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Reproducible asteroid orbit determination with the **General Open Orbital Dynamics (GOOD) platform**

and machine-learning-based astrometry

Gijs Verdoes Kleijn

OmegaCEN Astronomical Science Data Center
Kapteyn Astronomical Institute, University of Groningen
Data Science Coordinator NOVA
Euclid Solar System Science Working Group & ESA Euclid Science Team

GOOD team, Emma Boberg, Eduardo Balbinot, Dominic Dirkx
Max Chong Margherita Revellino, Trienko Grobler, Rees Williams, Leon Koopmans, Luigi Gisolfi, Steve Gehly, Yin-Zhe Ma, Irene Ruvolo, Sandor Kruk

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Orbital dynamics planetary systems

- exoplanetary systems
- solar system planet dynamical evolution
- planetary defense
- space navigation
- testing gravity theory
- comets & asteroid dynamics

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orbital code:

TU Delft Astrodynamics Toolbox (Tudat)

860 followers

3d • Edited •

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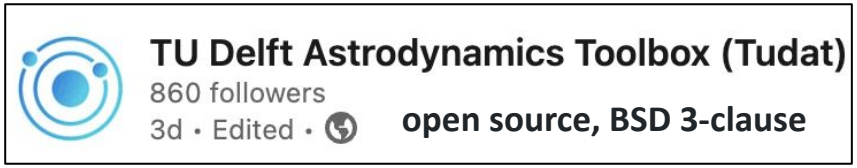
- *internal mass distribution*



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Orbital dynamics planetary systems

- exoplanetary systems
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- *internal mass distribution: solar quadrupole moment* $J_{2\odot}$

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Orbital dynamics planetary systems

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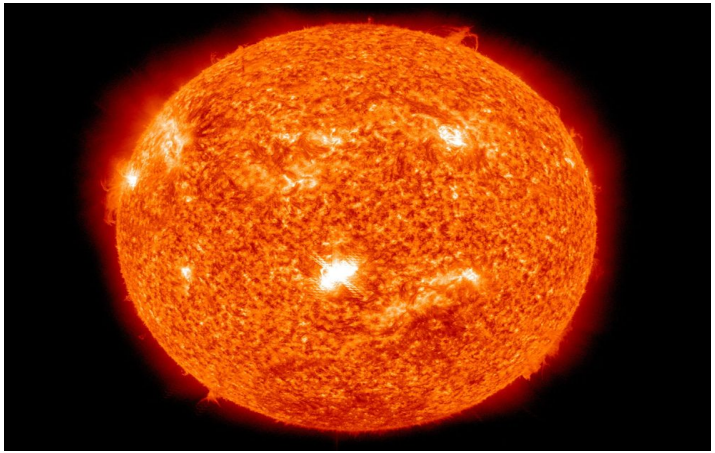
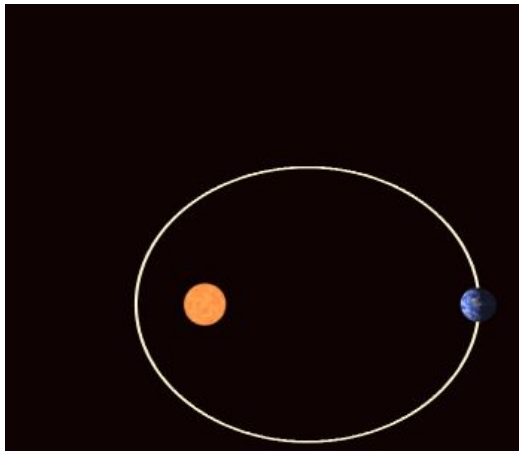


precession from oblate potential



Orbital dynamics planetary systems

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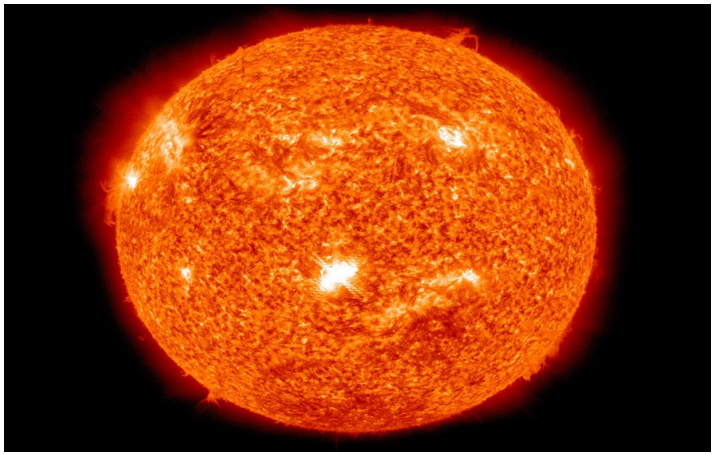

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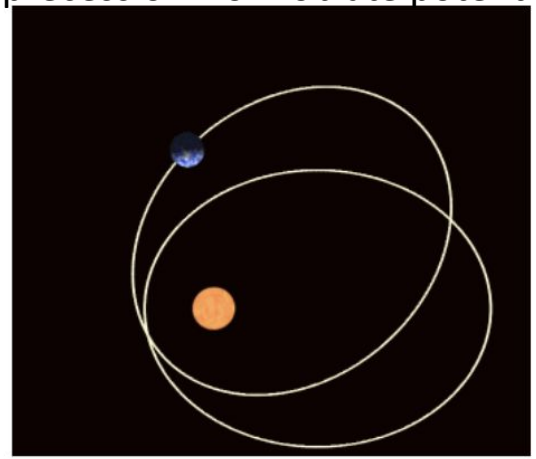

9 Near-earth asteroids to constrain solar quadrupole $J_{2\odot}$

potential of **stellar occultation** milliarcsecond astrometry.

10wk BSc project Emma Boberg

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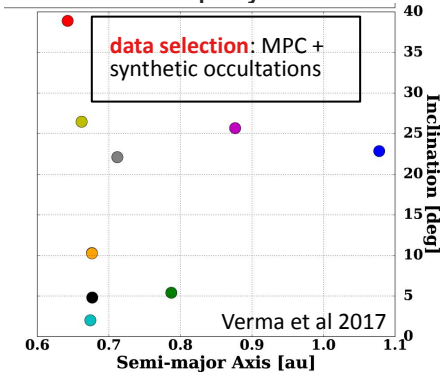

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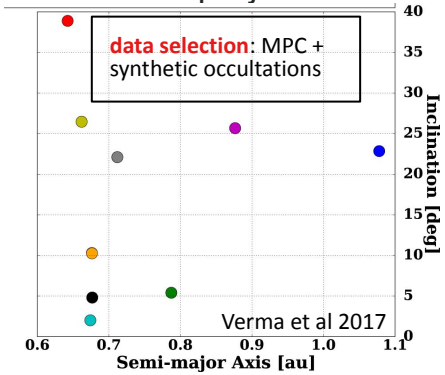

Settings: gravitational model with 8 planets, 14 moons, Ceres, 20 large asteroids, General Relativity (Schwarzschild), Yarkovsky (Greenberg+17), Runge-Kutta-Fehlberg 20hr integration step, weighted-least squares

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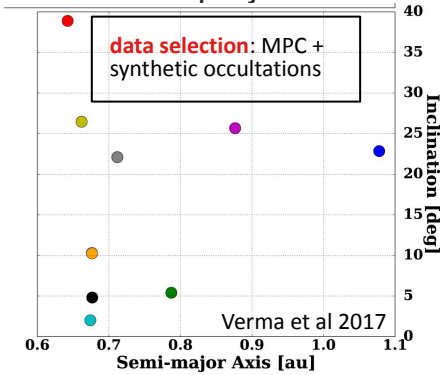

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software:

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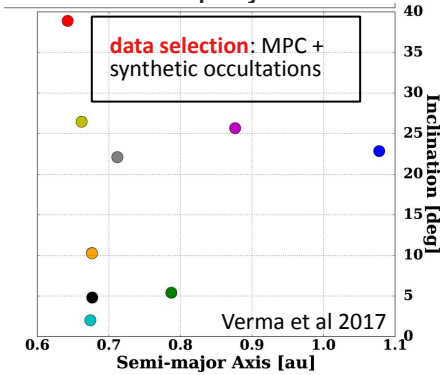

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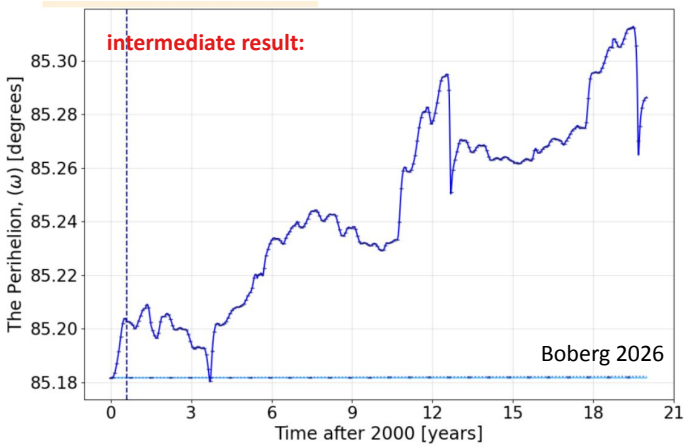

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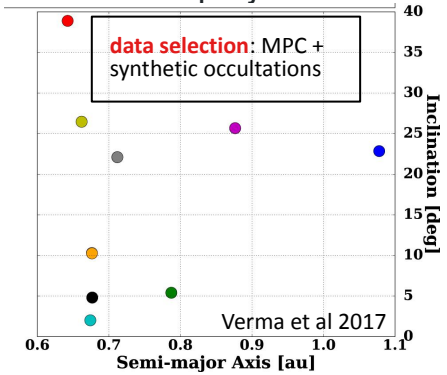

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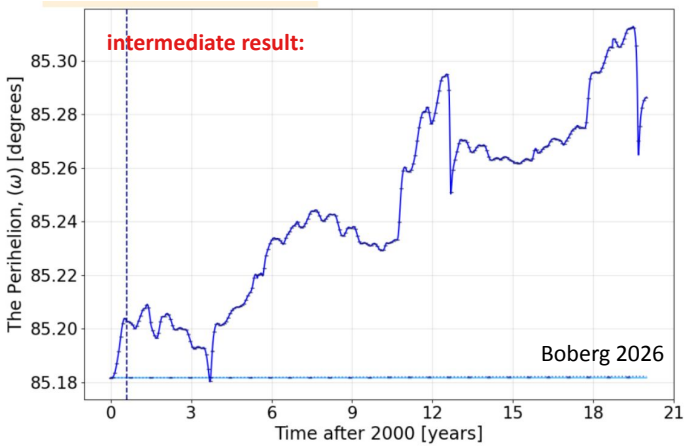

published end result:

Number of occultations	$\sigma_{J_{2\odot}} \cdot 10^{-7}$
0	4.010
1	3.957
2	3.767
3	3.720
4	3.699

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university of groningen

founded in 1614 - top 100 university

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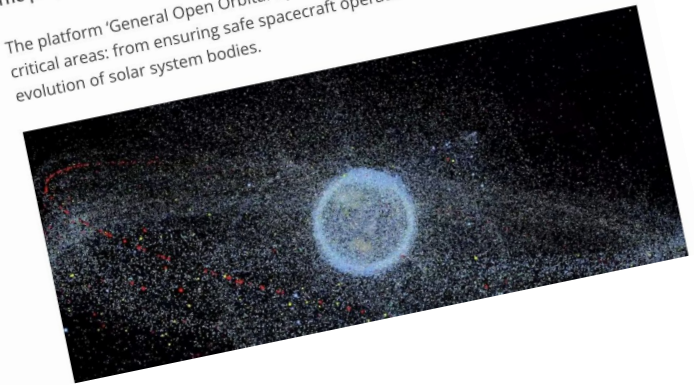
About us › Faculty of Science and Engineering › News

1.5 million NWO grant for open science platform for orbital calculations

09 Feb 2026

The University of Groningen partners in a EUR 1.5 million funded research project from the Netherlands Organisation for Scientific Research (NWO) to develop an open science platform for orbital calculations in space research. The UG will receive EUR 670.000 for developing a digital platform which will be hosted by the Big Data handling AI and Robotics for Research (BDAIRR) group. The project is led by Dr. ir. Dominic Dirkx from Delft University of Technology.

The platform 'General Open Orbital Dynamics (GOOD)' will support progress in critical areas: from ensuring safe spacecraft operations to studying the origin and evolution of solar system bodies.



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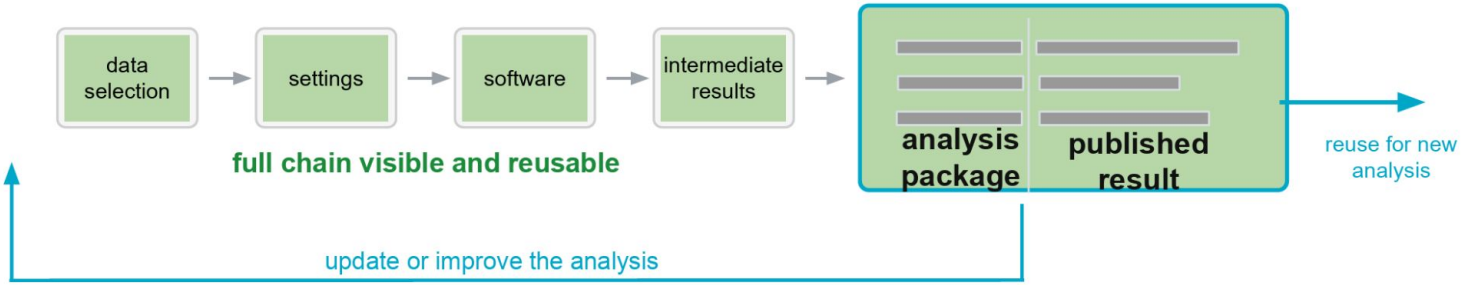
General Open Orbital Dynamics Platform (GOOD)

- An **open repository** of orbital-dynamics **analyses and solutions**, combining a data archive with the infrastructure needed to **run, reproduce, update** and **extend** them
  - Kicked off earlier this year, development fully funded until late 2029
  - Collaboration between universities of Delft and Groningen, with input and support from 10 cooperation partners



"These are our published results. Here is everything you need to continue where we left off."

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GOOD platform

The core technologies

Tudat

- Open-source computational engine
- Dynamics and observation modelling
- Estimation and uncertainty analysis

tudat

WISE

- Versioned management of data, configurations and results
- Provenance and workflow management
- Discovery, access, controlled re-execution
- WISE used in wide-field imaging missions of ESA and ESO

AstroWISE

Tudat executes the analysis; WISE makes it managed, traceable and reusable

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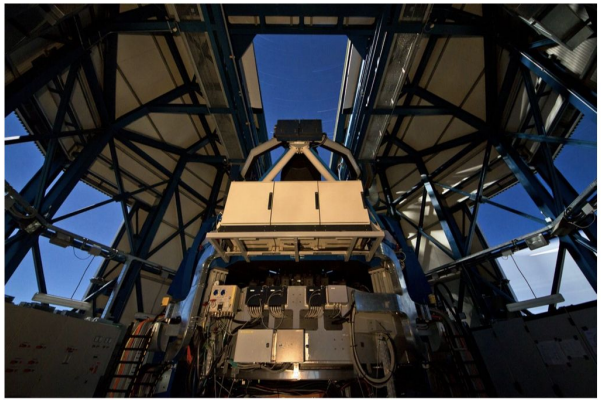
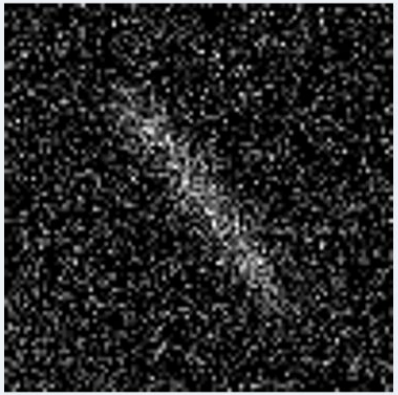
extracting asteroid streaks with deep-learning AI from ESO VLT Survey Telescope imaging surveys inside AstroWISE

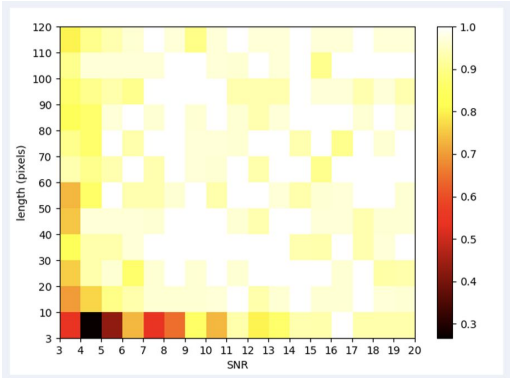


VLT Survey Telescope (above): A 2.6 m telescope located in Chile.

Real



Simulated



Max Chong PhD (Kapteyn & Stellenbosch) et al, 2026 in prep

Polarimetric Characterisation of Minor Planets with VSTPOL EPSC2026-902, poster, Thu

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GOOD community

15 Jun 2026 kick-off participant overview

Observatoire de Paris

UCLouvain

CHALMERS UNIVERSITY OF TECHNOLOGY

Netherlands Space Agency

ecosmic

KNMI

Radboud Universiteit

BLACKSWAN SPACE

esa

TNO

Stellenbosch UNIVERSITY IYUNIVESITHI UNIVERSITEIT

TECHNISCHE UNIVERSITÄT BERLIN

der Bundeswehr Universität München

UNIVERSITY of TASMANIA AUSTRALIA

LPG

ROYAL OBSERVATORY OF BELGIUM

JIVE Joint Institute for VLBI ERIC

HUN REN CSFK

IAA INSTITUTO DE ASTROFÍSICA DE ANDALUCÍA

University of Strathclyde Glasgow

DOA Dutch Occultation Association Dutch Observers of Asteroids

netherlands eScience center

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TU Delft

We welcome you to:

- apply for GOOD Users Committee and advisory board

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TU Delft

We welcome you to:

- apply for GOOD users committee or advisory board
- sign up for platform release announcements

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We welcome you to:

- apply for GOOD users committee and advisory board
- sign up for platform release announcements
- propose priority datasets (imaging and/or catalogs)

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TU Delft

We welcome you to:

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- propose priority datasets (imaging and/or catalogs)
- suggest scientific analyses for public benchmarks -> we welcome cross-validation with closed-source systems

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We welcome you to:

- apply for GOOD users committee and advisory board
- sign up for platform release announcements
- propose priority datasets (imaging and/or catalogs),
- suggest scientific analyses for public benchmarks -> we welcome cross-validation with closed-source systems
- contact points: d.dirkx@tudelft.nl, g.a.verdoes.kleijn@rug.nl

The GOOD long-term goal: make small-body orbit propagation, orbit estimation, and planetary-defense data products open, reproducible, and reusable by design. With the help of AI.

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END
THANK YOU!
Dirkx et al, EPSC2026-279 MITM10 **Fri 08:45**
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END

THANK YOU!

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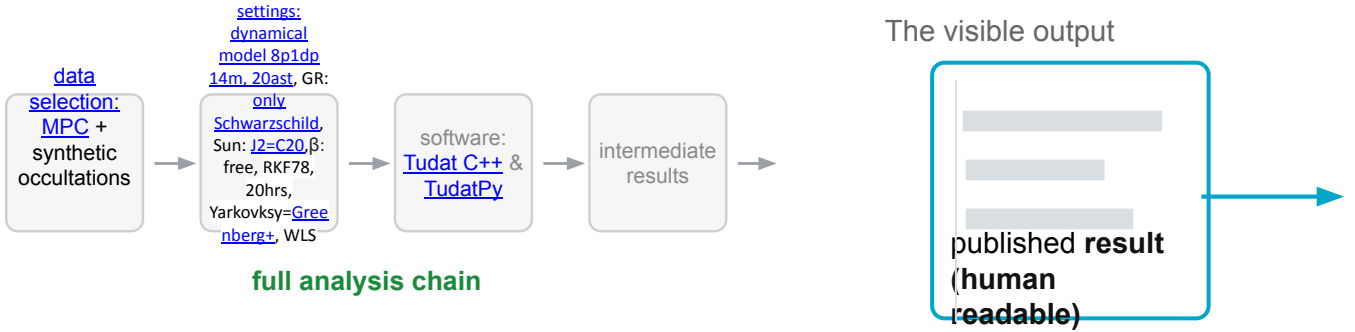
Ephemerides of Near-Earth Asteroids to Constrain General Relativity Parameter β and Solar Quadrupole Moment $J2_{\odot}$:
The Potential of Stellar Occultations (to complement radar ranging). An exploratory 10wk BSc project by Emma Boberg



Expose analysis by using open source: TU Delft Astrodynamics Toolbox (Tudat, BSD 3-clause)

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More asteroid/comet astrometry science using **Tudat open-source**

- Margherita Revellino et al 2026 in prep: study of the non-gravitational forces acting on long period comets: EPSC2026-15, SB2, Thu 11am

- Ruvolo et al 2026 in progress, Asteroid dynamics using ESA Euclid asteroid detections, Euclid

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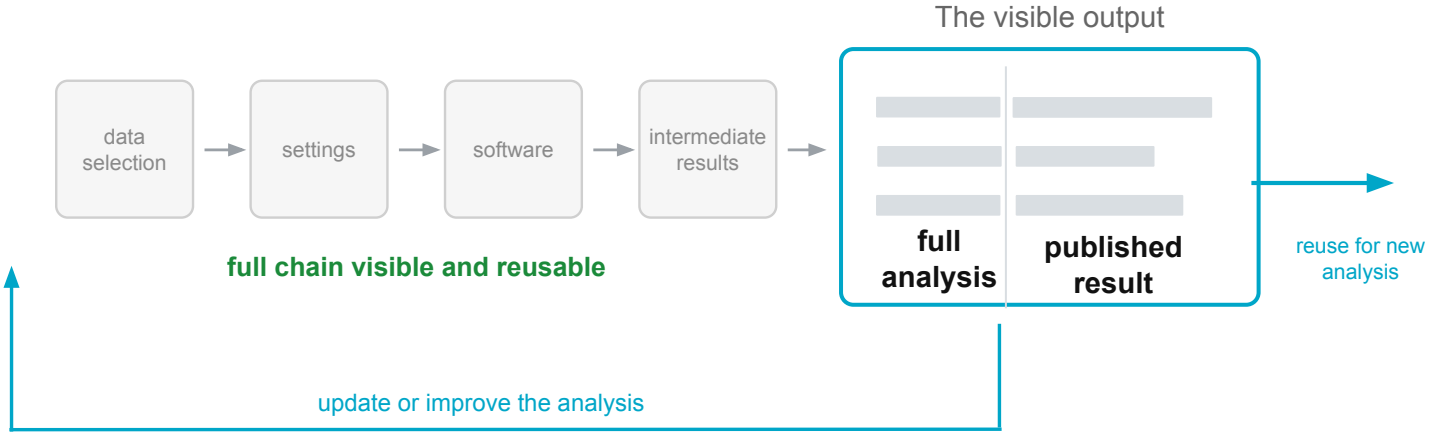
GOOD platform

What we aim to change:

Permit easier validation, testing of new ideas, extension to other applications, consistency between analyses, **to extend the existing ecosystem**



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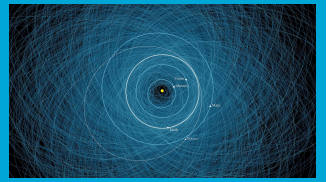

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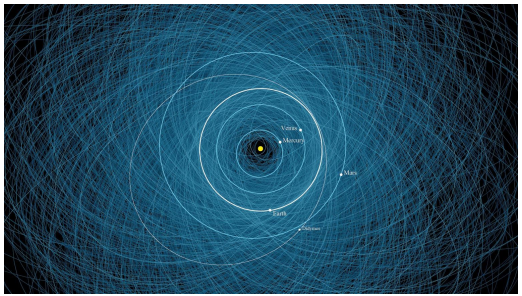

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Reproducible asteroid orbit determination with the **General Open Orbital Dynamics (GOOD) platform**

and machine-learning-based astrometry

Gijs Verdoes Kleijn

OmegaCEN Astronomical Science Data Center
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GOOD team, Emma Boberg, Eduardo Balbinot, **Dominic Dirkx**, Max Chong Margherita Revellino, Trienko Grobler, Rees Williams, Leon Koopmans, Luigi Gisolfi, Steve Gehly, Yin-Zhe Ma, Irene Ruvolo, Sandor Kruk

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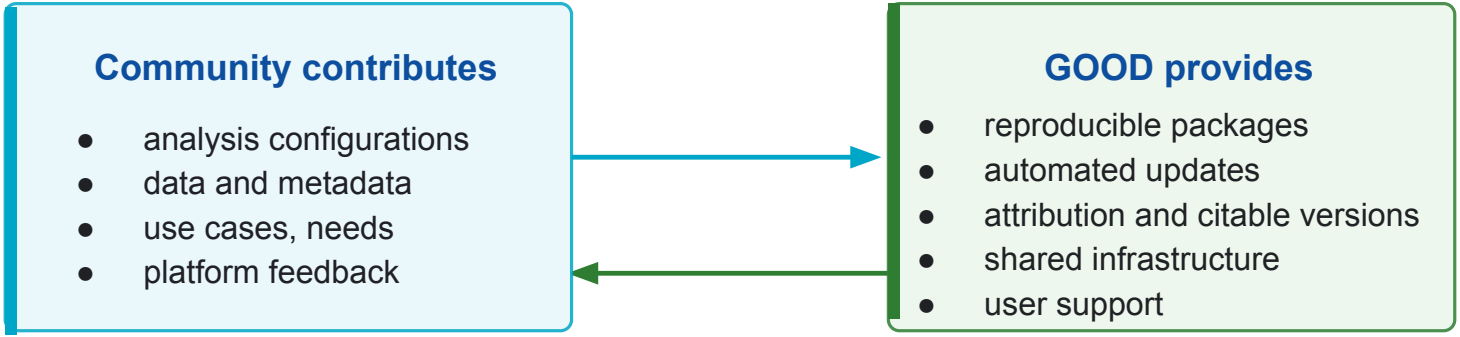
GOOD platform

A platform built with and for the community



- GOOD turns complete orbit-estimation analyses into versioned packages that others can retrieve, reproduce, update and extend.
- Platform functionality and interfaces ***must meet community needs***
  - Which analyses should your community never have to rebuild from scratch?
  - Which challenges in your field could the platform help tackle?
  - Join the GOOD advisory committee or mailing lists (***d.dirkx@tudelft.nl***)

END

Auxiliary slides after this one

Outline for 10min talk = ~ 7 slides + title slide

1min: Orbital-dynamics analyses are central to understanding the orbital evolution, transport mechanisms, impact risk, and long-term dynamical behaviour of asteroids and comets. They are also essential for planetary defense, where reliable orbit determination, uncertainty propagation, and reproducible impact-hazard assessment are critical. However, many orbit-propagation and orbit-estimation pipelines remain closed-source, application-specific, or difficult to reproduce outside the originating team. This limits independent validation, reuse of previous analyses, systematic combination of heterogeneous observations, and broader community participation. At the session, we will present the scientific motivation, architecture, initial asteroid-focused use cases, and development roadmap of GOOD and the ML-based astrometric extraction.

4min: We present the General Open Orbital Dynamics (GOOD) platform, an open-science infrastructure for reproducible orbit-dynamics analysis of Solar System bodies. GOOD combines the TU Delft Astrodynamics Toolbox (Tudat), which provides open-source high-fidelity numerical propagation and estimation capabilities, with the University of Groningen's WISE-based data-handling technology, which supports scalable data management, detailed lineage tracking, and reproducible workflows. The project is funded by OpenScience NL and supported by five three-year researcher/scientific-software-development positions. GOOD will allow researchers, data providers, and citizen-science contributors to run, validate, archive, retrieve, and update orbit-dynamics analyses together with their input data, configuration files, software versions, processing history, and output products. A central goal is that the complete setup for a published orbit-determination analysis can be retrieved through a single web action or terminal command. This will allow users to continue from previous analyses instead of reconstructing processing chains from publications, local scripts, or undocumented assumptions. The platform will support established data sources such as MPC, PDS, PSA, Gaia, Euclid, and LSST and AstroWISE, while also allowing users to upload and share their own datasets.

4min: A key use case is asteroid and comet orbit determination from optical astrometry extracted from wide-field imaging surveys. To feed GOOD with scalable astrometric measurements, we are implementing machine-learning-based streak detection within AstroWISE. Convolutional neural networks have the potential to outperform traditional parameter-tuned detection methods for asteroid streaks. Building on earlier work, we train and test a CNN on simulated and real asteroid streaks in OmegaCAM images, together with real non-asteroid sources retrieved through AstroWISE. In training, simulated streaks are injected into raw images to preserve realistic backgrounds to improve the performance.

1min: We invite applications for GOOD Users Committee and advisory board. We also seek feedback on priority datasets, dynamical-model requirements, configuration standards, and community-contributed use cases, with the long-term goal of making small-body orbit propagation, orbit estimation, and planetary-defense data products open, reproducible, and reusable by design with the help of AI.

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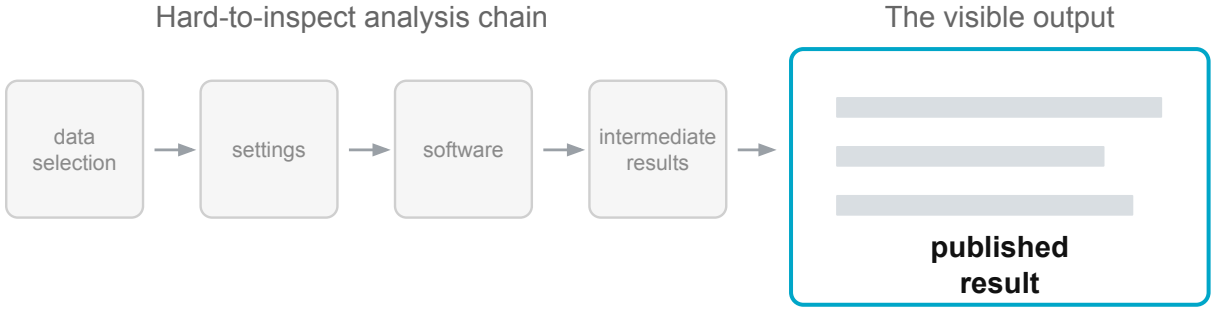
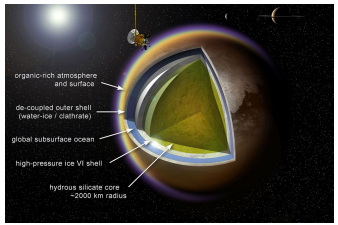
GOOD platform

Current state of the field

Orbital dynamics software, data, and configurations are often not (fully) transparent



- Difficult to reproduce, validate, compare results
- Impossible to directly continue from existing analysis, or re-analyze with different settings



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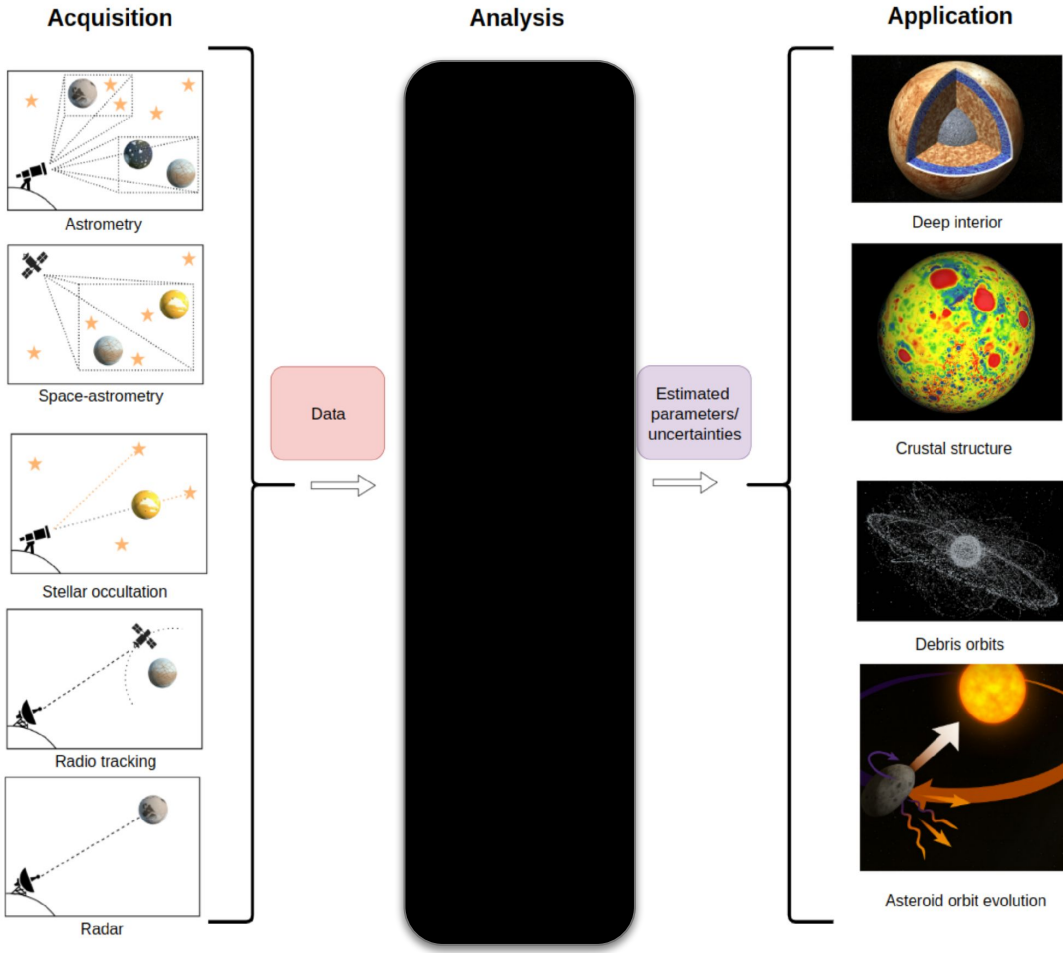
Orbit Estimation

Its role in planetary science

- Fit **tracking data** to a **dynamical model** - **estimate parameters**
- Analyses are often **closed and untransparent**



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Intro (1min)

- objective: state my presentation objectives at beginning of talk: a billboard/reclameboard
- Orbital-dynamics usage list visually?
- outline
- Situation: very advanced orbit dynamics out there: walk through Verma science case as example
- P: closed-source
- A: GOOD platform project
  - platform objectives requirements, preliminary architecture,
- C: development roadmap of GOOD
  - project associates: includes ML-based astrometric extraction.
- E:

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The General Open Orbital Dynamics (GOOD) Platform

Making orbital dynamics and estimation transparent and accessible

Dominic Dirkx (TU Delft), Gijs Verdoes Kleijn (RUG) and the GOOD team

TU Delft

GOOD platform

The core technologies

Tudat

Open-source orbit estimation software

…..

WISE

Astronomical data handling and databasing system

……

Existing joint project for Space Situational Awareness provided experience in linking platforms

GOOD platform

The core applications for planetary science

Planetary Missions

.....

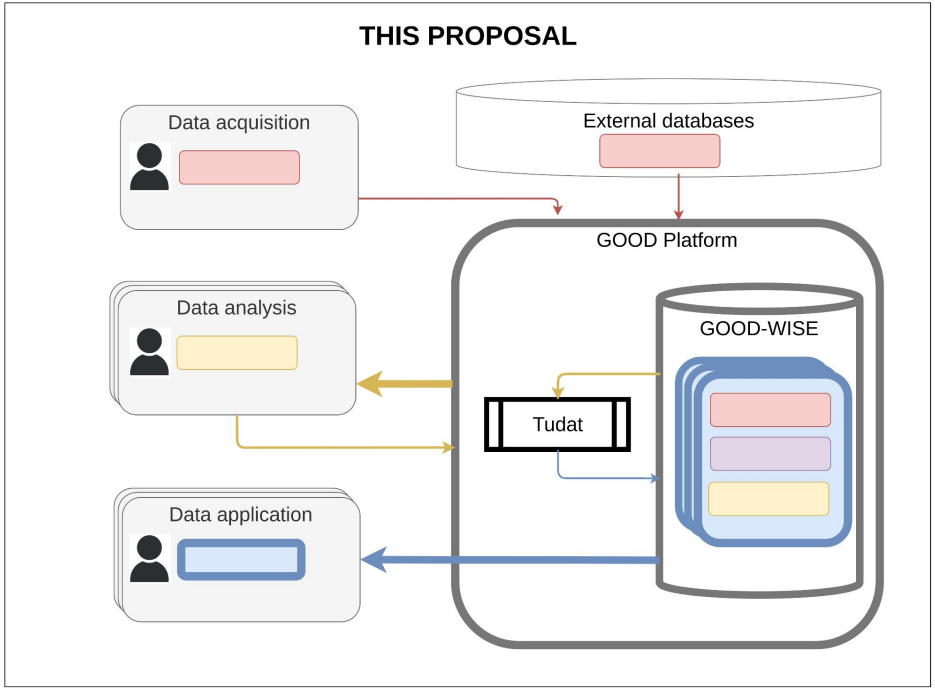
Solar system dynamics

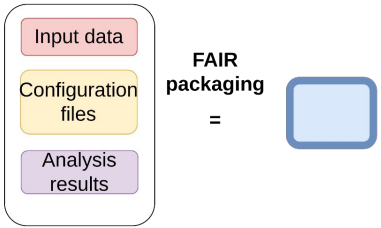
.....

GOOD platform

The core concept

- **Run, validate, archive** and automatically **update** community-provided analyses and datasets
- **Retrieve and reproduce** existing analyses





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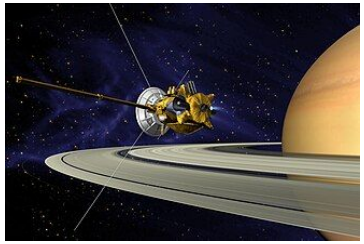
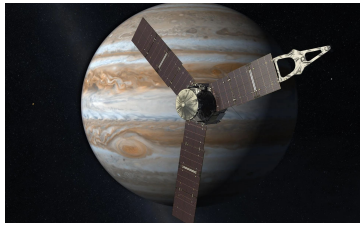
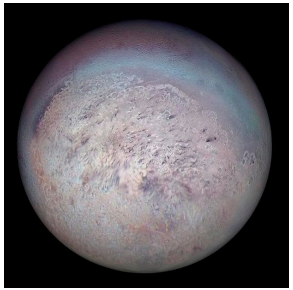
Populating the platform

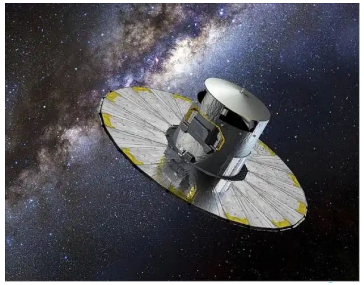
Where we start from

- The platform needs (among others) a **critical mass of analyses** to have an impact
  - Many cooperation partners involved in definition
  - Many are in progress using Tudat
  - More will be created specifically for the project
  - But more will be needed!
- How to **motivate and engage** the broader community to take up the platform?









esa TNO DLR

UNIVERSITY of TASMANIA AUSTRALIA

CHALMERS UNIVERSITY OF TECHNOLOGY

Universität der Bundeswehr München

ROYAL OBSERVATORY OF BELGIUM

JIVE Joint Institute for VLBI ERIC

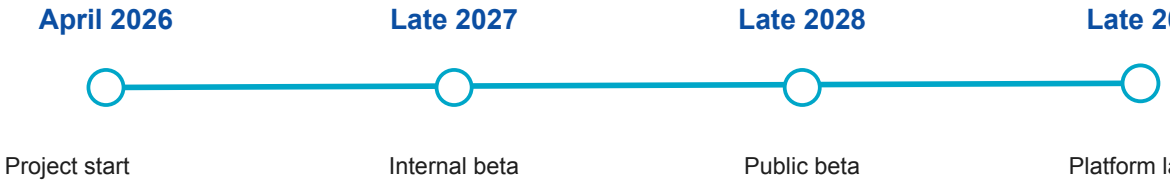
netherlands eScience center

DOA Dutch Occultation Association Dutch Observers of Asteroids

TU Delft

GOOD platform

Timeline



10
cooperation partners

3.5 years
project duration

~14
researcher/developer person-years

6
researchers/developers

rijksuniversiteit groningen

GOOD platform

A community effort!

- A platform for **open-source and transparent** orbit estimation, prediction, simulation, powered by Tudat and WISE
- Part of the implementation and process still to be defined - we need your input!
    - What should the platform do/be to be useful for you and your community?
    - Which challenges in your field could the platform help tackle?
    -

TU Delft

Orbit Estimation Planetary systems

1. exoplanetary systems, solar system, comets, asteroids, system dynamical evolution, planetary defense, space navigation, internal mass distribution, testing gravity theory
2. asteroid precision astrometry -> orbits -> perihelion precession rates to
   a. constrain solar quadrupole moment J_2
   b. test General Relativity: β=1.0000, 10 parameters in Post Newtonian formalism