Simulations of Laser Ranging Instrument Data in Future Gravity Missions

Laura Müller[1,2], Vitali Müller[1,2], Malte Misfeldt[1,2] and Gerhard Heinzel[1,2]

1 Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Hannover, Germany
2 Gottfried Wilhelm Leibniz Universität, Hannover, Germany

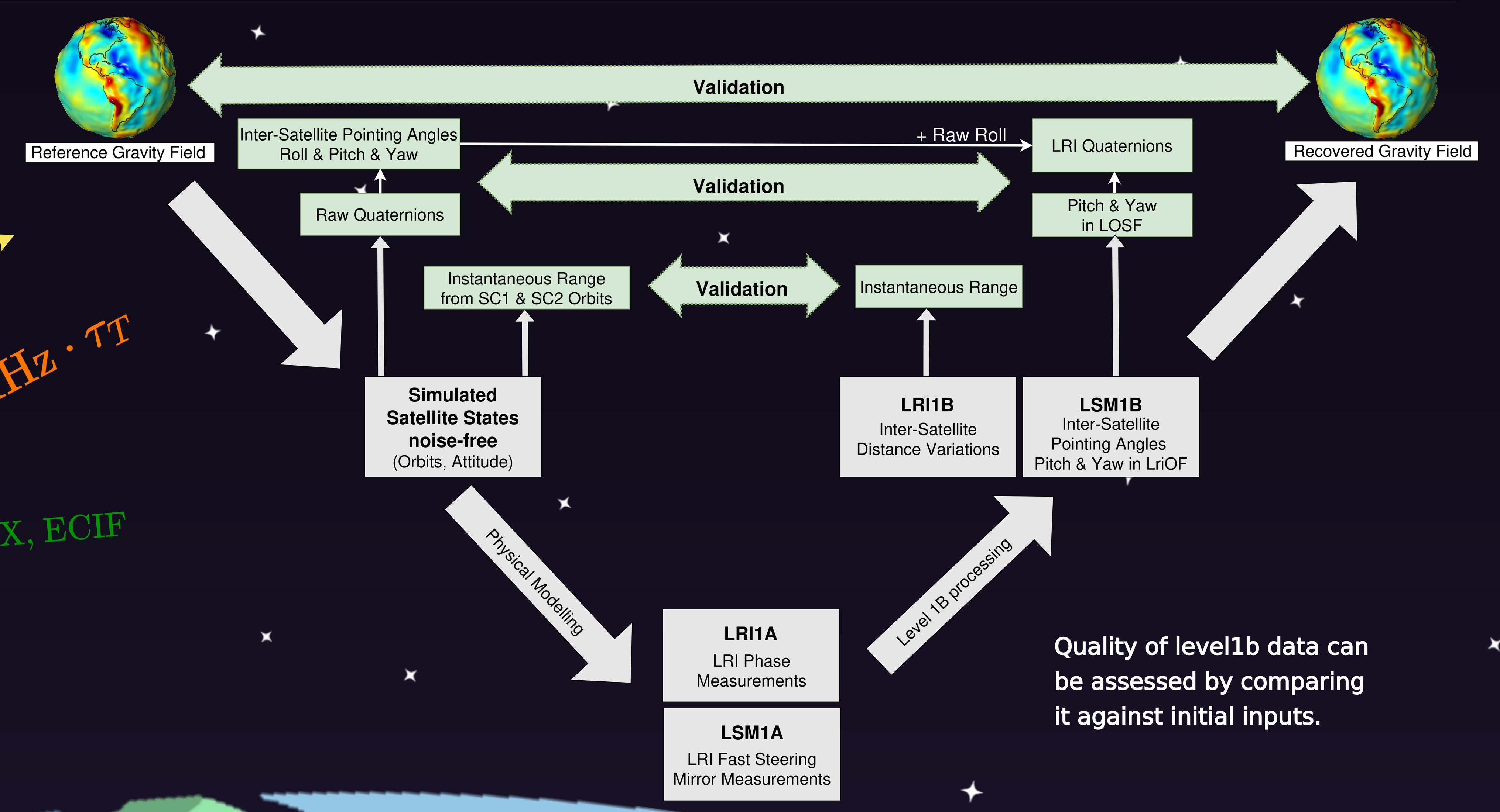
Contact Information: laura.mueller@aei.mpg.de

Background

The Gravity Recovery and Climate Experiment (GRACE, 2002-2017) and its successor GRACE Follow-On (GRACE-FO, 2018 - *) recorded changes in the Earth's mass distribution, providing valuable insights in redistributions of groundwarter, rising sealevels and melting ice caps. Future gravity missions, such as NGGM, GRACE-C and TianQin-2 are currently under development and will use a Laser Ranging Instrument (LRI) to measure the main observable - distance variations between two satellites which are orbiting the Earth in a separation of 200 km.

Introduction

To support studies for future gravity missions, the Albert Einstein Institute (AEI) developed a novel LRI Level 1A data simulator, using noise-free orbits and attitude. The simulator derives LRI phase measurements, sensor values of the LRI Fast Steering Mirror (FSM), and outputs for a scale factor measurement system. Produced level1a files are further processed to level1b, using the AEI in-house derived GRACE-FO real-data processing chain. These LRI simulations are helpful to understand the behaviour of different noise contributors within the instrument and allow to derive realistic LRI data for gravity field recovery.



Quality of level1b data can be assessed by comparing it against initial inputs.

LRI Simulator Modules

Inputs:
- Error-free orbits and attitude are required inputs for the LRI simulator.
- Additional information such as temperatures can be used to derive more realistic data.

Timing:
- Local time: simple model based on spacecraft velocity and Earth gravity potential.
- Considering a clock stability model and static datation bias between GNSS receiver and LRI computer.
- Level1b chain: POD noise model and datation readout noise is added to time-tag correction.

Pointing Angles:
- Rotation matrices yield inter-satellite pointing angles between LRI optical Frame (LRIOF) and Line-of-Sight Frame (LOSF).
- Readout noise of Positioning Sensing System (PSS), thermal coupling effects and digitization yield FSM sensor values.
- Level1b chain: sensor values are converted to LRI yaw and pitch information, considering calibration errors.

Reference Points (RP):
- RX- and TX-RP are converted from Satellite Reference Frame (SRF) to Earth Centered Inertial Frame (ECIF).
- Naturally incorporates Tilt-to-Length (TTL) and Angular Rate Coupling (ARC).

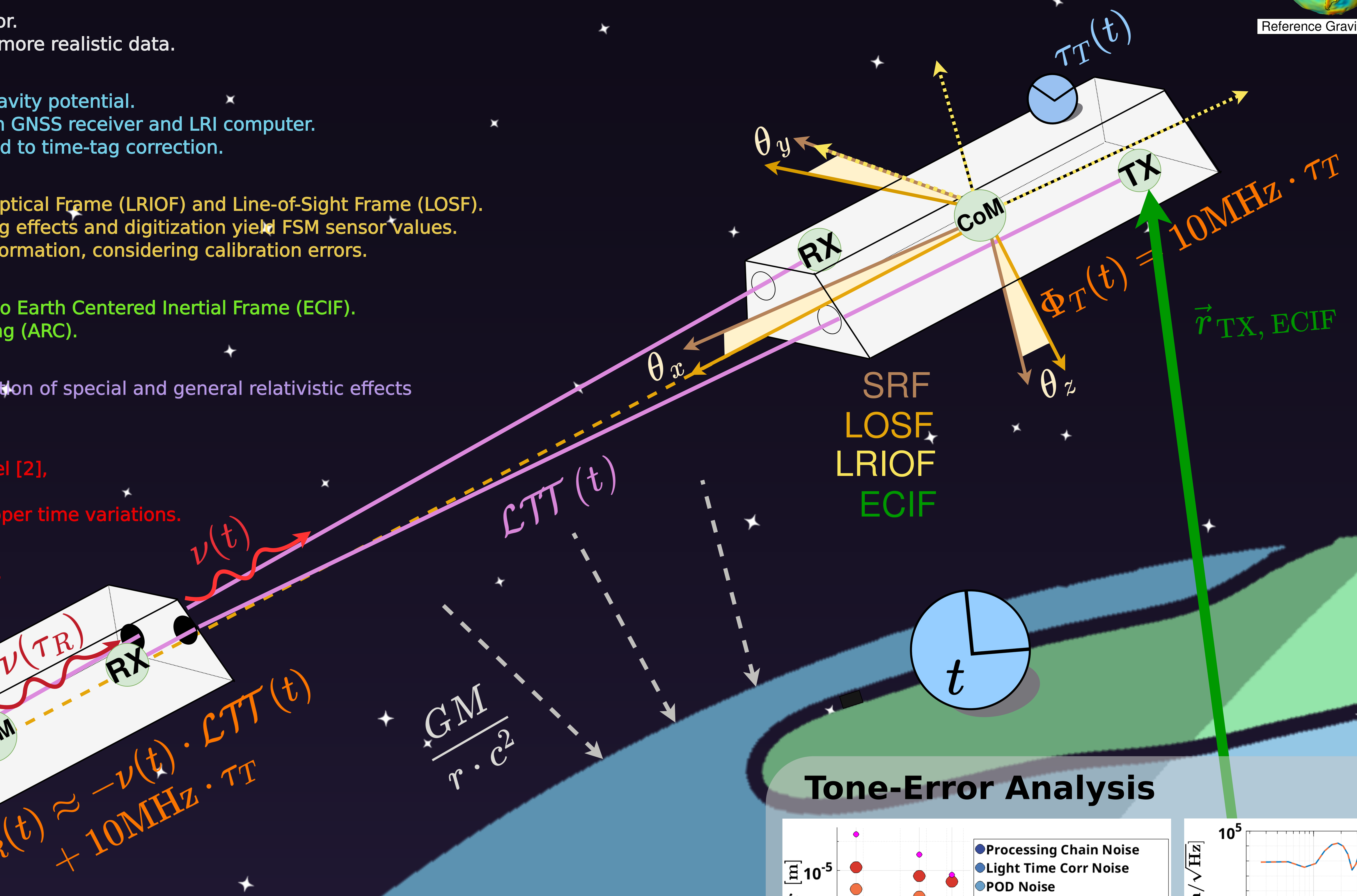
Light Travel Time (LTT):
- Signal propagation time [1] along TX-RX connection, with consideration of special and general relativistic effects due to relative velocities and Earth gravity potential.

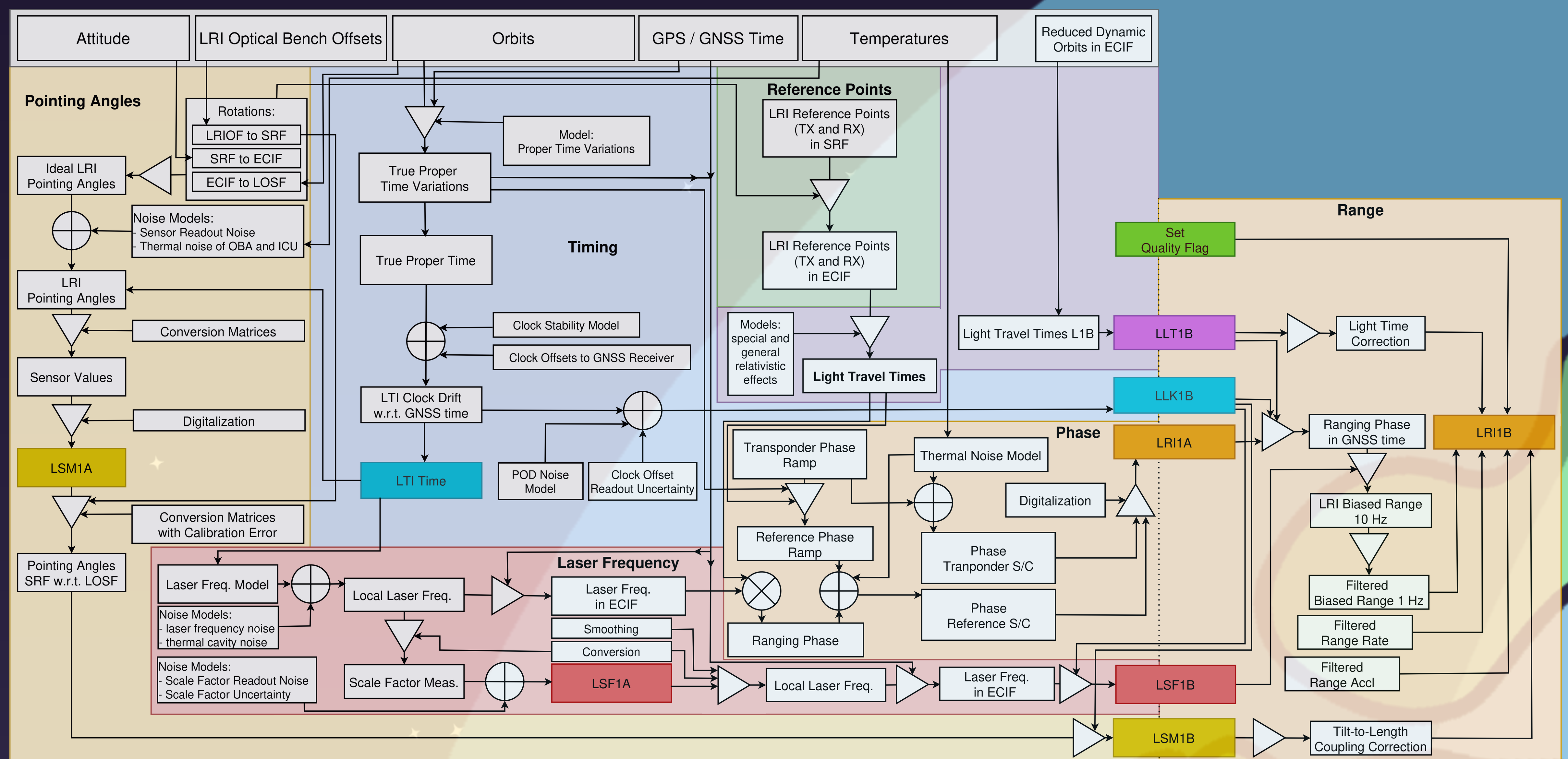
Laser Frequency:
- Local laser frequency is based on an exponential cavity decay model [2], laser frequency noise and temperature-induced errors in cavity.
- For phase derivation it is converted into the ECIF by considering proper time variations.

Scale Factor:
- Local laser frequency is converted into a scale factor measurement, based on the free-spectral-range.
- DC value uncertainty and readout noise are considered.

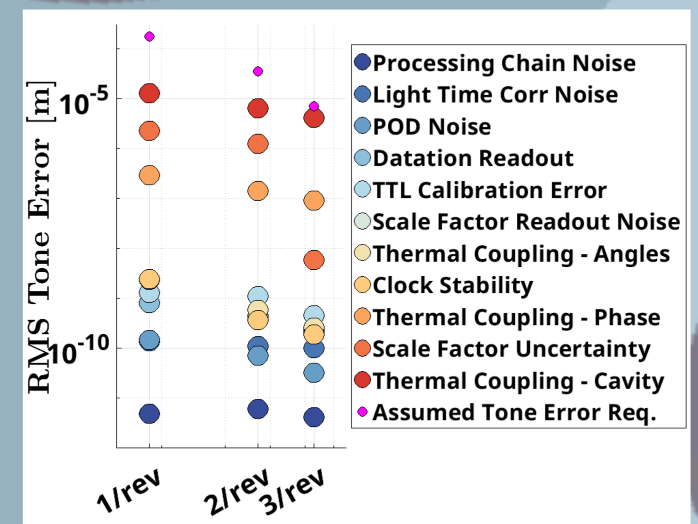
LRI Phase:
- Transponder phase ramp propagates to reference.
- Phase ramp and variations derived from laser freq. and LTT, are combined to reference phase.
- Thermal coupling models are considered.

Range [4,5]:
- Convert LRI to GNSS time.
- Compute phase difference of two satellites.
- Use scale factor measurement to convert phase to range.
- Compute TTL (with cal. errors), ARC and Light Time Correction [1,3].



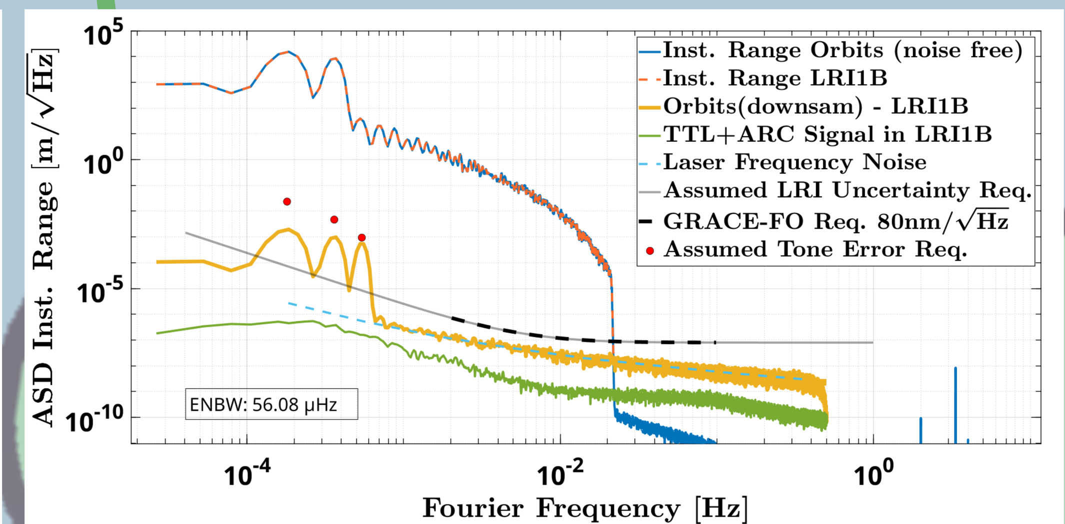


Tone-Error Analysis

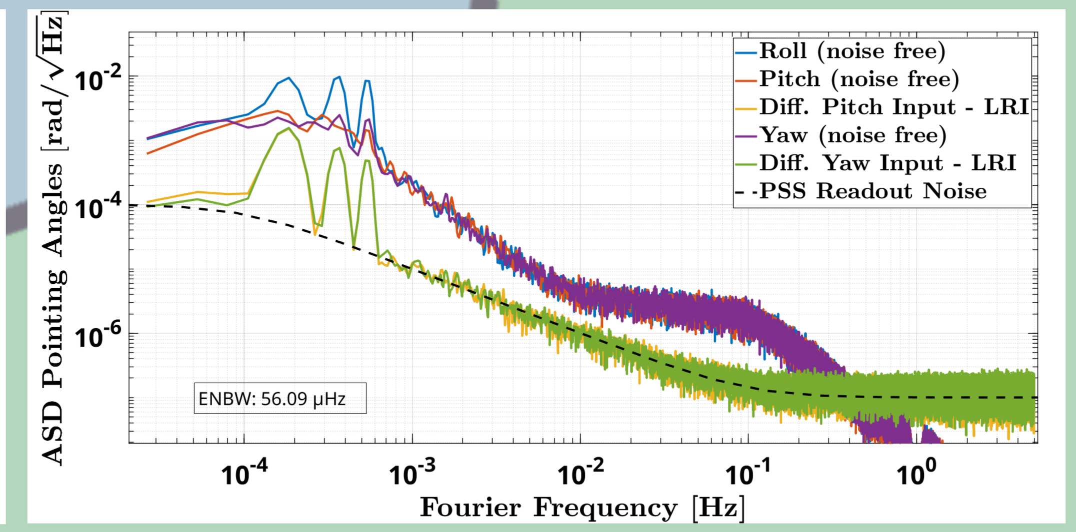


- En- and disable different noise contributors in LRI simulator.
- Evaluate RMS amplitudes at once, twice and three per revolution.
- Largest errors from thermal coupling and scale factor uncertainty.
- Summed tone-error amplitudes are dominated by temperature-induced errors.
- Tone-errors remain below assumed mission performance requirements.

Performance Assessment



- Difference of **LRI instantaneous range** and range derived from input orbits provides the LRI ranging noise in yellow.
- f > 1mHz limited by laser frequency noise.
- f < 1mHz limited by tone-errors from thermal coupling.



- Noise of **LRI yaw and pitch angles** w.r.t. the input attitude is shown in yellow and green.
- f > 1mHz limited by PSS readout noise.
- f < 1mHz limited by tone-errors from thermal coupling.

Conclusion

- LRI simulator is capable of deriving realistic data.
- Error contributions for future LRIs can be tested and assessed in level1b ranging and pointing data.
- Resulting noise can be compared to mission requirements.
- Simulator contributes to ESA's NGGM and MAGIC End-To-End Mission Performance Evaluation Study.

Outlook

Simulator will become more comprehensive and realistic as
- additional noise contributors will be implemented
- simplified models might be replaced
- as mission preparations advance, more detailed parameters become available, which can be updated / incorporated into the simulator.

References:

[1] Yihao Yan et al, 2020, Revisiting the Light Time Correction in Gravimetric Missions Like GRACE and GRACE Follow-On, https://doi.org/10.1007/s00190-021-01498-5
[2] Malte Misfeldt et al. 2022, Scale Factor Determination for the GRACE-Follow On Laser Ranging Interferometer including Thermal Correction, https://doi.org/10.3390/rs15030570
[3] Henry Wegener, 2020, Tilt-to-Length Coupling in the GRACE Follow-On Laser Ranging Interferometer, https://doi.org/10.2514/1.A34790
[4] Laura Müller, 2021, Generation of Level 1 Data Products and Validating the Correctness of Currently Available Release 04 Data for the GRACE Follow-On Laser Ranging Interferometer, Master's thesis, http://doi.org/10.15488
[5] AEI LRI1B and RTC1B Release Notes, Sep 2024, https://www.aei.mpg.de/grace-fo-ranging-datasets

Acknowledgement: This work is performed under ESA contract 4000145266/24/NL/SC – NGGM and MAGIC End-to-End Mission Performance Evaluation Study.