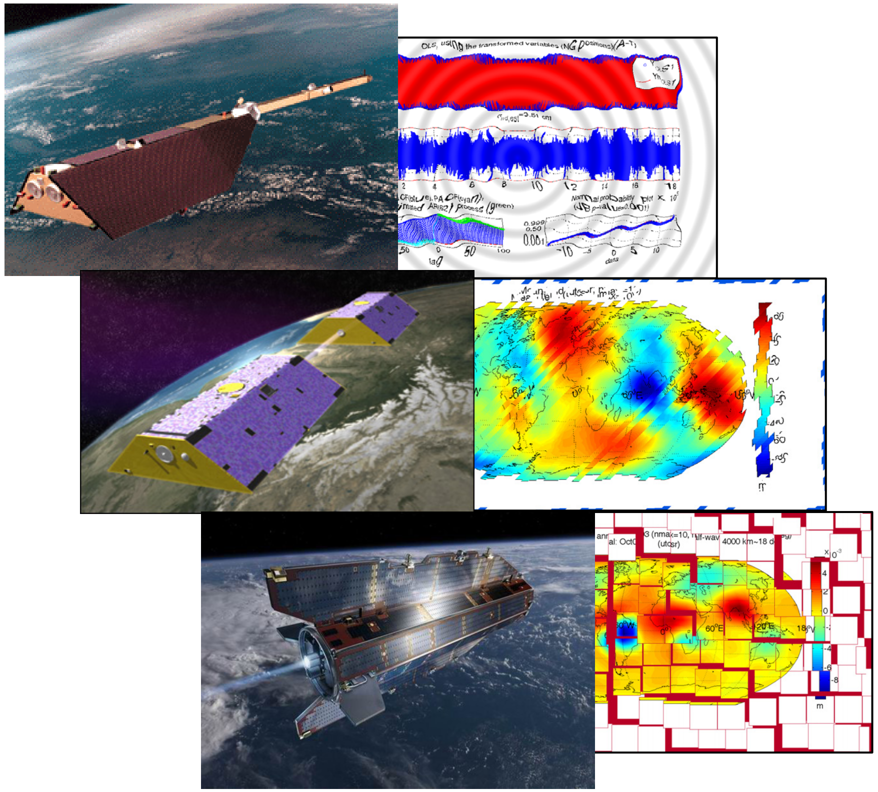
Average time-variable gravity from GPS orbits of recent geodetic satellites



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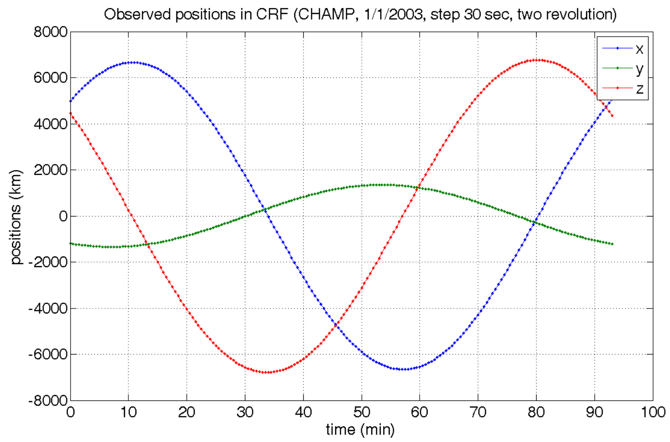
Average time-variable gravity from GPS orbits: Contents

- Overview of our inversion method
- Time series tools: PACF, AR
- Results using real data (CHAMP, GRACE A/B, GOCE)
  - Static & time-variable solutions
  - Geocentre motion from GPS orbits

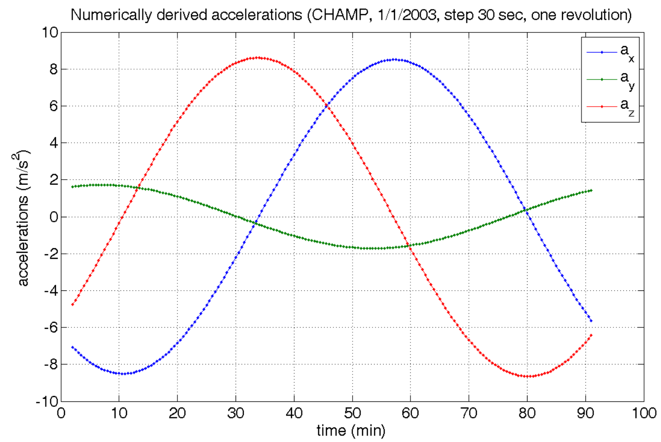
Gravity field from orbit: acceleration approach

SST:high-low (CHAMP, GRACE, GOCE)

- long time series of positions with constant time step



- Positions $\mathbf{r}_{gps}(t)$ → by numerical derivative we obtain observations: "**GPS-based accelerations**" $\mathbf{a}_{GPS}$



- Newton second law:

  $\mathbf{a}_{GPS} \approx d^2\mathbf{r}/dt^2 = \mathbf{a}_{geop} + \mathbf{a}_{LS} + \mathbf{a}_{TID} + \mathbf{a}_{NG}$

  $\mathbf{a}_{geop}(\mathbf{r}) \equiv \sum GC \times \nabla SSH(r,\theta,\varphi)$ … geopotential in spherical harmonics SSH, GC…geopotential coefficients

  $\mathbf{a}_{LS}, \mathbf{a}_{TID}, \mathbf{a}_{NG}$ …lunisolar, tides, nongravitational

- Newton law → **linear system**:

$$\sum \mathbf{GC} \times \nabla SSH(r,\theta,\varphi) + \boldsymbol{\varepsilon} = \mathbf{a}_{GPS} - (\mathbf{a}_{LS} + \mathbf{a}_{TID} + \mathbf{a}_{NG}) \qquad (*)$$

- Now **geopotential coefficients (GC)** can be solved for using (∗).

Acceleration approach: ASU[1] version

Linear system of observation equations to estimate **geopotential coefficients GC**:

$$\sum \mathbf{GC} \times \nabla SSH(r,\theta,\varphi) + \boldsymbol{\varepsilon} = \mathbf{a}_{GPS} - (\mathbf{a}_{LS} + \mathbf{a}_{TID} + \mathbf{a}_{NG}) \qquad (*)$$

Solution method:

- Polynomial smoothing filters: positions $\mathbf{r}_{gps}(t) \rightarrow$ GPS-based acceleration $\mathbf{a}_{GPS} \equiv d^2Q(\mathbf{r}_{gps})/dt^2$
- Assumption: uncertainty in $\mathbf{a}_{LS}$, $\mathbf{a}_{TID}$, $\mathbf{a}_{NG}$ is negligible relative to that of $\mathbf{a}_{GPS}$

- Problem: **Numerical derivative amplifies noise** in GPS positions
  - Solution: **Generalized least squares (GLS)**
    $\rightarrow$ linear transformation of system $(*)$

- Problem: Real data $\rightarrow$ GPS positions have **correlated errors**
  - Solution: **partial autocorrelation function (PACF)** $\rightarrow$ **autoregressive model (AR)**
    $\rightarrow$ linear transformation of system $(*)$

Solving transformed system $(*)$ we get geopotential coefficients **GC** by ordinary least squares

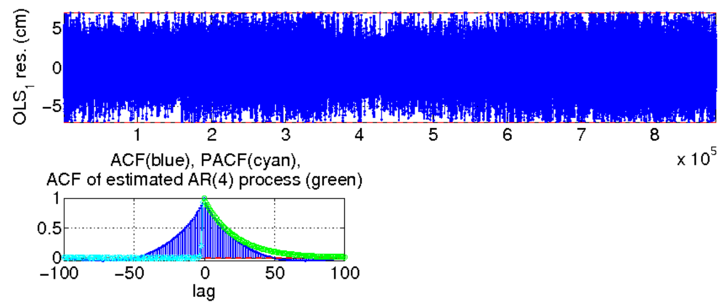
- no a priori gravity field model
- no regularization

[1]ASU…Astronomical Institute ASCR

Decorrelation of GPS position errors using AR process

Problem: Real GPS positions have <u>correlated errors</u>

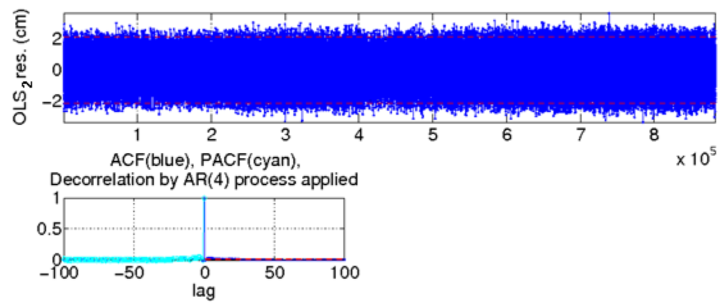
- Indicated by sample autocorrelation function ACF
  - ➢Unrealistic error bars
  - ➢Possibly biased parameter estimates



Partial autocorrelation function PACF

Rapid decay of PACF → suitability of AR model to represent the correlation structure

- In figure, fitted **autoregressive model AR** of order 4 approximates ACF of residuals

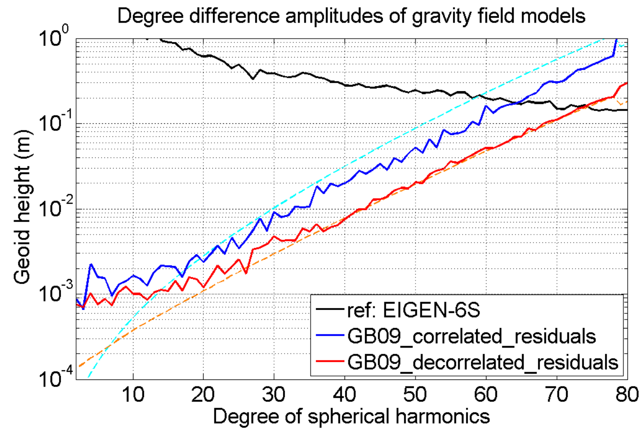


Decorrelation of residuals using fitted AR models

- by linear transformation of linear system (∗)
- ACF and PACF become approx. delta functions

Estimation of **geopotential coefficients GC**

- <u>After decorrelation, GC are **more accurate** by factor 2–3!</u>
- More realistic uncertainty estimate of GC

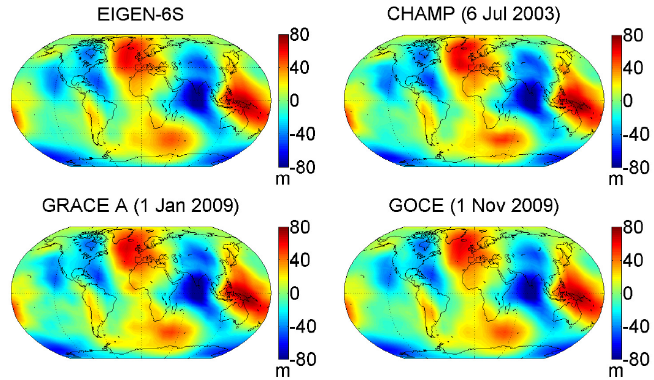


(Figures: GRACE B real data, year 2009)

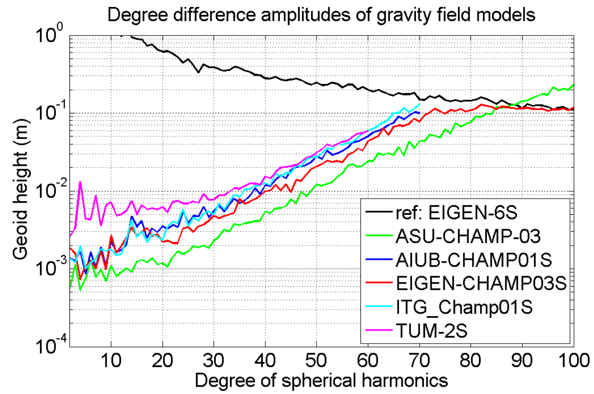
Static gravity field models (CHAMP, GRACE, GOCE)

Examples of successful application of the presented inversion method to estimate geopotential coefficients.

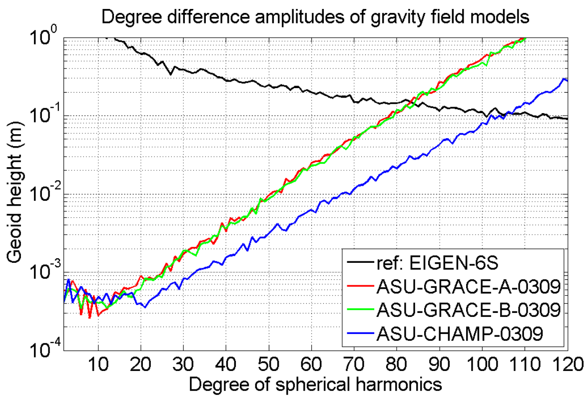
- One-day solutions

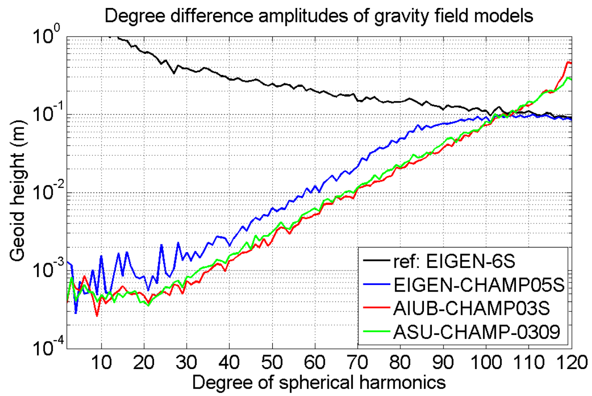


- CHAMP yearly solution for 2003



- CHAMP and GRACE A/B solutions (2003–2009)





Time-variable gravity from GPS orbits (GRACE, CHAMP)

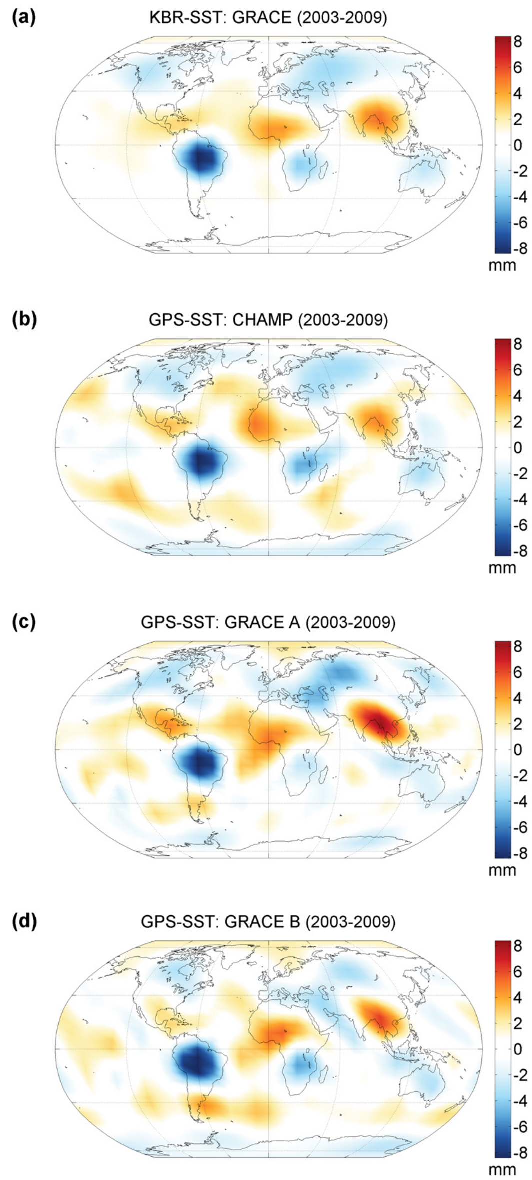
- CHAMP, GRACE A/B kinematic orbits (2003–2009)
- monthly solutions estimated up to degree 20
- to reduce aliasing due to truncation error
  → we subtract signal from suitable static geopotential model for degrees 21–100 (e.g. EGM2008)

<u>Monthly solutions to degree 10</u> used in <u>**time series model**</u>:

- ➢ mean, trend, seasonal sinusoid

<u>Figures: Seasonal gravity, average October variation</u>

- (a) from GRACE microwave ranging (KBR)
- (b)–(c) **time-variable gravity from GPS tracking**
  - ➢ most important continental areas with seasonal hydrology
  - ➢ noisier compared to KBR solutions
  - ➢ spatial resolution smaller than KBR solutions



Geocentre motion from GPS orbits (GRACE A/B)

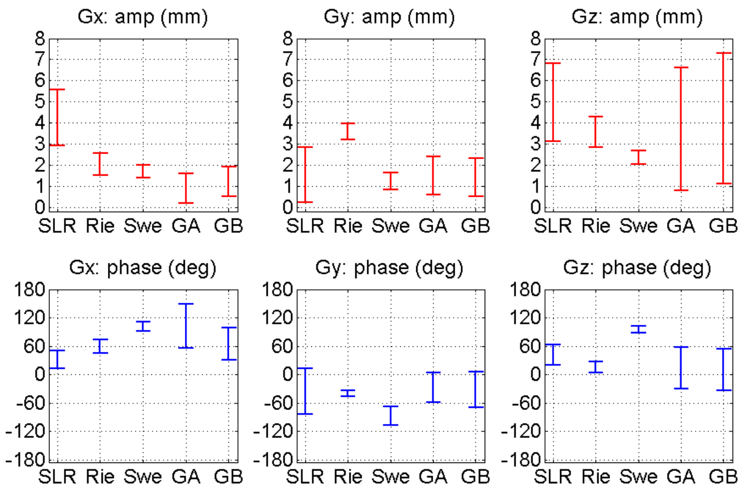
- In our monthly solutions, we fitted also **degree-one geopotential coefficients** C_{10}, C_{11}, S_{11}
- Usually they are identically zero ↔ origin of coordinate system at centre of mass (CM)
- If fitted, they may show motion of CM relative to centre of Earth figure (e.g. ITRF):

$$G_x = \sqrt{3}\, R\, C_{11} \qquad G_y = \sqrt{3}\, R\, S_{11} \qquad G_z = \sqrt{3}\, R\, C_{10}$$

- Kang et al. (2009) found geocentre motion from GPS tracking using GRACE KBR fields

Figure: Annual cycle in geocentre motion (2005–2009)

- 3-σ confidence intervals for amplitudes and phases
  - ➢ all the results are rather noisy
  - ➢ order-of-magnitude agreement
  - ➢ probable existence of annual systematic variation



SLR: Cheng et al. (2010), ftp://ftp.csr.utexas.edu/pub/slr/geocenter/

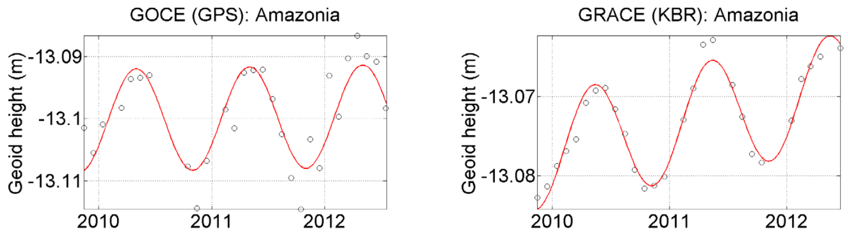
Rie: Rietbroek et al. (2012), http://igg.uni-bonn.de/apmg/index.php?id=geozentrum

Swe: Swenson et al. (2008), ftp://podaac.jpl.nasa.gov/allData/tellus/L2/degree 1/

GA, GB: our fits to GRACE A/B monthlies, http://www.asu.cas.cz/bezdek/vyzkum/geopotencial/

Time-variable gravity from GPS orbits (GOCE)

- GOCE kinematic orbits (2009–2012)
- monthlies estimated to degree 20
- aliasing from degrees 21–120 reduced by time-wise GOCE model (Release 4)
- time series model: monthlies up to degree 10

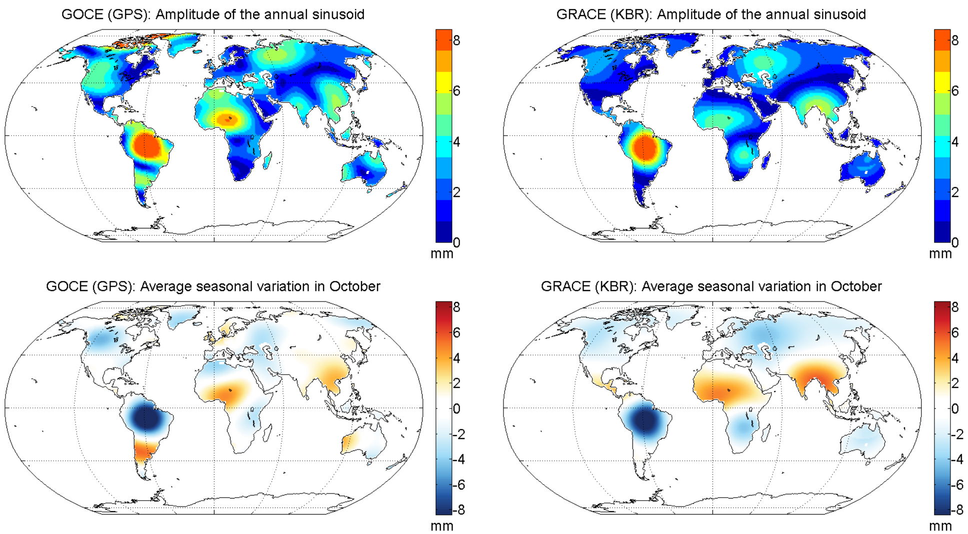


<u>Figure: Time variable gravity in Amazonia</u>

- agreement in seasonal component
- mean & trend different: short time span

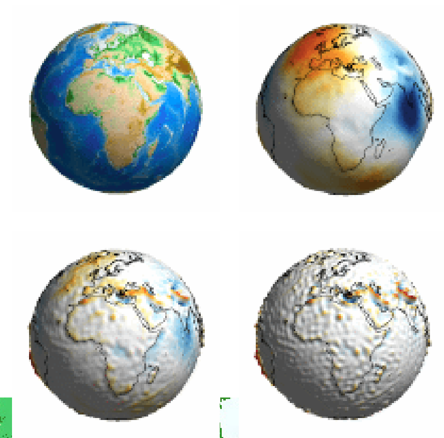
<u>Figure: Seasonal gravity variation</u>

- important continental hydrology areas
- noisier compared to KBR solutions
- spatial resolution smaller than KBR
- first GOCE-only time-variable gravity



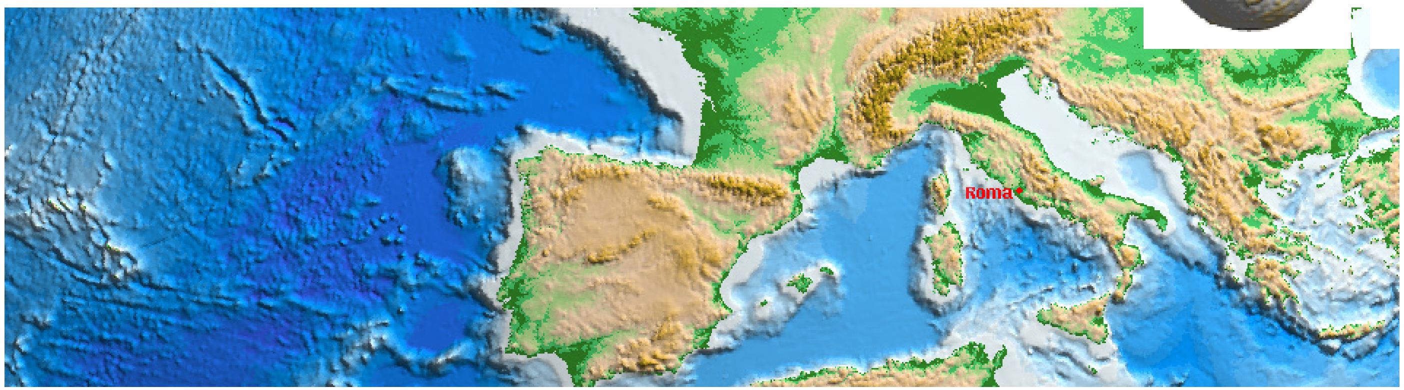
Average time-variable gravity from GPS orbits: Conclusions

- Well identified continental areas with pronounced seasonal hydrology variation
- Much reduced spatial resolution vs. GRACE KBR monthly solutions
- Advantages:
  - possibly many satellite missions equipped with GPS
  - independent source of information on time-variable gravity



Website: http://www.asu.cas.cz/~bezdek/

- long-term geopotential solutions (CHAMP, GRACE)
- their full covariance matrices
- computational details (preprint, under review)
- free Matlab package for 2D/3D visualising



Thank you for your attention