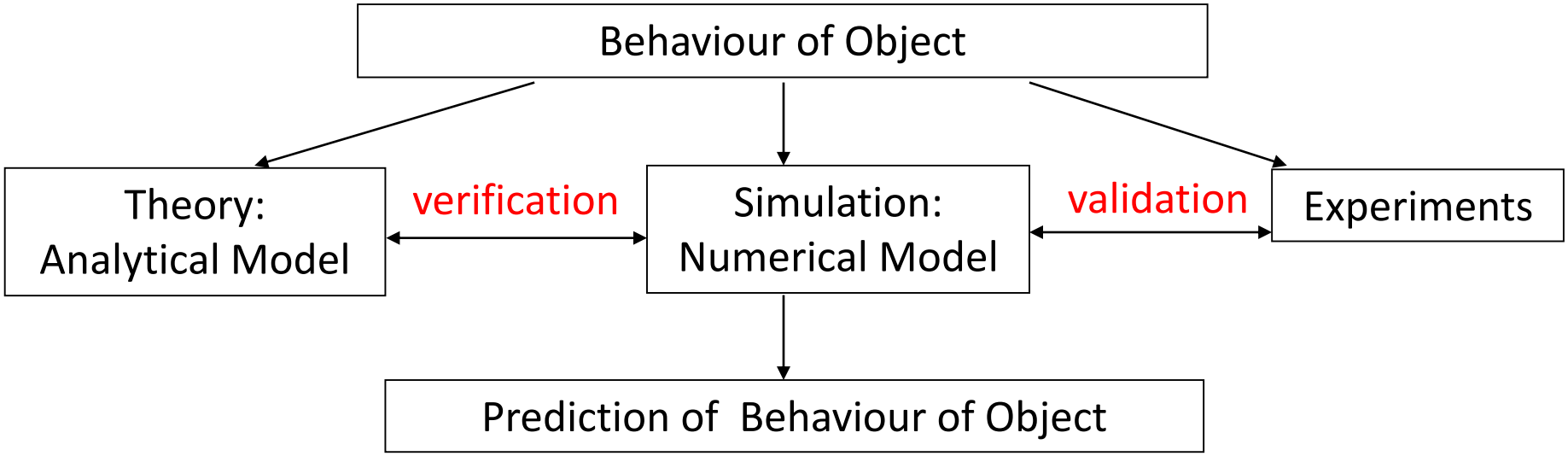
HOUR 3: EXAMPLE

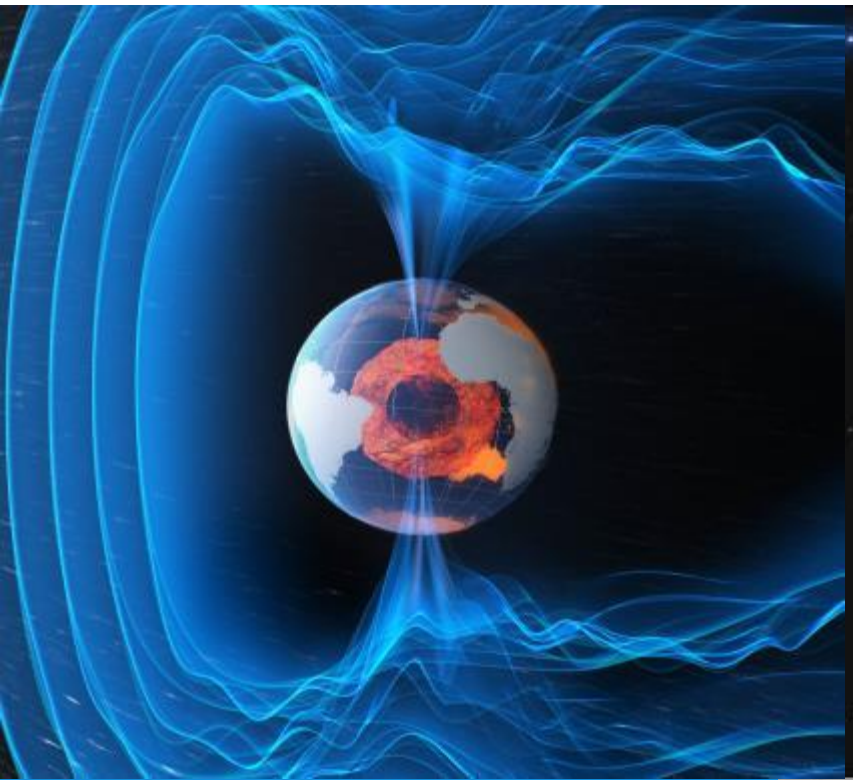
Summary: Verification and Validation



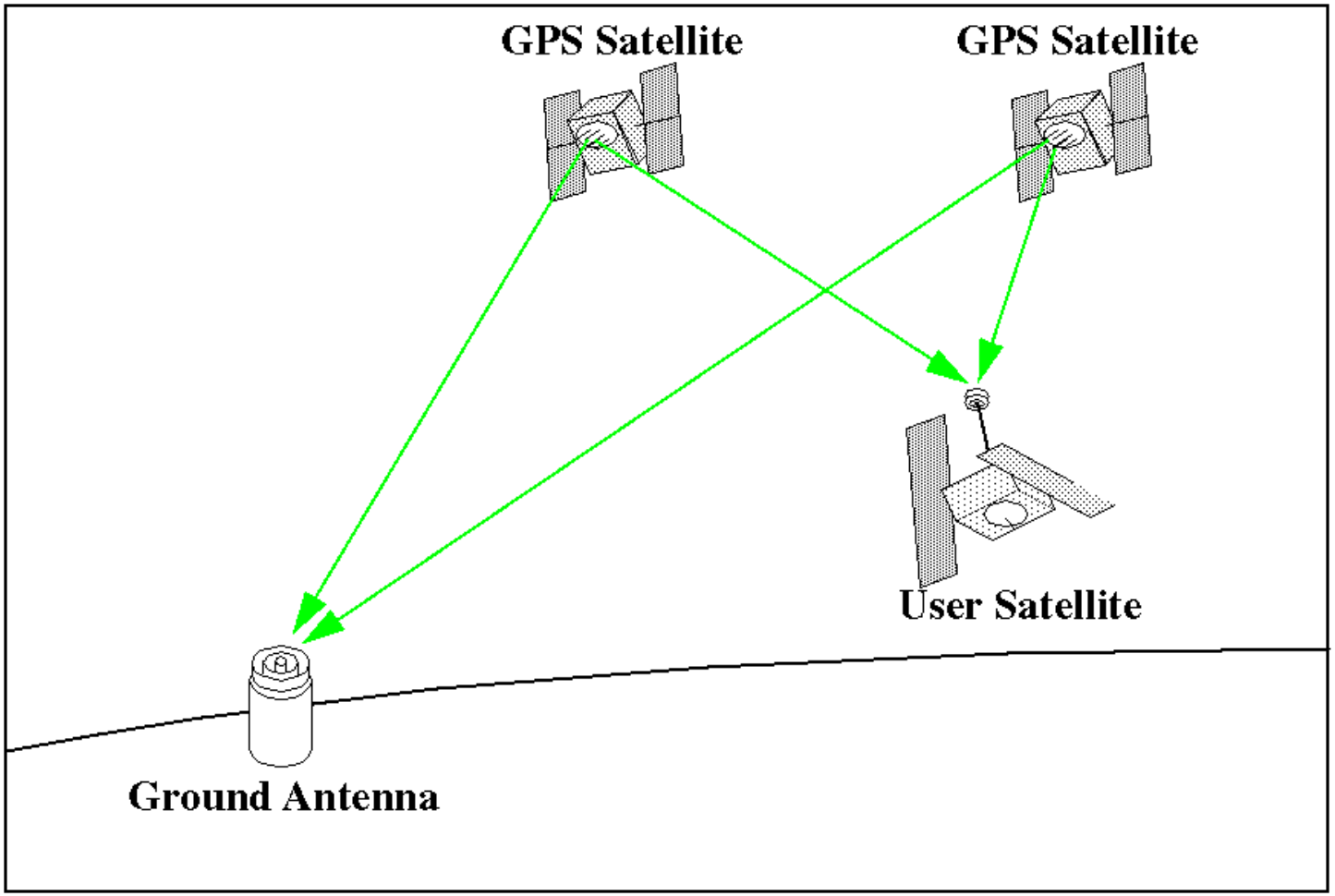
Verification: “Are you solving it right?”
Validation: “Are you solving the right thing?”

Problem description

- Compute orbit of Swarm satellite with cm precision
- **Requirements! (see DSE)**



Data available

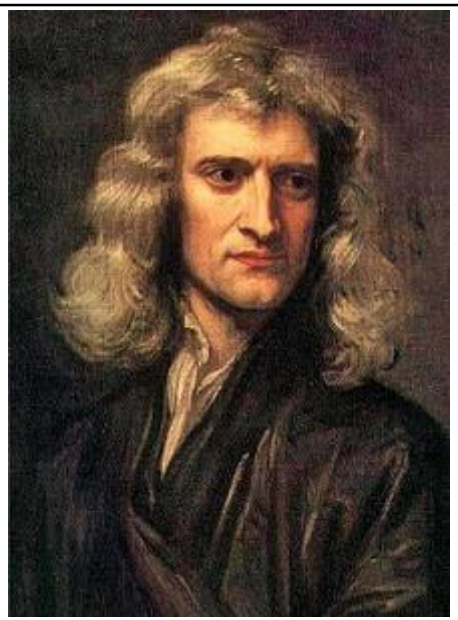


Choose the method

DYNAMICS

Integrating differential eqs

(gravity, drag, solar radiation)

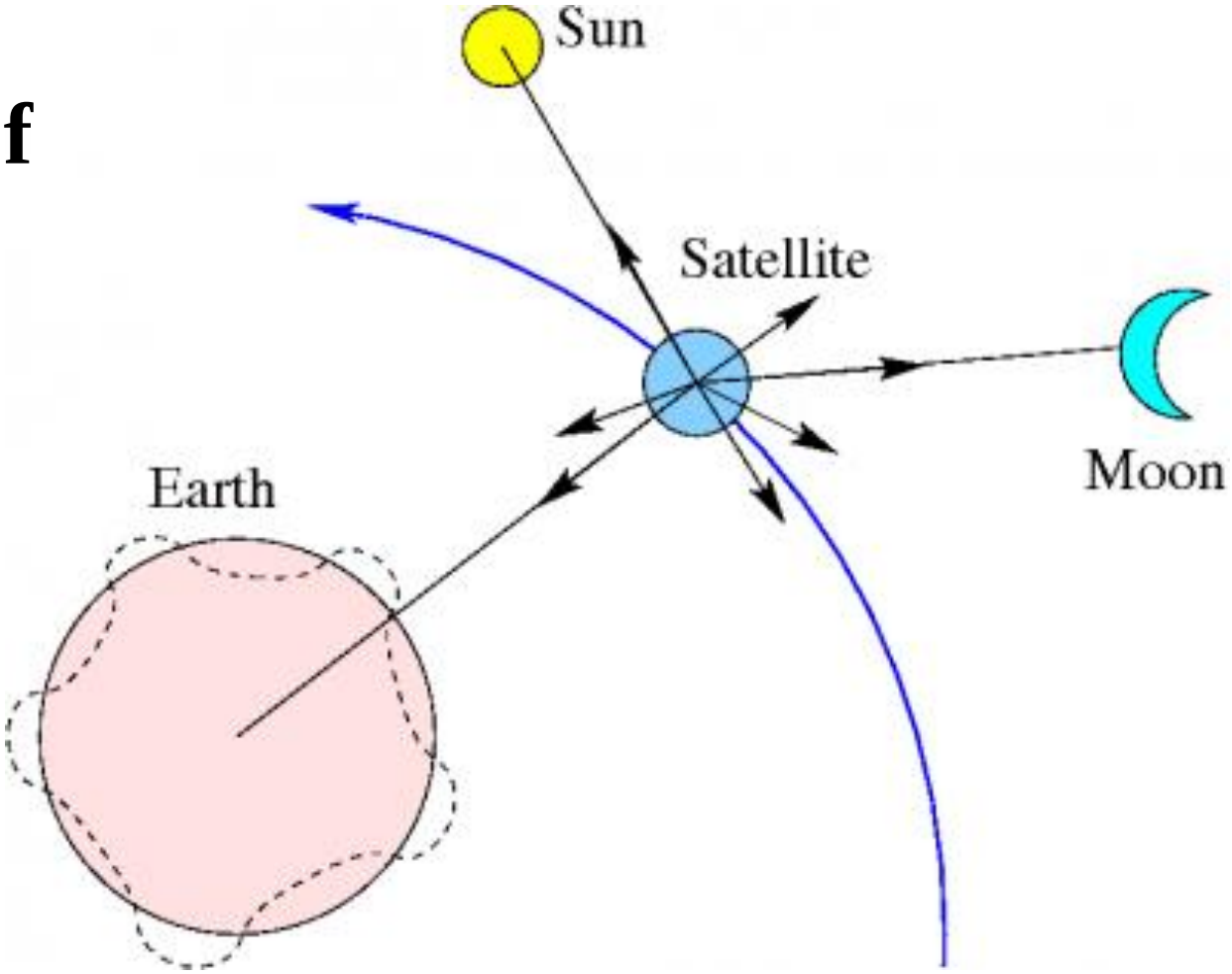


DATA,

GPS data measuring range

Choose the model

$$\ddot{\mathbf{r}} = -\frac{\mu \mathbf{r}}{r^3} + \mathbf{f}$$



Assumptions

Which forces are neglected?

e.g. variations in the Earth's gravity field

What is assumed in the force modelling?

e.g. known value for absorption coefficient of satellite surface

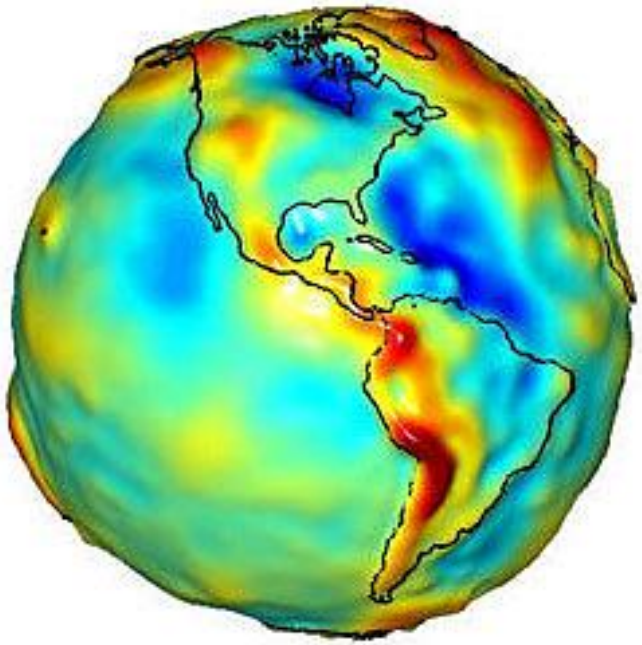
Effect of assumptions

What are the effects of assumptions?

variations in the Earth's gravity field

Look for a higher model of the Earth's gravity field

and compute the effect



Choose the method

Numerical integration: Euler integration

$$\dot{\mathbf{r}} = F\left(\dot{\mathbf{r}}, t\right)$$

$$\mathbf{r}\left(t_0 + \Delta t\right) \approx \mathbf{r}(t_0) + \dot{\mathbf{r}}\Delta t$$

Assumptions

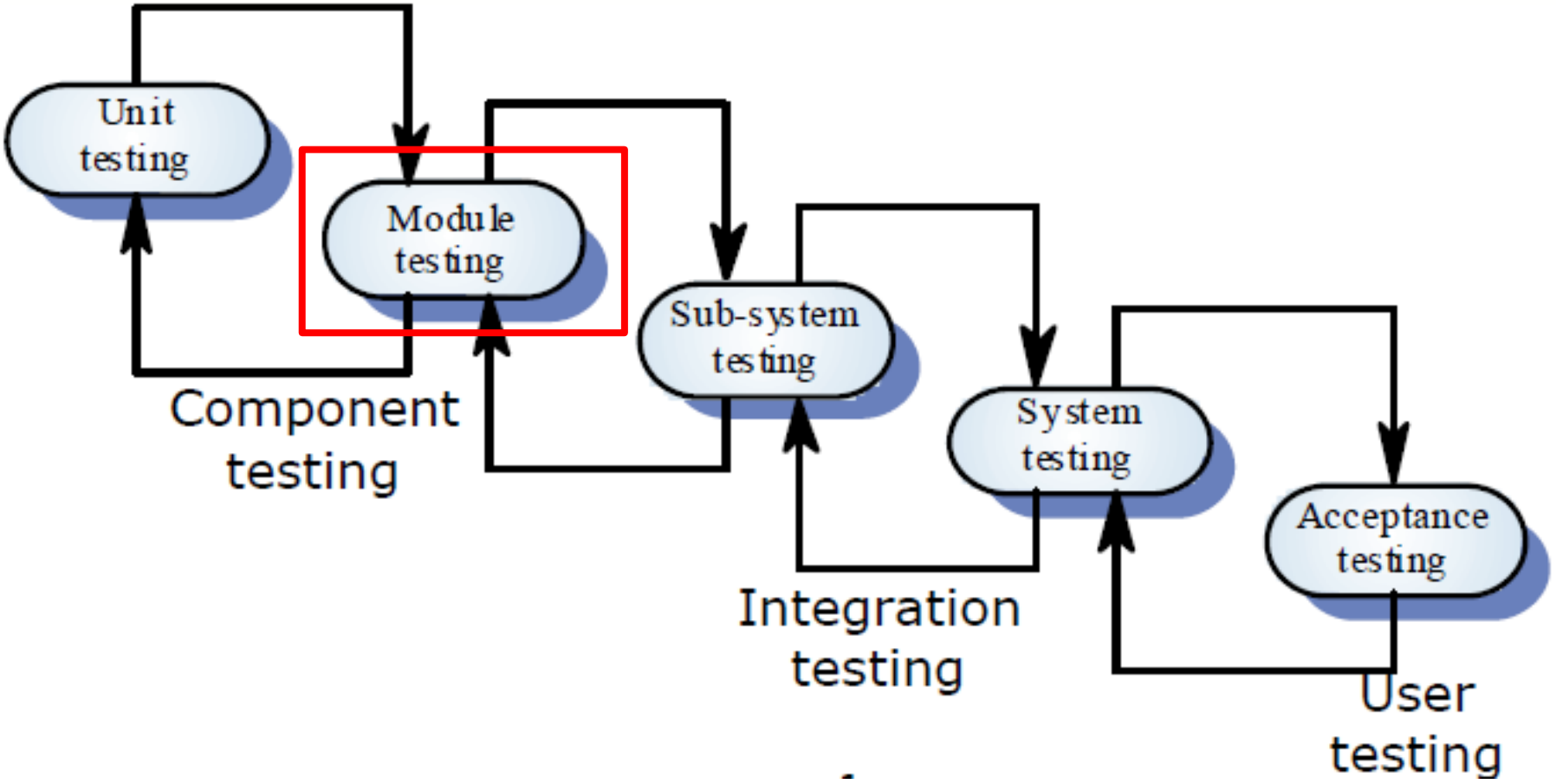
- Time step is small enough
- Total integration time is limited

Describing the code: pseudocode

```
read input parameters
define initial state
for each epochs
      compute da/dr
      call numerical integration
end
```

Translating to computer language (Python, Matlab, Fortran, …)

Design verification: module testing



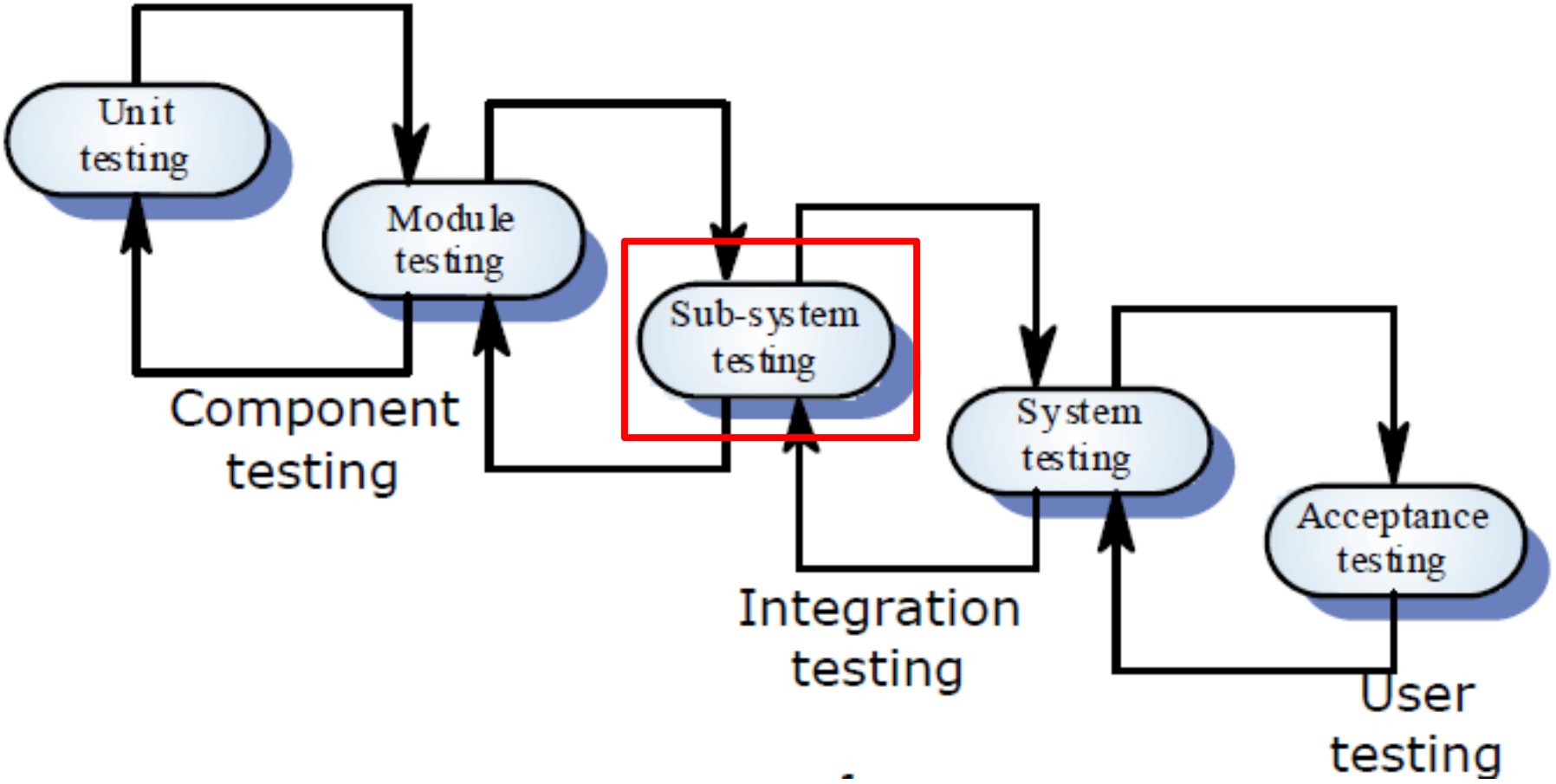
Verification: module testing

Unit numerical integration. **Did I make an error in my computer program?**

$$\mathbf{r}\left(t_0 + \Delta t\right) \approx \mathbf{r}(t_0) + \dot{\mathbf{r}}\Delta t$$

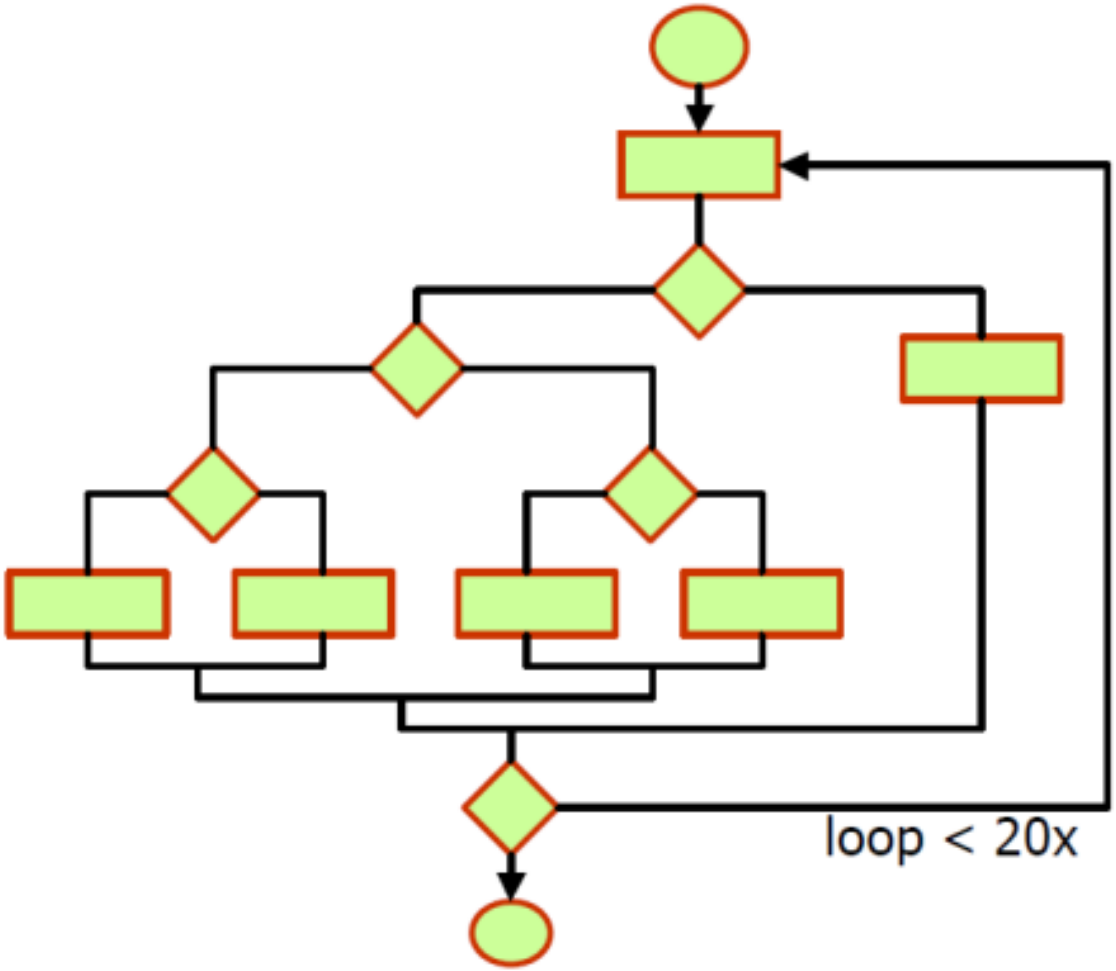
- Fill in zeros for the derivative in x-direction, does it result in movement in the y-z plane?
- Compute the derivative for a certain position by hand
- …

Design verification



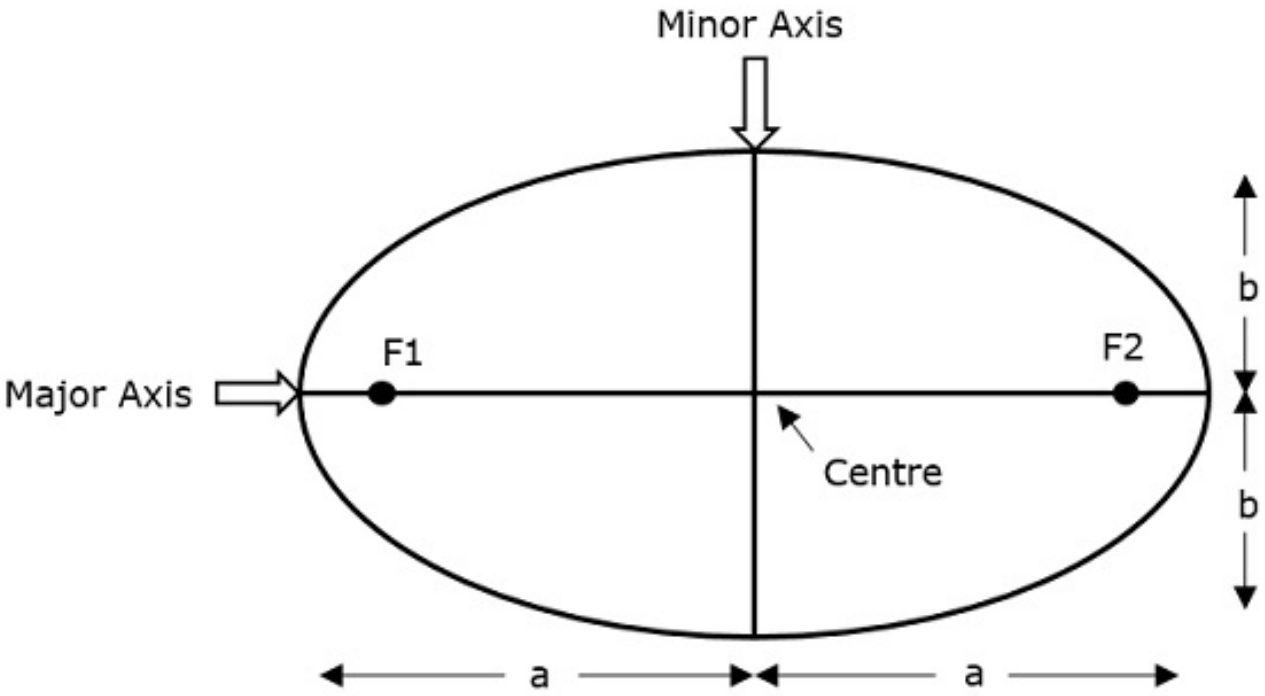
Design verification

Do the tests cover the entire model?



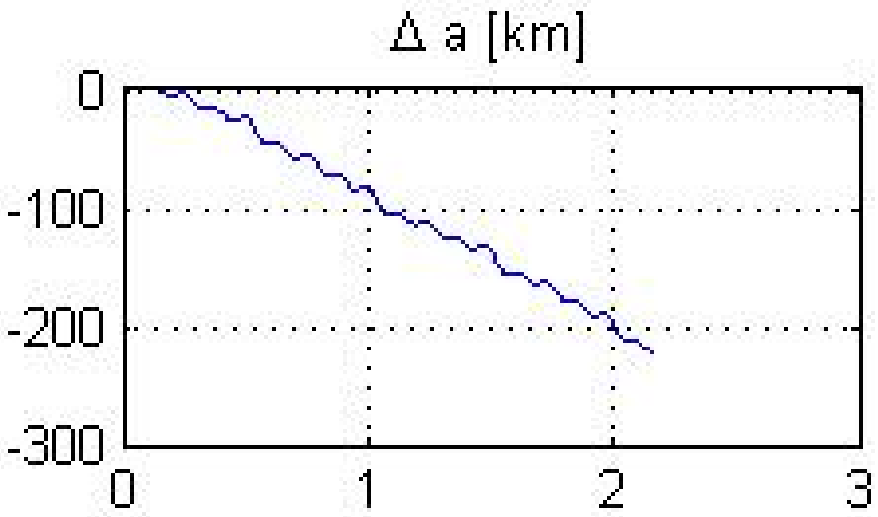
Verification: subsystem test

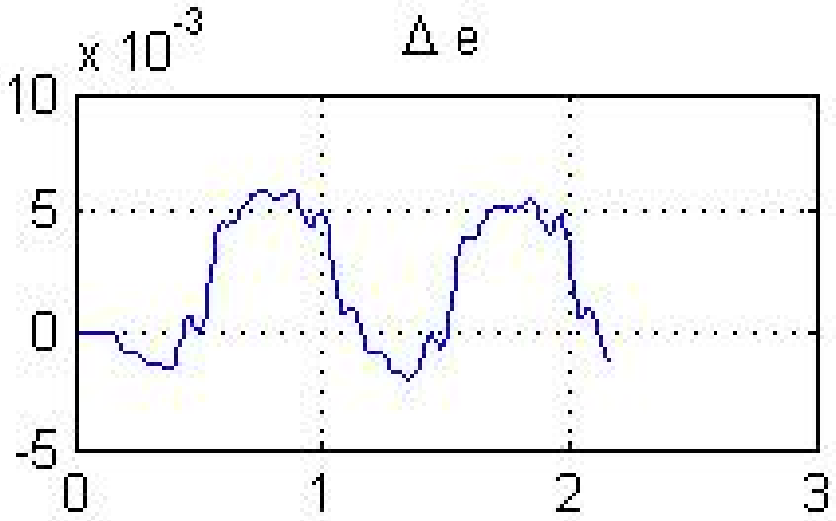
How can it be tested for a simple case?



Kepler's 1st law

Verification: subsystem test

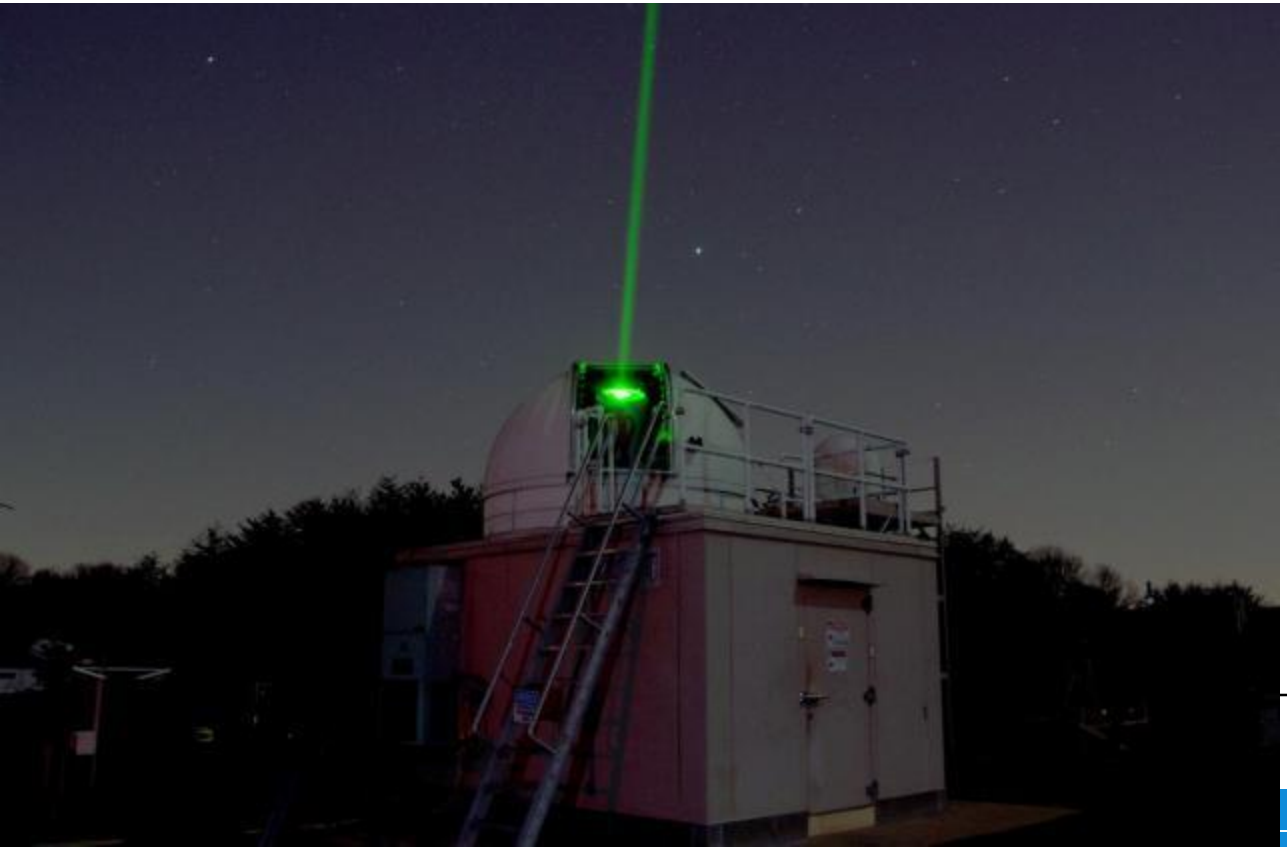




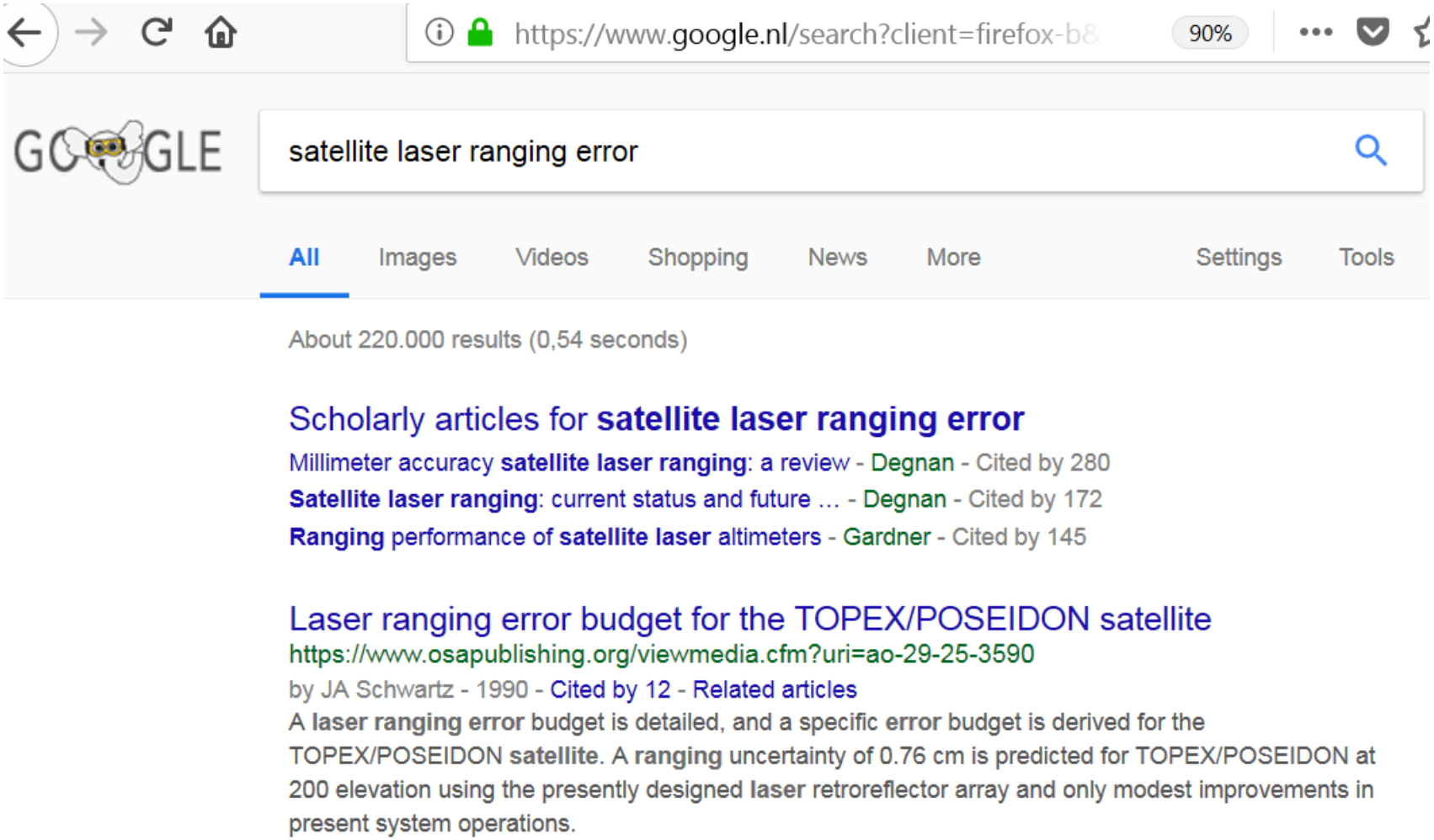
Is this level of agreement acceptable?

Validation

Experiment: satellite laser ranging

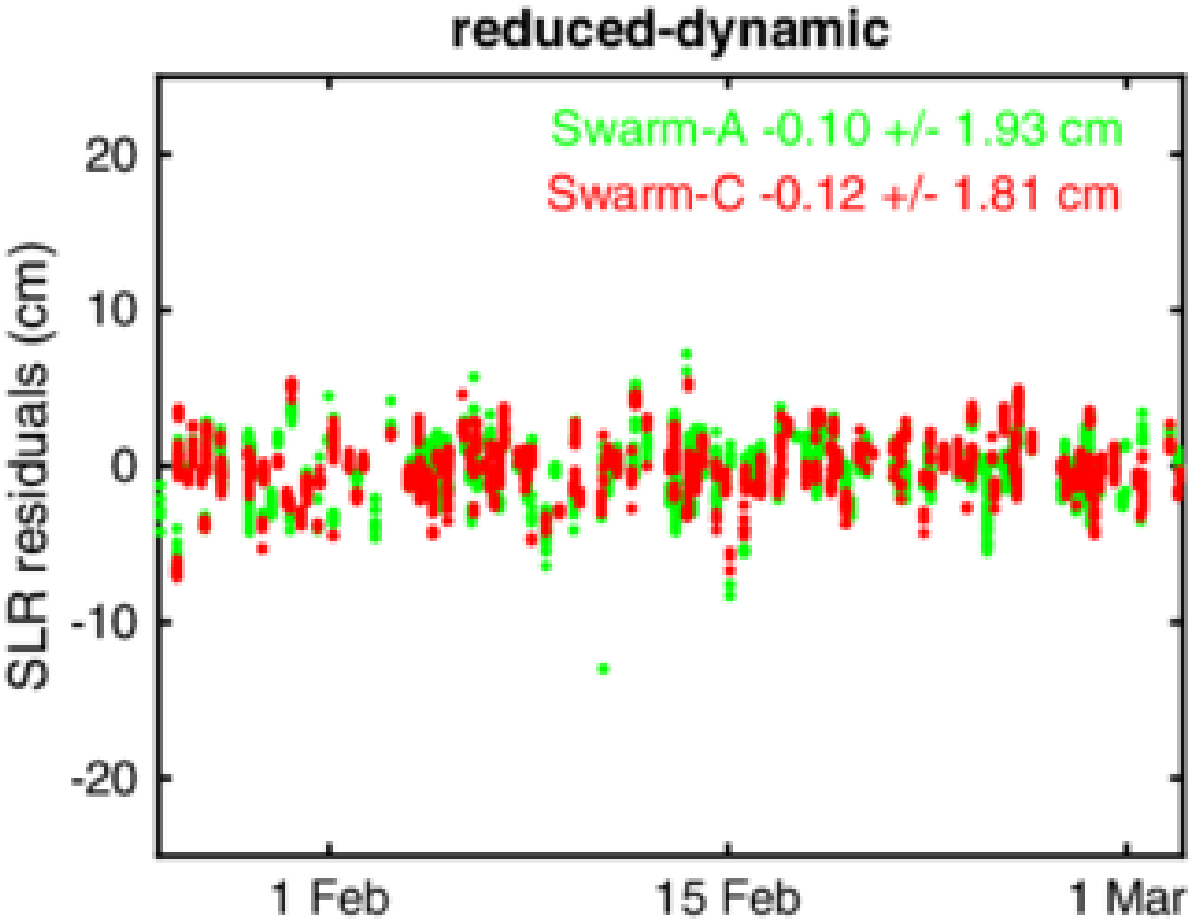


Experimental Data



Validation

"Determine if the simulation results represent the physical problem accurate **enough**"



van den IJssel et al. (2016)

Course Overview

- Course is 4 ECTS, of which 3 ECTS (= 84 hrs) are scheduled
- Two knowledge domains:
  - Structural Analysis (SA) – Julien van Campen
  - Flight Dynamics (FD) –Xander in ‘t Veld and Hans Mulder

    AE3212-II contains the data processing part of the Flight Test but the actual test is part of AE3212-I (Flight Dynamics)
- Supervision/support by Teaching Assistants & Staff
- **See ‘Guidelines and Rules’ and ‘CourseChanges.pdf’ on Brightspace**

Course Schedule

- Week 1 – Introduction of SA assignment; allocation of groups of 6
  If a group member didn't respond, email: w.vanderwal@tudelft.nl until 19:00h.
- Week 1 – Hand-in Simulation Plan: before Friday 17:00

- Week 3 – Hand-in report: before Friday 17:00
  Peer evaluation

- Week 4 – Introduction FD assignment, new groups are formed
  March 2: Lecture is mandatory for the flight test!
  March 4: 8:45 Computer test SVV and debugging (pass/fail),
  Simulation plan **may** be handed-in, no grade

- Week 7 – Hand-in report: before Wednesday 12:30
  Peer evaluation

Rules

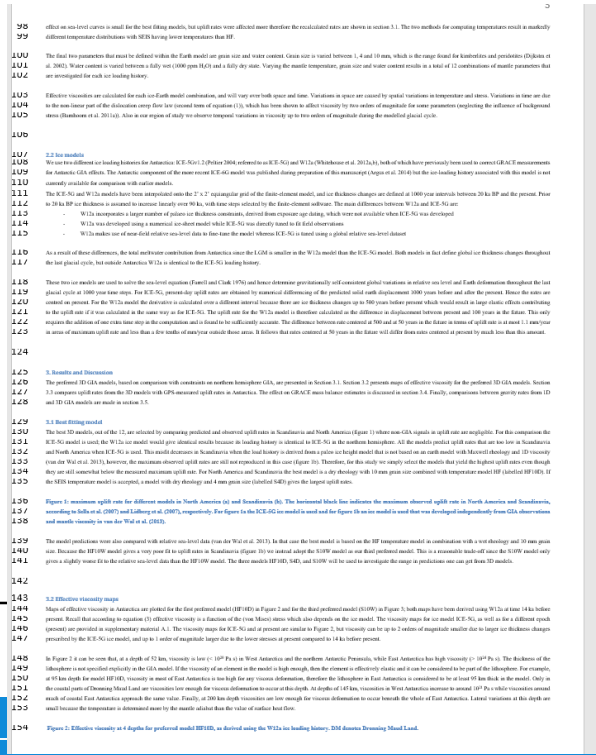
- You can only participate in the course when you completed all projects in the first and second year.
- In each deliverable, everybody has to work on 2 out of 3 tasks, simulation, verification and validation.

Sign-up Flight Test

- Website will open end of February (to be announced)
- Not all dates will be opened right away
- You choose a flight on a certain time and date
- Your group for the flight test will be the group for the SVV assignment

Rules: Simulation Plan

- Submit as pdf in Turnitin (in the folder ‘Deliverables’) by one of the group members. Name the simulation plan as: ‘Axx_sim’
- The page limit for the simulation plan is 23 pages including everything (also cover page). So the pdf should not have more than 23 pages. For every page over the page limit 1 point will be subtracted.
- Check font size and print margin rules
- Late hand-ins are not accepted.



effect on sea-level curves is small for the best fitting models, but uplift rates were affected more therefore the recalculated rates are shown in section 3.1. The two methods for computing temperatures result in markedly different temperature distributions with SEIS having lower temperatures than HF.

The final two parameters that must be defined within the Earth model are grain size and water content. Grain size is varied between 1, 4 and 10 mm, which is the range found for kimberlites and peridotites (Dijkstra et al. 2002). Water content is varied between a fully wet (1000 ppm H_2O) and a fully dry state. Varying the mantle temperature, grain size and water content results in a total of 12 combinations of mantle parameters that are investigated for each ice loading history.

Effective viscosities are calculated for each ice-Earth model combination, and will vary over both space and time. Variations in space are caused by spatial variations in temperature and stress. Variations in time are due to the non-linear part of the dislocation creep flow law (second term of equation (1)), which has been shown to affect viscosity by two orders of magnitude for some parameters (neglecting the influence of background stress (Rambcourt et al. 2011a)). Also in our region of study we observe temporal variations in viscosity up to two orders of magnitude during the modelled glacial cycle.

2.2 Ice models

We use two different ice loading histories for Antarctica: ICE-5G(v1.2 (Peltier 2004; referred to as ICE-5G) and W12a (Whitehouse et al. 2012a,b), both of which have previously been used to correct GRACE measurements for Antarctic GIA effects. The Antarctic component of the more recent ICE-6G model was published during preparation of this manuscript (Argus et al. 2014) but the ice loading history associated with this model is not currently available for comparison with earlier models.

The ICE-5G and W12a models have been interpolated onto the 2° x 2° equiangular grid of the finite-element model, and ice thickness changes are defined at 1000 year intervals between 20 ka BP and the present. Prior to 20 ka BP ice thickness is assumed to increase linearly over 90 ka, with time steps selected by the finite-element software. The main differences between W12a and ICE-5G are:

- W12a incorporates a larger number of palaeo ice thickness constraints, derived from exposure age dating, which were not available when ICE-5G was developed
- W12a was developed using a numerical ice-sheet model while ICE-5G was directly tuned to fit field observations
- W12a makes use of near-field relative sea-level data to fine-tune the model whereas ICE-5G is tuned using a global relative sea-level dataset

As a result of these differences, the total meltwater contribution from Antarctica since the LGM is smaller in the W12a model than the ICE-5G model. Both models in fact define global ice thickness changes throughout the last glacial cycle, but outside Antarctica W12a is identical to the ICE-5G loading history.

These two ice models are used to solve the sea-level equation (Farrell and Clark 1976) and hence determine gravitationally self-consistent global variations in relative sea level and Earth deformation throughout the last glacial cycle at 1000 year time steps. For ICE-5G, present-day uplift rates are obtained by numerical differencing of the predicted solid earth displacement 1000 years before and after the present. Hence the rates are centred on present. For the W12a model the derivative is calculated over a different interval because there are ice thickness changes up to 500 years before present which would result in large elastic effects contributing to the uplift rate if it was calculated in the same way as for ICE-5G. The uplift rate for the W12a model is therefore calculated as the difference in displacement between present and 100 years in the future. This only requires the addition of one extra time step in the computation and is found to be sufficiently accurate. The difference between rates centred at 500 and at 50 years in the future in terms of uplift rate is at most 1.1 mm/year in areas of maximum uplift rate and less than a few tenths of mm/year outside those areas. It follows that rates centred at 50 years in the future will differ from rates centred at present by much less than this amount.

3. Results and Discussion

The preferred 3D GIA models, based on comparison with constraints on northern hemisphere GIA, are presented in Section 3.1. Section 3.2 presents maps of effective viscosity for the preferred 3D GIA models. Section 3.3 compares uplift rates from the 3D models with GPS-measured uplift rates in Antarctica. The effect on GRACE mass balance estimates is discussed in section 3.4. Finally, comparisons between gravity rates from 1D and 3D GIA models are made in section 3.5.

3.1 Best fitting model

The best 3D models, out of the 12, are selected by comparing predicted and observed uplift rates in Scandinavia and North America (figure 1) where non-GIA signals in uplift rate are negligible. For this comparison the ICE-5G model is used; the W12a ice model would give identical results because its loading history is identical to ICE-5G in the northern hemisphere. All the models predict uplift rates that are too low in Scandinavia and North America when ICE-5G is used. This misfit decreases in Scandinavia when the load history is derived from a paleo ice height model that is not based on an earth model with Maxwell rheology and 1D viscosity (van der Wal et al. 2013), however, the maximum observed uplift rates are still not reproduced in this case (figure 1b). Therefore, for this study we simply select the models that yield the highest uplift rates even though they are still somewhat below the measured maximum uplift rate. For North America and Scandinavia the best model is a dry rheology with 10 mm grain size combined with temperature model HF (labelled HF10D). If the SEIS temperature model is accepted, a model with dry rheology and 4 mm grain size (labelled S4D) gives the largest uplift rates.

Figure 1: maximum uplift rate for different models in North America (a) and Scandinavia (b). The horizontal black line indicates the maximum observed uplift rate in North America and Scandinavia, according to Sella et al. (2007) and Lidberg et al. (2007), respectively. For figure 1a the ICE-5G ice model is used and for figure 1b an ice model is used that was developed independently from GIA observations and mantle viscosity in van der Wal et al. (2013).

The model predictions were also compared with relative sea-level data (van der Wal et al. 2013). In that case the best model is based on the HF temperature model in combination with a wet rheology and 10 mm grain size. Because the HF10W model gives a very poor fit to uplift rates in Scandinavia (figure 1b) we instead adopt the S10W model as our final preferred model. This is a reasonable trade-off since the S10W model only gives a slightly worse fit to the relative sea-level data than the HF10W model. The three models HF10D, S4D, and S10W will be used to investigate the range in predictions one can get from 3D models.

3.2 Effective viscosity maps

Maps of effective viscosity in Antarctica are plotted for the first preferred model (HF10D) in Figure 2 and for the third preferred model (S10W) in Figure 3; both maps have been derived using W12a at time 14 ka before present. Recall that according to equation (5) effective viscosity is a function of the (von Mises) stress which also depends on the ice model. The viscosity maps for ice model ICE-5G, as well as for a different epoch (present) are provided as supplementary material A.1. The viscosity maps for ICE-5G and at present are similar to Figure 2, but viscosity can be up to 2 orders of magnitude smaller due to larger ice thickness changes prescribed by the ICE-5G ice model, and up to 1 order of magnitude larger due to the lower stresses at present compared to 14 ka before present.

In Figure 2 it can be seen that, at a depth of 52 km, viscosity is low (< 10^{20} Pa s) in West Antarctica and the northern Antarctic Peninsula, while East Antarctica has high viscosity (> 10^{21} Pa s). The thickness of the lithosphere is not specified explicitly in the GIA model. If the viscosity of an element in the model is high enough, then the element is effectively elastic and it can be considered to be part of the lithosphere. For example, at 95 km depth for model HF10D, viscosity in most of East Antarctica is too high for any viscous deformation, therefore the lithosphere in East Antarctica is considered to be at least 95 km thick in the model. Only in the coastal parts of Dronning Maud Land are viscosities low enough for viscous deformation to occur at this depth. At depths of 145 km, viscosities in West Antarctica increase to around 10^{21} Pa s while viscosities around much of coastal East Antarctica approach the same value. Finally, at 200 km depth viscosities are low enough for viscous deformation to occur beneath the whole of East Antarctica. Lateral variations at this depth are small because the temperature is determined more by the mantle adiabat than the value of surface heat flow.

Figure 2: Effective viscosity at 4 depths for preferred model HF10D, as derived using the W12a ice loading history. DM denotes Dronning Maud Land.

Rules: Report

- Reports should include a pdf of the code **as text** in the appendix.
- Codes should also be submitted in a separate Turnitin folder as zip file (excluding common libraries)
- The report should include a table with number of hours spent per group member on each task.
- Scans of hand drawings are allowed.
- The page limit for the SA report is 28 pages which includes everything (also cover page) except the appendix with the code. For the FD report the page limit is 35 pages. For every page over the page limit 1 point will be subtracted.

Grading

- See ‘Assessment’
- Simulation plan (1/6), Structures Report (2/6), Flight Dynamics Report (3/6)
- Computer test: pass/fail (resit to be announced)
- Revisions required for the report if the structures grade < 5.8, or the Flight dynamics grade < 5.8
- Peer evaluation (NOT seen by TA’s, NOT used for grading)
- Hour registration per week (excel sheet in group locker)

Grading

- There are TA's for structural analysis and for flight dynamics
- Simulation plan or report is graded by **two** TA's
- You get partial grades according to the rubrics for the simulation plan or report, and comments in the pdf
- The pdf can only be seen by the person that submitted it. So please distribute to your group
- In case comments are not clear, you can talk to a TA during the next SVV session

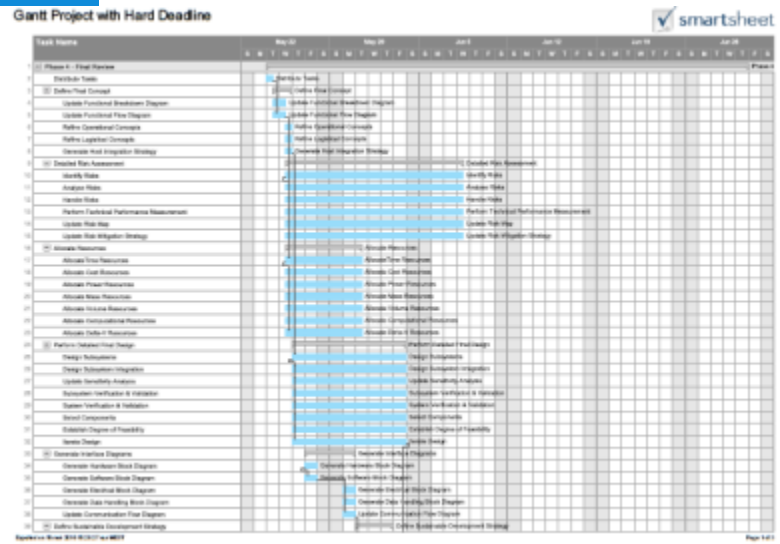
Support

- Come by if you have questions
- TA's will not tell you whether the answer is correct or wrong, or debug your program, but point you in the right direction if you are unsure of the approach
- Asking questions will not affect your grade negatively!
- Outside project sessions questions will be answered on the forum (and not by email)
- All communication through Brightspace

Group work

- Check the table allocation for the project tables and TA room (it changes!)
- In case of problems in the group, please send an email to w.vanderwal@tudelft.nl or come to the TA room during the SVV sessions

Tips: Planning



Tips: Commenting and debugging