}
- Filters can be directly used to differentiate data





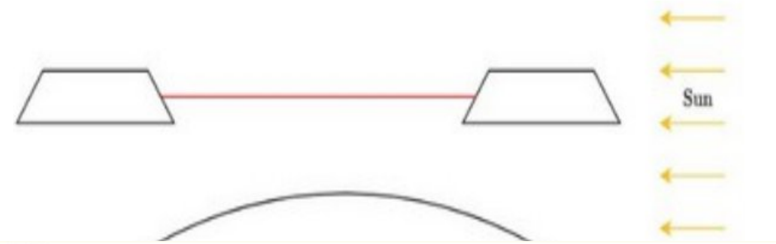
[Master thesis, Laura Müller, 2021, AEI]

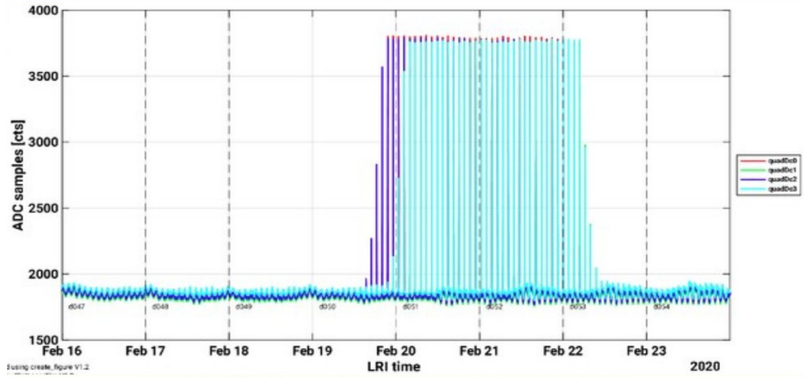
Parameter	Value
Sampling rate f_s	~10 Hz
Optimal frequency f_0	0.176 mHz
Cut-off frequency f_c	0.25 Hz
Filter length in samples N_f	747
Convolution number N_c	9

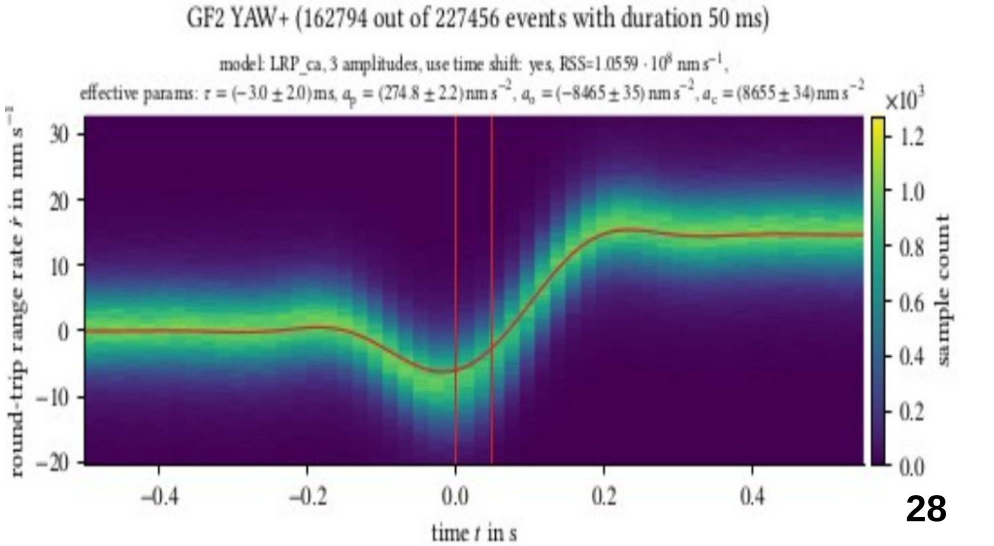


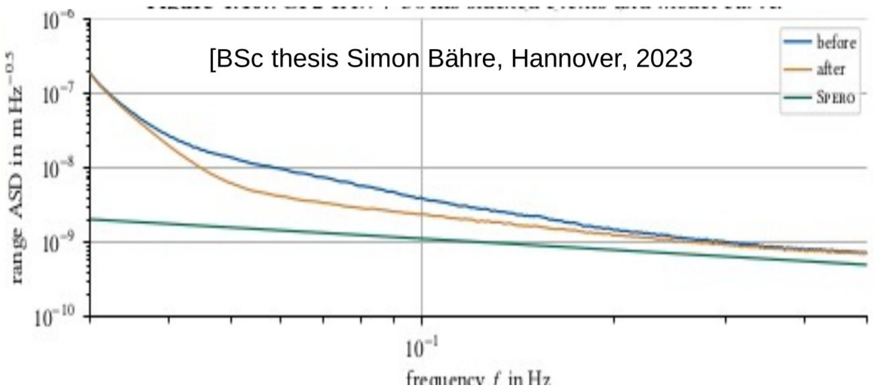
EVENTS IN LRI DATA I

- **Sun-Blinding**
  - LRI receives into baffles direct sun-light at particular locations in orbit
  - occurs every ~161 days for a few days
  - DC channels of LRI saturate, higher noise possible in ranging data
  - Laser link is maintained
- Parasitic accelerations/velocity change along line-of-sight from **attitude control thruster**
  - individual events not useful (low rate, noise)
  - stacking of several thousand events provides clear model/curve
  - estimated dv values can be used to improve ACC models/processing
  - lowers spectrum of LRI data



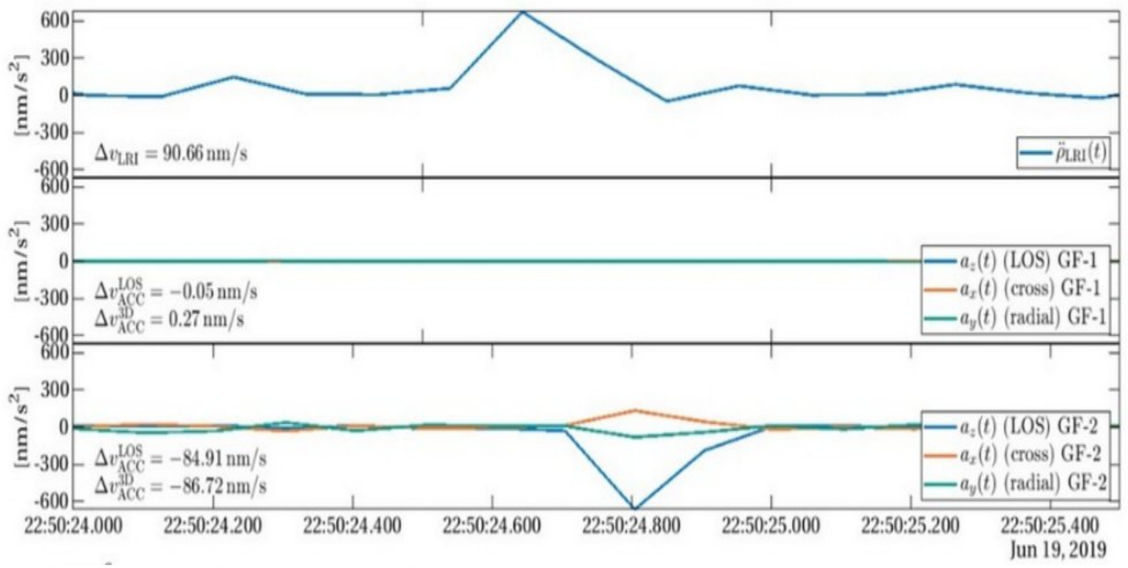


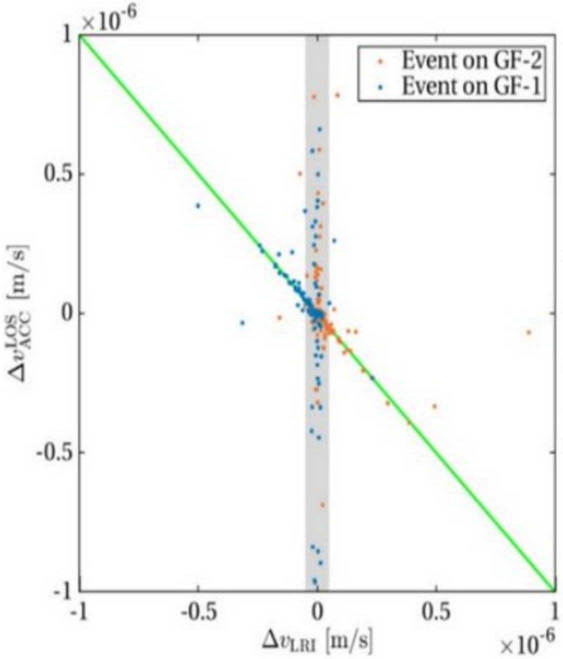


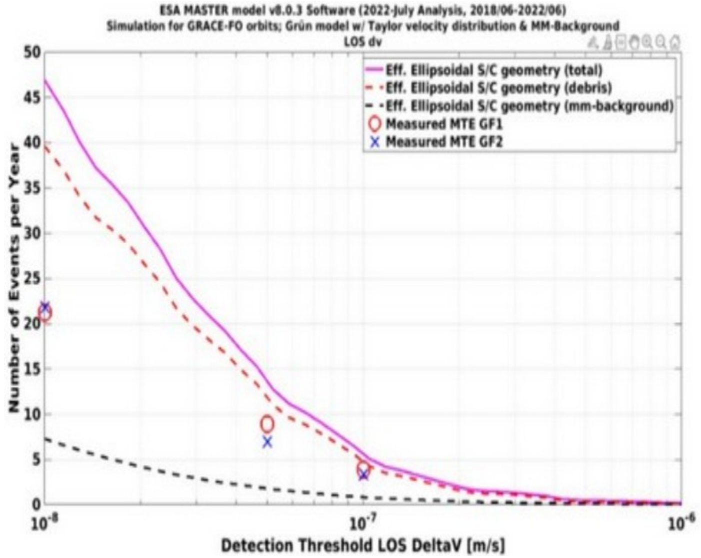


EVENTS IN LRI DATA II

- Momentum-Transfer Events
  - sporadic disturbances in the LRI data
  - some of them are correlated with disturbances in ACC GF1 and GF2 (level1a)
  - events have non-zero momentum / velocity change
    - area under acceleration curve
  - likely micro-meteorides impinging onto S/C
    - µgram scale objects, a few 10 µm size
  - Some events show large delta-V in LRI, but ~zero in ACC
    - disturbances not properly resolved by ACC
  - Observed event rates consistent with models of space-debris & micro-meteoride background
    - 50% error bars on models
  - Events not visible in KBR due to higher noise







SUMMARY

What is Level0, Level1A, Level1B instrument data?

Where to get it? Documentation -> Handbook

Basic understanding how to convert level0 to level1b data?

Most important data corrections for ranging data

- Ionospheric correction, Antenna-Offset, Light-Time-Correction

Similarity of KBR and LRI data & processing

What are the challenges in level1 processing?