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GEORB: Release for precise orbit determination of low Earth orbiters and satellite gravity missions

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ABSTRACT

Gravity and precisE ORBit determination system (GEORB) is a software for precise orbit determination of low Earth orbiters, gravity field recovery based on satellite gravity missions and orbit design of future space missions. GEORB has been applied in orbit determination of the Gravity Recovery And Climate Experiment (GRACE), GRACE Follow-On (GRACE-FO) and Gravity Field and Steady-State Ocean Circulation (GOCE) missions. GEORB has been recently released as open source on GitHub (https://github.com/Thomas-Loudis/georb). The current release provides features focusing on orbit determination of the GRACE missions including the calibration of the on-board accelerometers and the analysis of intersatellite ranging observations.

Code metadata

Current code version	*v.1.7.5*
Permanent link to code/repository used for this code version	https://github.com/SoftwareImpacts/SIMPAC-2023-88
Permanent link to reproducible capsule	https://codeocean.com/capsule/1752354/tree/v1
Legal code license	*GNU General Public License (GPL): GPL-3.0 license*
Code versioning system used	*git*
Software code languages, tools and services used	*Matlab*
Compilation requirements, operating environments and dependencies	
If available, link to developer documentation/manual	https://www.thomaspap.com/sw.html
Support email for questions	georb@thomaspap.com

1. Introduction

Orbit determination is a fundamental topic of celestial mechanics, astrodynamics and satellite geodesy. The study of the orbital motion of artificial satellites provides insight to the underlying forces and dynamic parameters such as the gravity field, Earth/body rotation, tides, non-gravitational effects, atmosphere models [1–3]. Precise orbits are applied in the data processing of satellite missions observing Earth or another planet and the design of future space missions.

Precise orbit determination is required in the case of satellite gravity missions such as the Gravity Recovery And Climate Experiment (GRACE) and the GRACE Follow-On missions [4,5]. The requirements of these missions refer to high level of orbit precision (cm level) in order to capture the static and time-variable components of the gravity field and further support Earth science research and applications such as climate change, sea level and glaciers monitoring, Earth mass and water changes [6,7]. The mission's on-board accelerometers form a key instrument for the direct measurement of the non-gravitational perturbations and thus, the accelerometry data processing and in-orbit calibration is an essential tool [8–10].

2. GEORB design and principles

GEORB (Gravity and precisE ORBit determination system) is a software for precise orbit determination of Low Earth Orbiters (LEOs) and satellite gravity missions, gravity field recovery and design of future space missions. GEORB current release is presented in this short article. The source code has been written in Matlab without making use of any special library or toolbox.

The code (and data) in this article has been certified as Reproducible by Code Ocean: (https://codeocean.com/). More information on the Reproducibility Badge Initiative is available at https://www.elsevier.com/physical-sciences-and-engineering/computer-science/journals.

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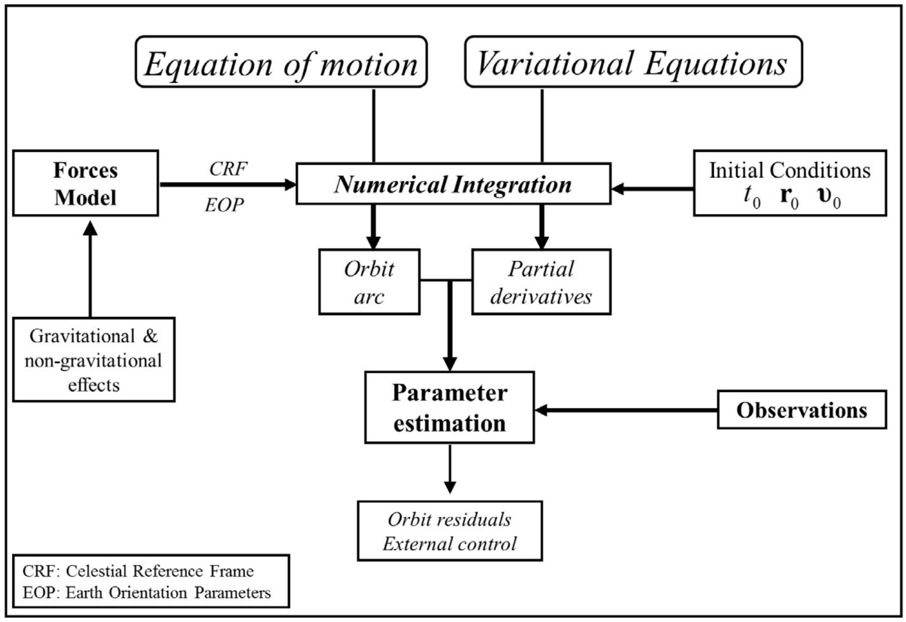


Fig. 1. GEORB is designed based on the principles of dynamic orbit determination as presented by Papanikolaou [14].

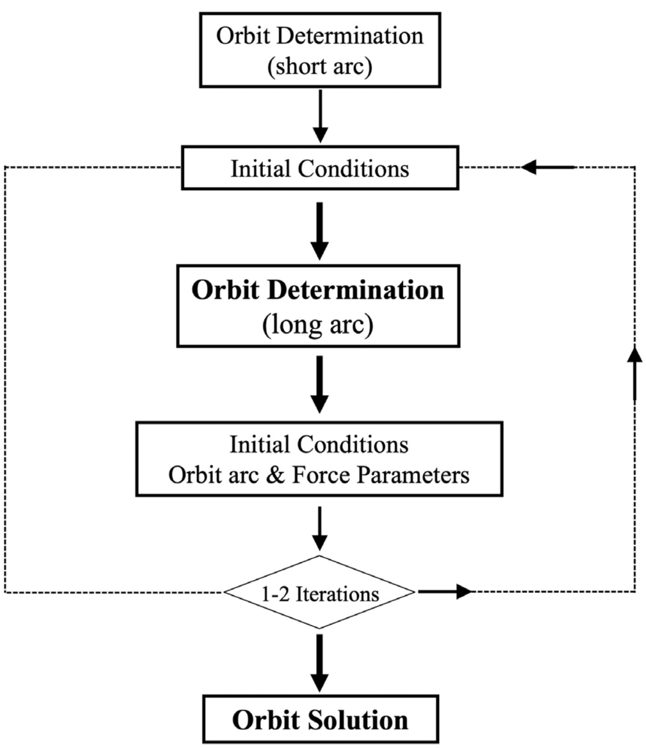


Fig. 2. GEORB design expressed by the basic steps of the algorithm.

GEORB was released as open source in 2022 [11,12] and is publicly available on GitHub [13]. The software provides the results in the form of orbit data products written in its' own adopted data format. Description on the software configuration (orbit modelling and methods, satellite data processing) and the output data format are provided on the corresponding GitHub repository (https://github.com/Thomas-Loudis/georb).

GEORB design and principles are represented by Figs. 1 and 2 that show an overview of the principles and the basic steps of the orbit determination algorithm respectively. A summary of the orbital dynamics models and methods that have been implemented into the source code are given in Table 1. The orbit determination method that has been implemented here follows the principles of dynamic orbit determination where the orbit is represented by the equation of motion. The fundamental mathematical tool for the description of the equation of motion is based on Newton's second law. The overall equations system is composed by the equation of motion and its partial derivatives, the so-called variational equations. The equations, based on an extended variational equations system, are being solved through numerical integration methods and in particular, the integrators listed in Table 1. The equation of motion refers to a post-Newtonian frame where the Newtonian mechanics (Newton 2nd law) include relativistic effects as corrections.

The forces model is consisted by gravitational and non-gravitational effects. The orbit is estimated along with a set of additional force-related parameters. The estimation of these deterministic parameters is based on the least-squares method and the use of the orbital equations' solution along with a set of observations. The extended orbit parameter estimation aims at capturing the mismodelling effects of the underlying forces model as listed in Table 1. The force mismodelling is due to errors of the orbital dynamics models and instruments including the on-board accelerometers data calibration [11].

3. Impact

GEORB was released as open source in 2022 [11,12] while preliminary versions of the source code have been developed by Papanikolaou [14,27] for research purposes in topics of satellite geodesy and astrodynamics. The initial focus has been the dynamic orbit analysis of satellite gravity missions GRACE and GOCE aiming at capturing gravity signal discrepancies at orbital altitude through the introduction of a degree-wise cumulative approach of the gravity model contribution [14,28,29].

The numerical integration methods, that have been implemented into GEORB source code as listed in Table 1, have been thoroughly investigated as discussed by Papanikolaou [14], Papanikolaou and Tsoulis [30]. The orbit propagation based on numerical integration of the Equation of motion is used also to form an orbit simulation tool. The orbit simulation tool has been applied, considering a variety of gravitational forces model, to support studies of the ocean tides [31].

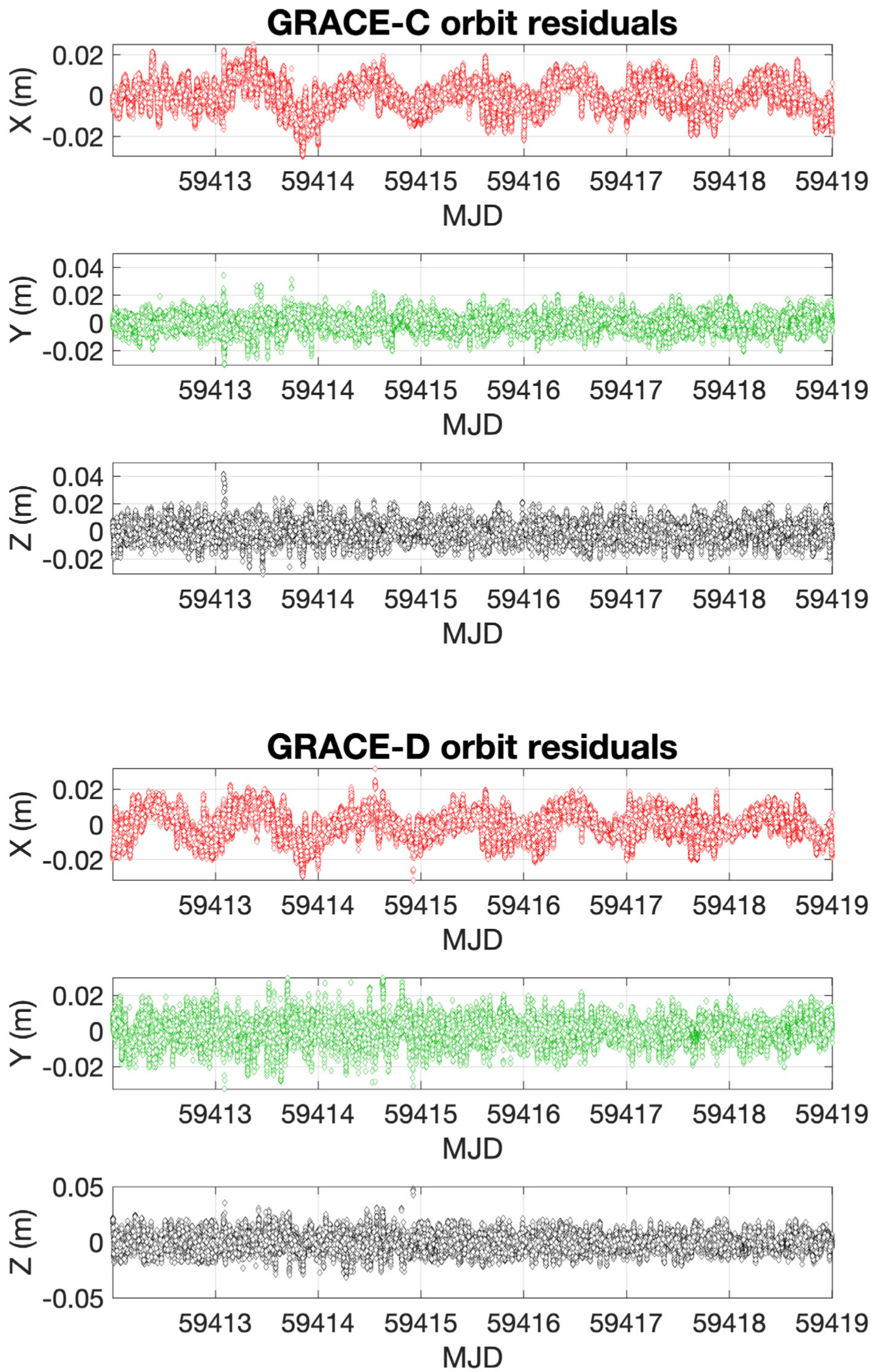
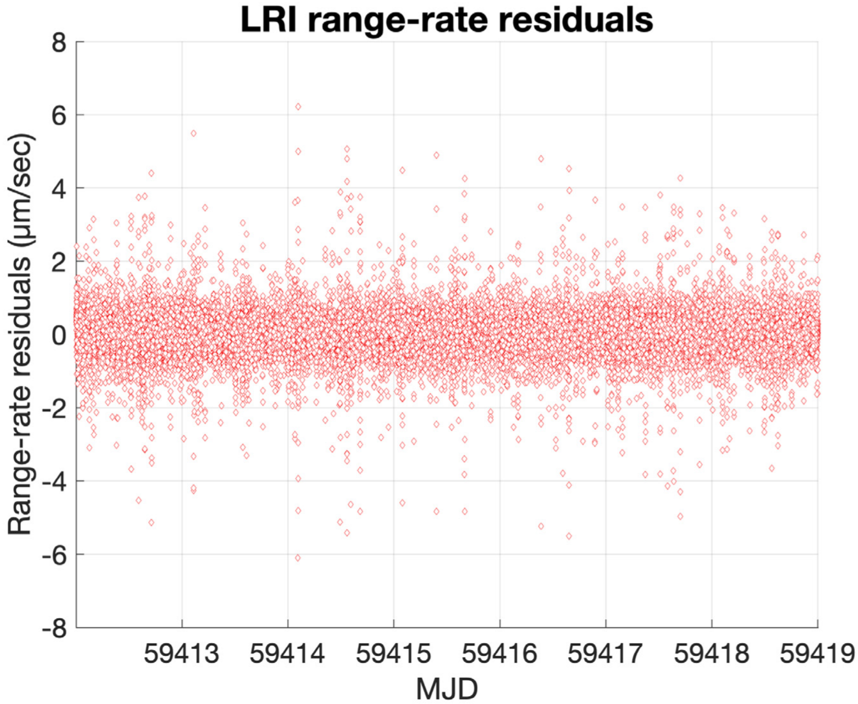


Fig. 3. Orbit determination application to GRACE-FO satellites. Performance is represented through the observation residuals as function of time. X axis is expressed in Modified Julian Day number (MJD) as time argument. Orbit residuals per epoch refer to results of 7 daily orbit arcs. Unit is m.

The current release of GEORB provides features of the precise orbit determination and the on-board accelerometer calibration modelling of the GRACE missions as demonstrated by Papanikolaou [11,12]. Represented results of the achieved POD performance in the case of the GRACE-FO mission are given in Figs. 3 and 4 that show the orbit residuals and the intersatellite laser ranging data residuals respectively. It is shown that the applied orbit determination approach leads to accuracy varying within a few mm to cm in terms of orbit residuals while the inter-satellite range-rate data residuals vary within few μm/s. The achieved orbit performance reaches level of accuracy similar to other studies of the GRACE-FO mission data analysis [32,33].



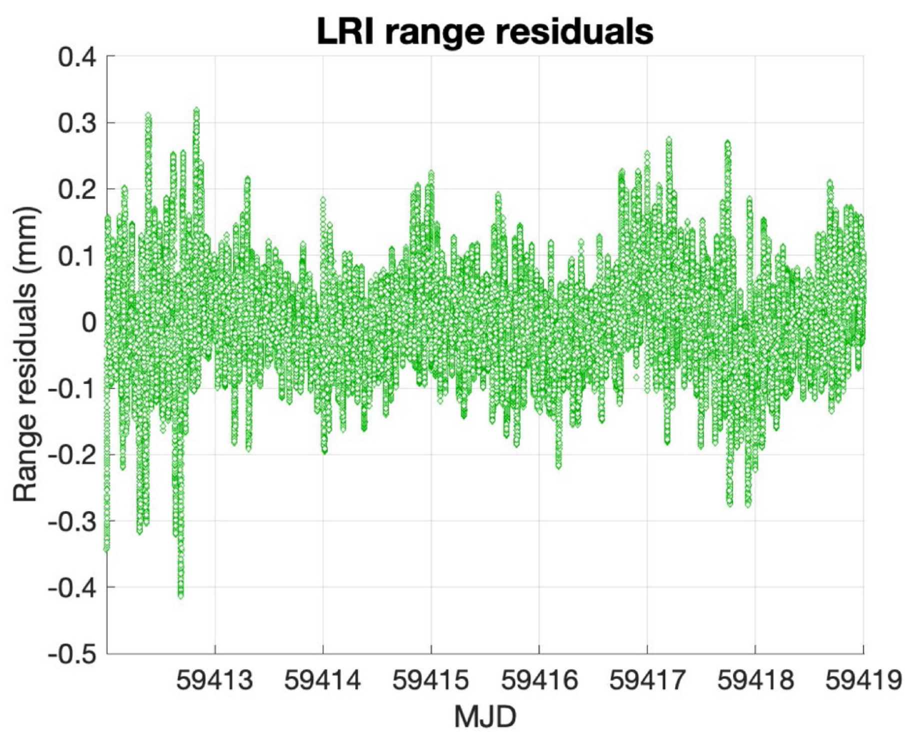


Fig. 4. GRACE-FO intersatellite observations residuals per epoch to the estimated orbits of a weekly period. The intersatellite range and range-rate data are obtained from the Laser Ranging Interferometry (LRI) instrument. RMS values are 0.43 μm/s and 0.08 mm for range-rate and range residuals respectively. Units are μm/s and mm for range-rate and range residuals respectively.

4. Conclusions and future development

The Gravity and precisE ORBit determination system (GEORB) software has been presented here through a brief overview of the design and capabilities. GEORB provides features of orbit determination and gravity field modelling while the current release supports the GRACE and GRACE-FO satellite missions. The feature of the on-board accelerometer calibration modelling is equally supported by the present release.

Further development in the near future aims at extending the POD capability to constellations of Low Earth Orbiters and the time series analysis of orbits. Another key feature that is currently in-progress is the estimation of gravity field solutions (time-variable gravity models)

Table 1
Orbit modelling: Summary of dynamics, methods and data.

Numerical integrators	*Multistep methods:* Adams Bashforth Adams Bashforth–Moulton Gauss–Jackson Gauss–Jackson predictor–corrector mode *Runge–Kutta-Nyström methods:* RKN7(6)-8 [15] RKN6(4)-6FD [16]
Earth orientation EOP data	IERS Conventions 2010 [17] IERS C04 solution [18]
Gravity field Lunar/Planetary ephemeris Solid earth tides Ocean tides Pole tide Atmosphere and Ocean De-Aliasing effects Relativistic effects	Gravity Models available by ICGEM [19] e.g. GOCO06s [20] JPL/NASA DE series [21] e.g. DE423 IERS Conventions 2010 [17] FES2004 [22]/ FES2014b [23] Solid Earth Tide and Ocean Pole Tide (IERS Conventions 2010) AOD1b RL06 data processing [24] IERS Conventions 2010 [17]
Non-gravitational forces	Accelerometer data processing: ACC1B data [25] + Calibration parameters estimation: Scale matrix, Bias, Bias drift [11]
Empirical forces of periodic terms	One-Cycle per revolution (1-CPR) accelerations in inertial frame/ orbital frame/ spacecraft frame
Empirical accelerations	Piecewise constant accelerations or Pulses (instant velocity changes) in inertial frame/ orbital frame/ spacecraft frame
Parameter estimator Observations Inter-Satellite ranging observations	Least Squares method Pseudo-Observations based on Kinematic Orbit data [26] Laser Ranging Interferometry LRI1B and K-Band Ranging KBR1B [25]
External orbit comparison	GNV1B orbit data [25]

based on an extended orbit determination scheme and the analysis of the inter-satellite laser ranging observations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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