Challenges of Space Geodesy in Monitoring Natural Hazards

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Space Geodesy

- Definition:

"Satellite Geodesy comprises the observational and computational techniques which allow the solution of geodetic problems by the use of precise measurements to, from, or between artificial, mostly near-Earth, satellites." (Seeber, 2003)

- Space Geodesy Systems:
  - Global Navigation Satellite Systems: GPS, GLONASS, BeiDou, Galileo
  - Very Long Baseline Interferometry (VLBI)
  - Satellite Laser Ranging (SLR)
  - Precise Range and Range-Rate Equipment (PRARE)
  - Doppler Orbitography and Radiolocation Integrated by Satellite(DORIS)
  - Etc !

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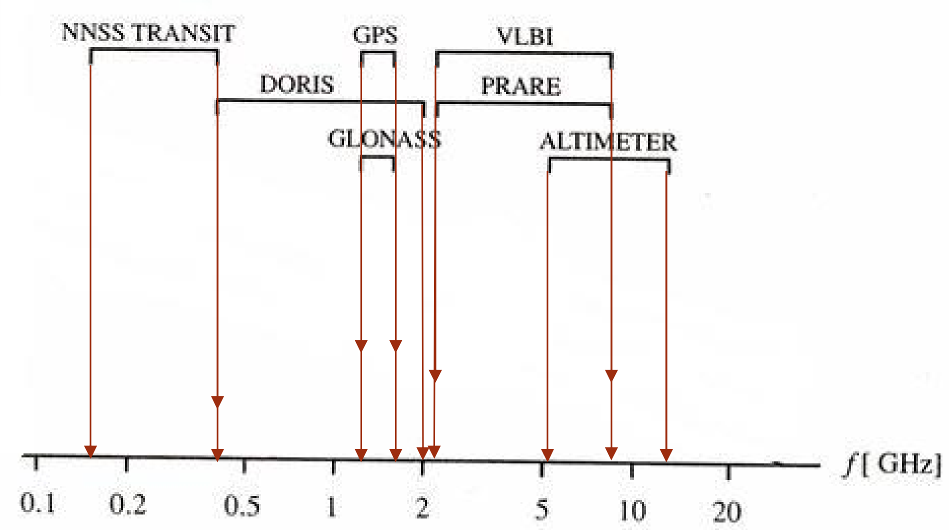
Space Geodesy-Characteristic features

- Frequency range

Reproduced and modified from Seeber (2003)



- The missions' target

They are not designed for monitoring the Earth's natural hazards!

Monitoring Natural Hazards

- Monitoring: The regular and continuous observation of some quantity

The Earth's Hazards

- Observations:
  - Carrier beat phases of electromagnetic signals received at/reflected from some targets
  - Travel time of electromagnetic signals received at/reflected from some targets
  - Doppler shift in the frequency of electromagnetic signals
  - Slant Wet Delays (SWDs)
  - Total Electron Content (STEC or VTEC)

Monitoring System

- Elements:
  - Sensors: GNSS satellites & GNSS receivers
  - An infrastructure for data transfer: Internet
  - Analysis center
  - Alarm system: A warning sound, a web interface
  - Model: required for prediction

Sensors: Space Segment-*general concerns*

- Space & ground segments: Space vehicles and receivers
  - ✓ Space segment is also the main concern in terms of the system cost
  - ✓ Space missions are designed to perform best in specific parts or all around the world
  - Example: GPS-MET versus GPS missions
  - ✓ Space segment plays a key role on the resolution of a monitoring system both in space and time

- Space configuration: *An important element in every space monitoring system!*

  constellation design is a multi-dimensional optimization problem
  - Minimum number of satellites
  - Orbits' geometry
  - Optimization measures or the mission's target
  - Geographical area which is to be covered

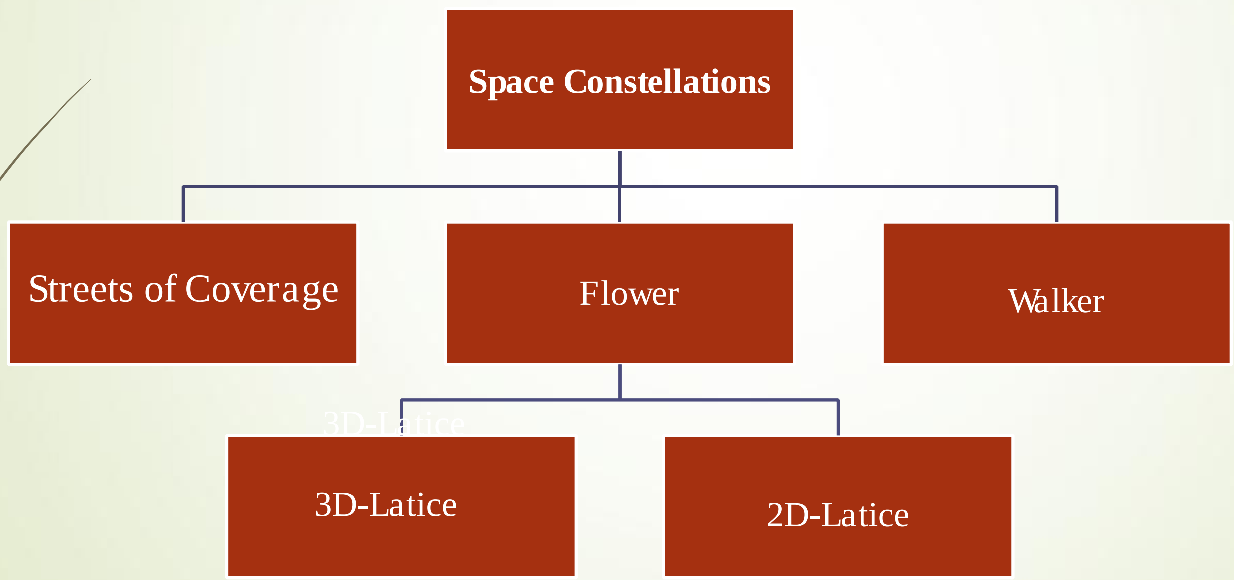
  guarantee the performance of a system

Challenges: Sensors-Space Configuration

- Satellite constellation: a group of satellites functioning in a coordinated manner
  significant improvement in temporal and spatial coverage
- Constellation design is an extraordinarily difficult problem (a multi-dimensional optimization problem)
  The infinite number of choices for the six Keplerian orbital parameters
  - the mission objectives (different fitness functions)
  - overall cost for realizing the mission (number of orbital planes & number of satellites)
  - geographical area that is to be covered
  - collisions or interference at orbit plane intersections (phasing of satellites)
  - Similar satellite orbits are preferred
    - reducing the fuel usage and hence increasing the life of the satellites
- *There is no defined common process for constellation design*

Challenges: Sensors-Space Segment

- Various constellation geometries were proposed to reduce this complexity



Walker

- A class of circular orbit geometries in an inertial frame I: T/P/F
- Orbit planes are evenly spaced on equator (360/P)
- Evenly spaces satellites in every orbit (360/S)

T: Satellite in *P* planes,

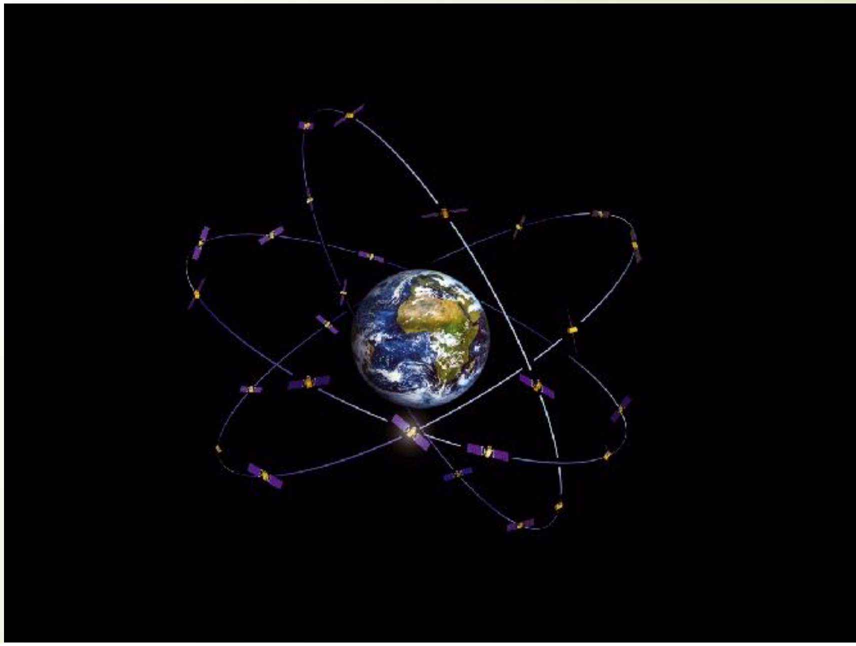
I: inclination,

T: total number of satellites

P: number of equally spaced planes

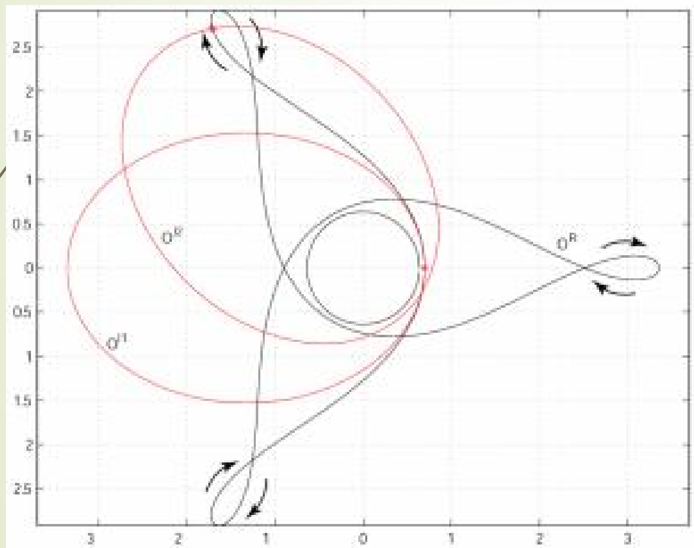
F: relative spacing between satellites in adjacent planes.

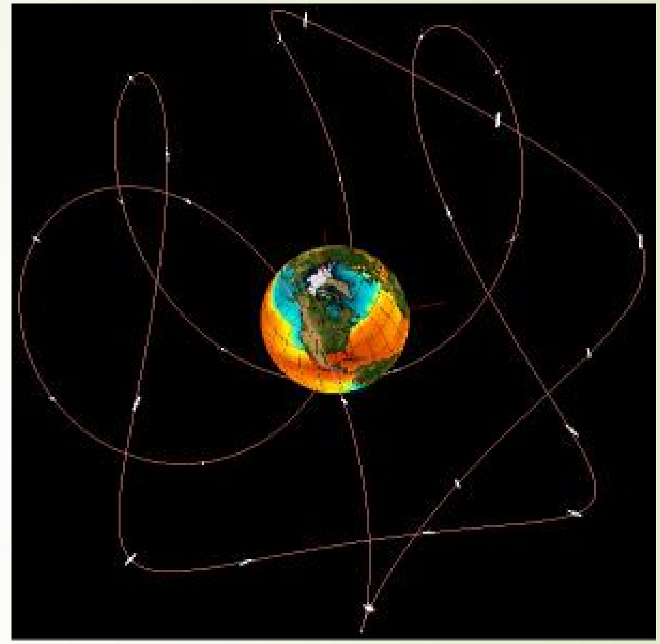
Global'naya Navigatsionnaya Sputnikovaya Sister
Walker Delta 56°:27/3/1 constellation



Flower

The constellation provides a closed orbit in a rotating coordinate frame





Flower constellation for Global Navigation

(I) $N_p T_p = N_d T_d$

(II) a, e, i & ω *are the same for all satellites*

(III) M_k & Ω_k *fulfill the following equation* $(k = 1, \ldots, N_S)$

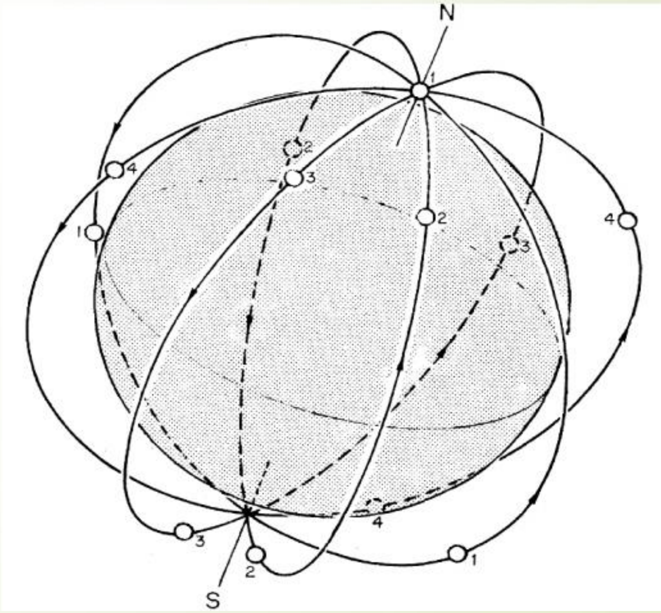
$$N_p \Omega_k + N_d M_k = const \bmod (2\pi)$$

Streets of Coverage

- The constellation consists of polar orbits
- Orbit planes are evenly spaced on equator: $180° / n_1$
- Evenly spaces satellites in every orbit: $360° / n_2$

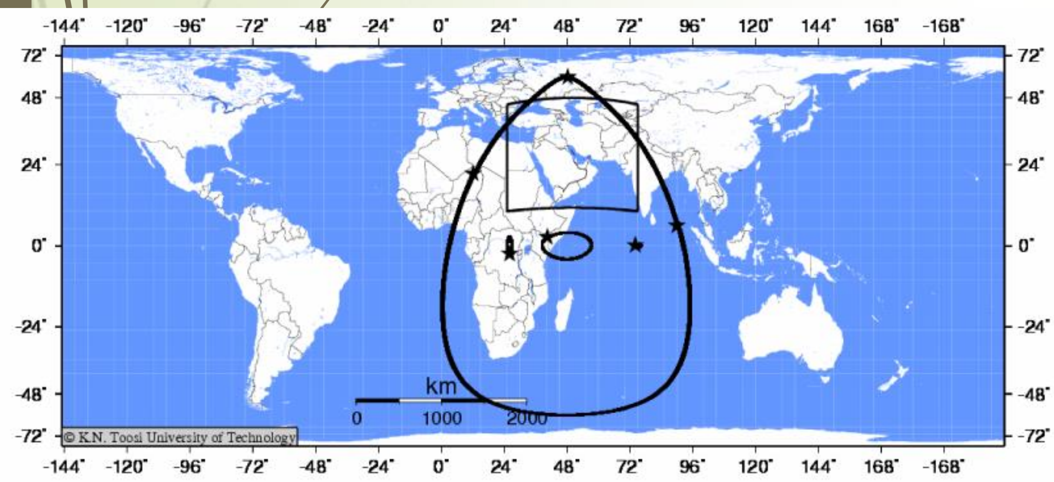
n_1 : number of orbital plane

n_2 : number of satellites

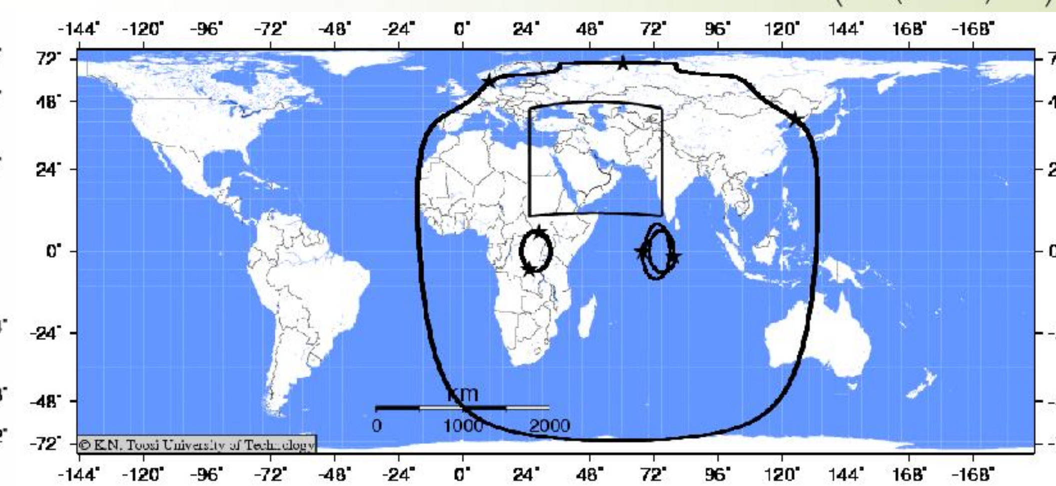


The mission objectives or fitness functions

- *Example 1: a regional positioning mission (the APSCO member states)*
  - *Satellite visibility* $\mathrm{PDOP} = \sqrt{Q_{xx} + Q_{yy} + Q_{zz}}$
  - *Dilution of Precision*
  - *Rate of success in ambiguity resolution* $\phi(x) = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}} \exp\left\{-\frac{1}{2}z^2\right\} dz$ $\quad P(\boxed{?} = z) \geq \prod_{i=1}^{n}\left(2\phi\left(\frac{1}{2\sigma_{\hat{z}_{i|I}}}\right) - 1\right)$



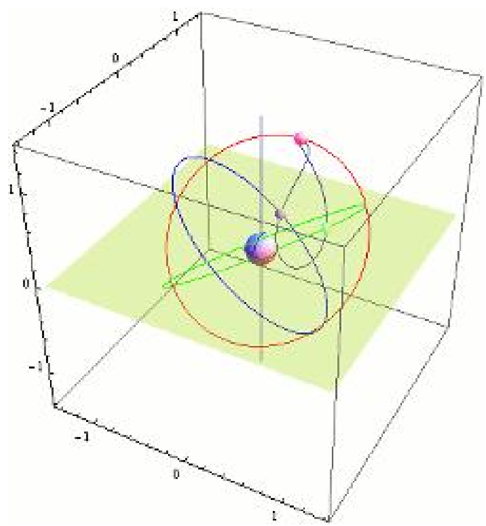
ground tracks for 6 satellites



ground tracks for 7 satellites

The mission objectives or fitness functions

- Example 2: QZSS mission (for comparison)



The mission objectives or fitness functions

- *Example 3: a regional RO-mission*
  - Point-to-point distribution norm

$$\{z_i\}_{i=1}^{N} \quad \gamma_i = \min_{j \neq i} |z_i - z_j| \qquad \bar{\gamma} = \frac{1}{N}\sum_{i=1}^{N}\gamma_i$$

$$\lambda = \frac{1}{\bar{\gamma}}\left(\frac{1}{N}\sum_{i=1}^{N}(\gamma_i - \bar{\gamma})^2\right)^{1/2}$$

  - Volumetric distribution norm

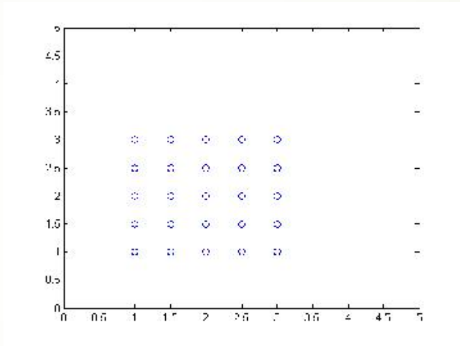
$$V_k = \{x \in X \mid d(x, P_k) \le d(x, P_j) \text{ for all } j \neq k\}$$

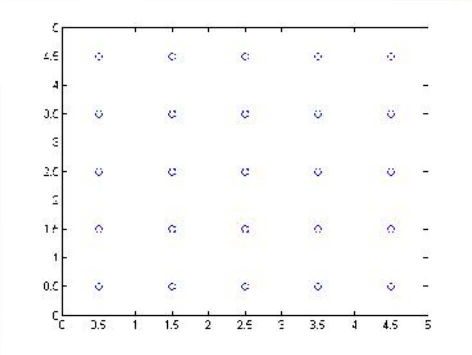
$$\nu_{ROE} = \{z_i, V_i\}_{i=1}^{N}$$

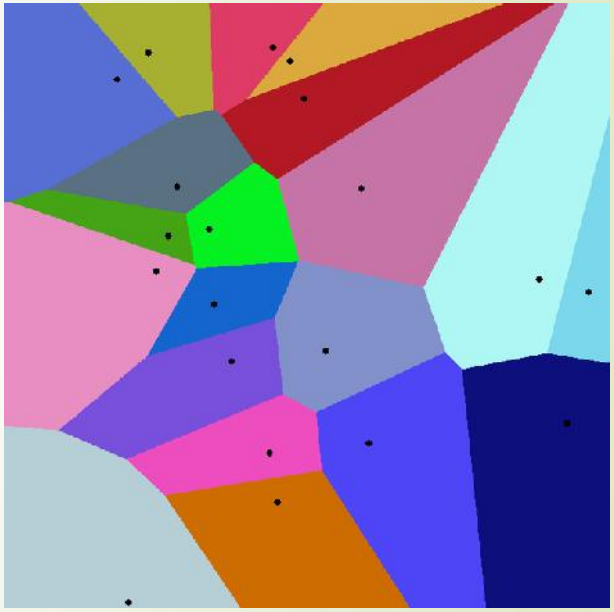
$$h_i = \max_{\substack{y \in V_i \\ i = 1,\dots,N}} |z_i - y|$$

$$h = \max(h_i)$$

3D-Latice





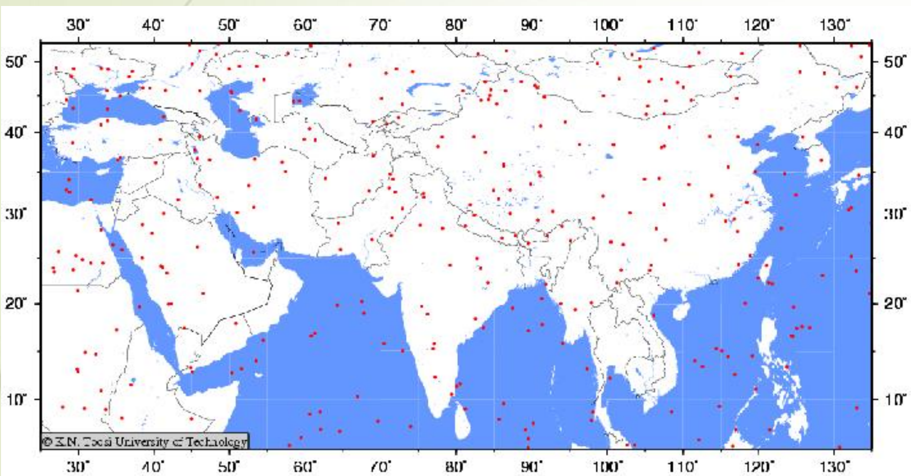


2D-Veronoi tessellation using 20 generators

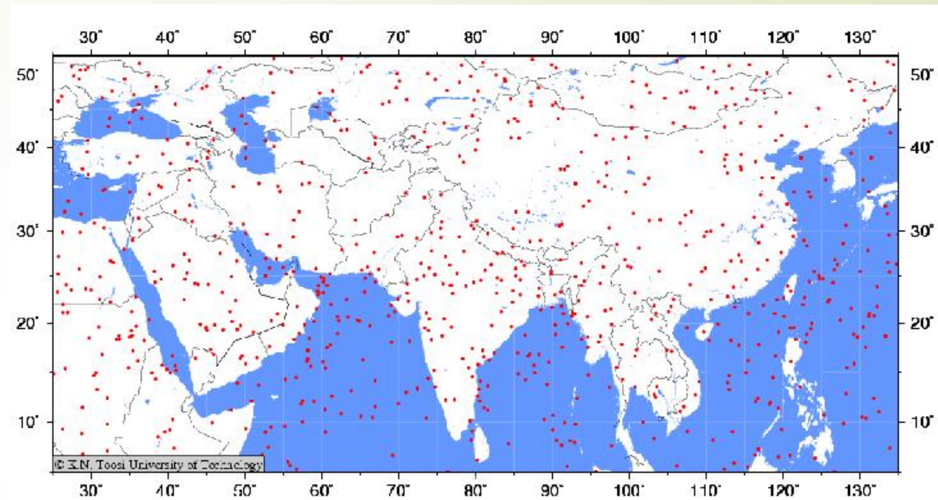
The mission objectives or fitness functions

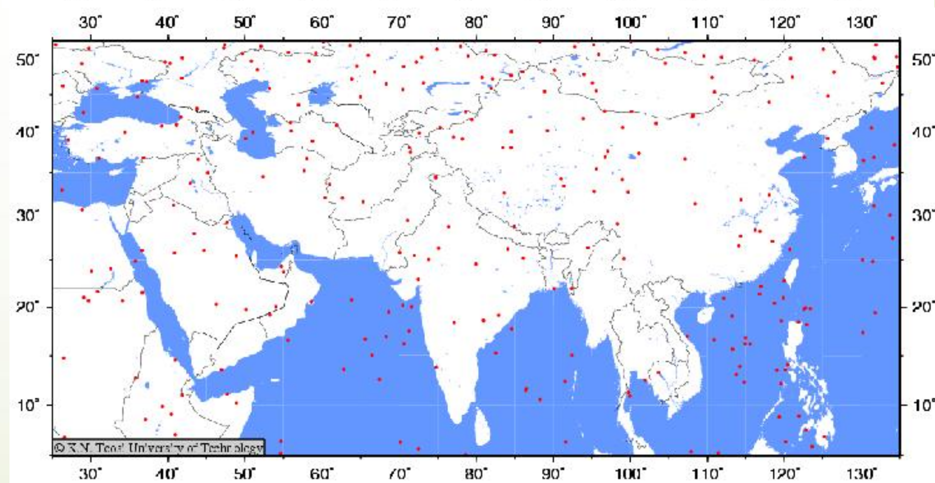
- *Example 3: a regional RO-mission*

World wide distribution of RO-profiles: FORMOSAT-3/COSMIC



World wide distribution of RO-profiles: 3D-LFC



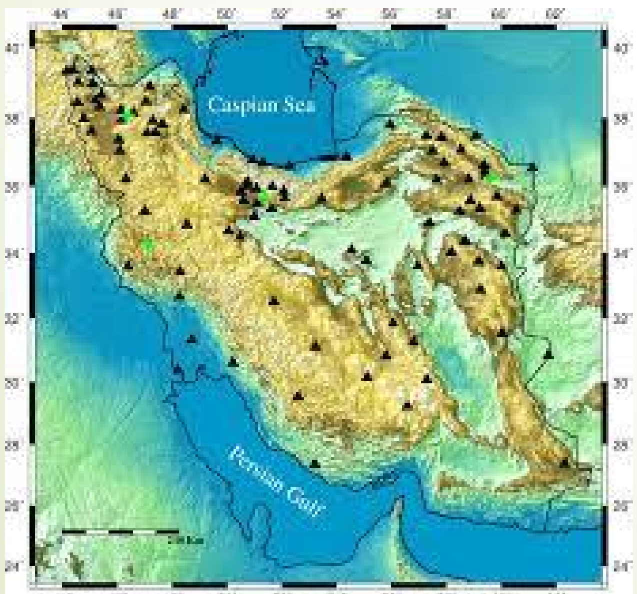


World wide distribution of RO-profile: 2D-LFC

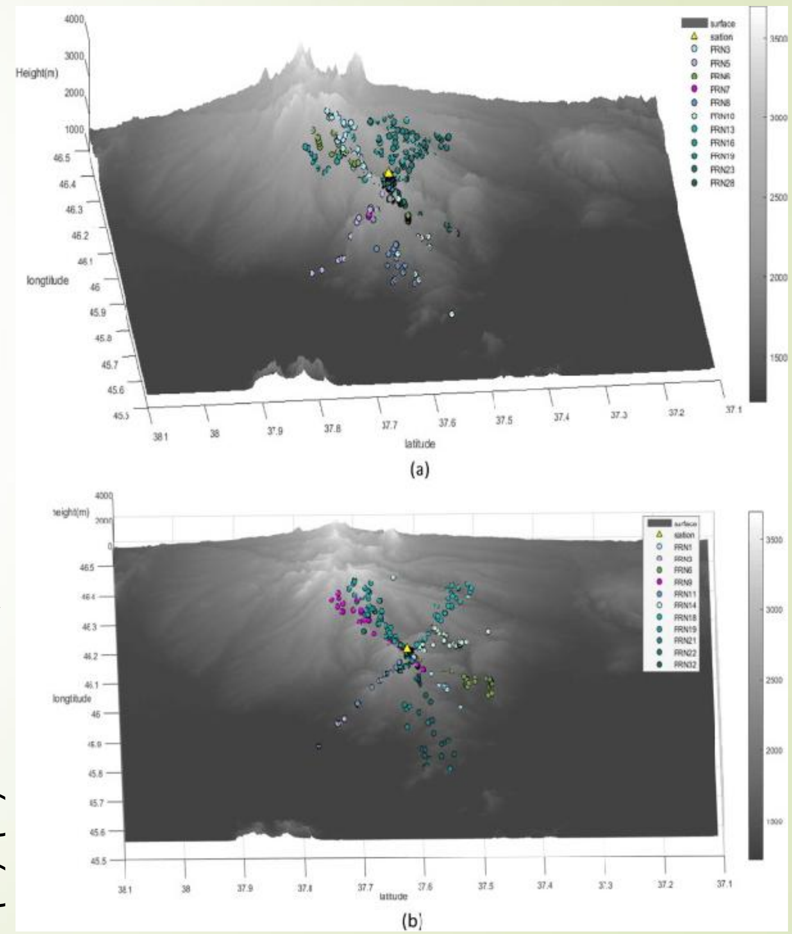
Challenges: Sensors-Ground segment

- Ground segment
  - Surface of the Earth:

  GNSS-R, Altimetry & SAR Interferometry
  - Receivers: *IPGN* (C-GPS)



Reflection points due to DEM for
(a) DOY 300, time interval 23–24 in local time &
(b) (b) DOY 301, time interval 17–18 in local time



Challenges: Modeling

- Model is the process of finding a solution of an inverse problem
  - Example 1: 3D-analysis of the Earth's surface deformations
- In Space Geodesy, inverse problems are improperly posed
  - Example 2: Troposphere monitoring

The problem is formulated in terms of the Fredholm integral equation of the first kind

  - Some does not have a unique solution
  - The model output is sensitive to the perturbation of input parameters (measurement errors)
- Constraints or additional information is inevitable

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Challenges: Modeling-Discretizing

- Measurements are not continuous

  Discretization is inevitable in practice

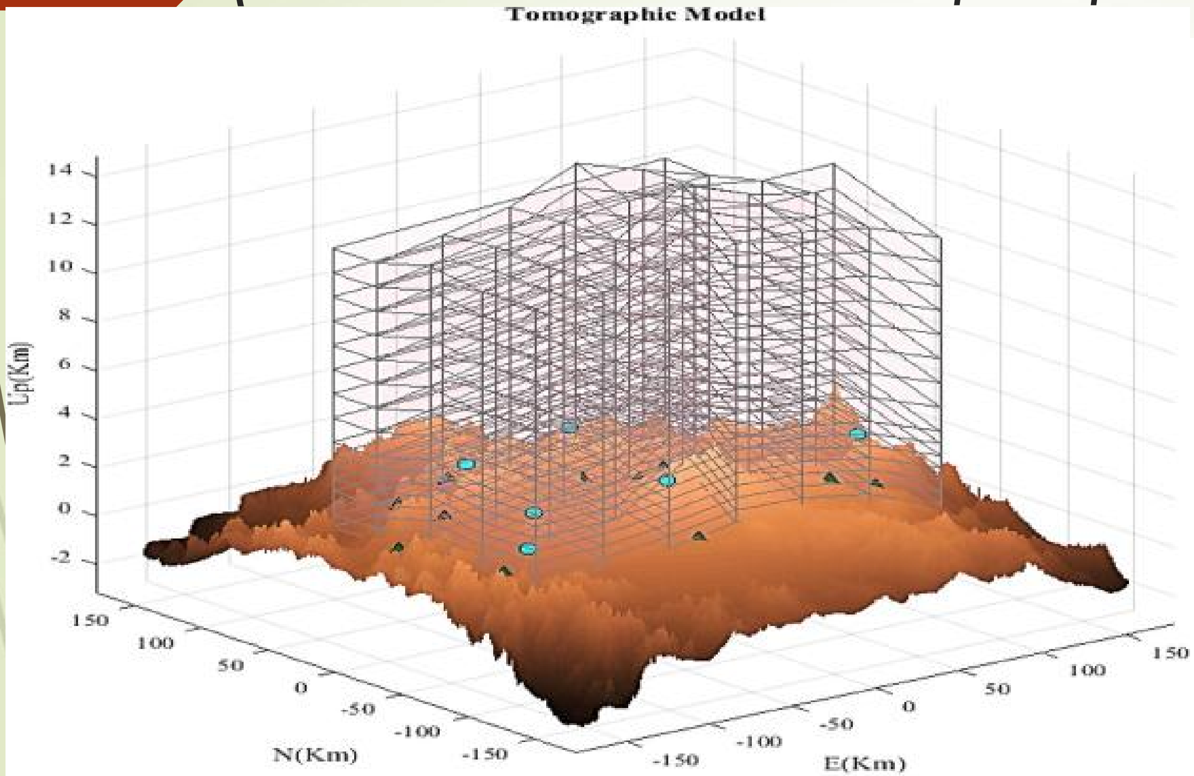
- Mesh of element

  Example 1: Deformation analysis

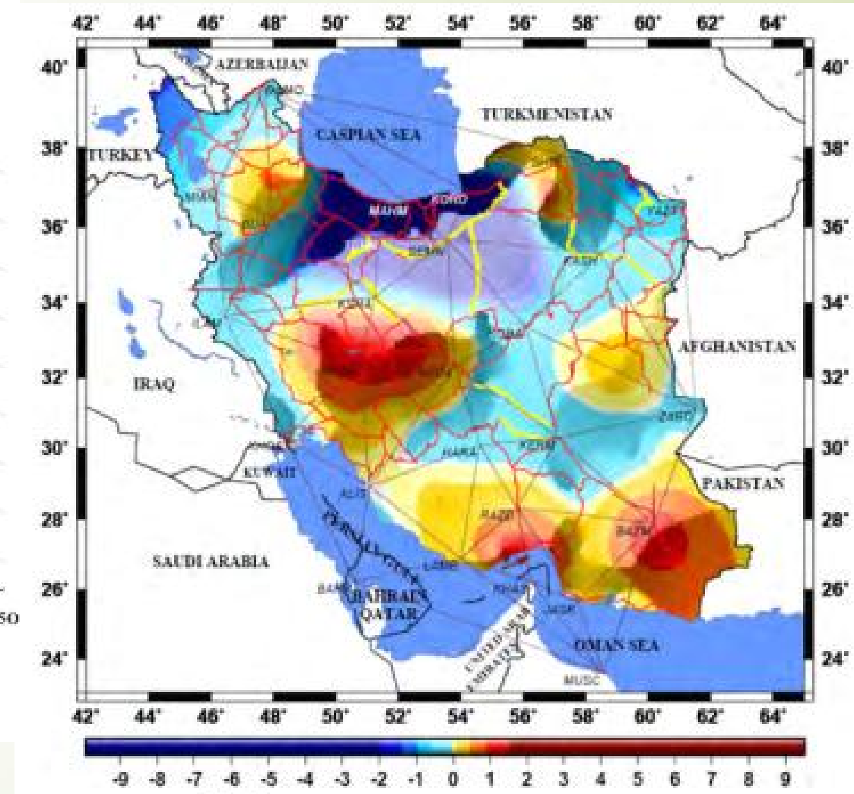
  Example 2: GNSS tomography

- Contributing parameters:
  - Geometry of the elements
  - Model resolution
  - Dynamics (physics) of the problem

Geometry of the elements (Deformation & Troposphere monitoring)

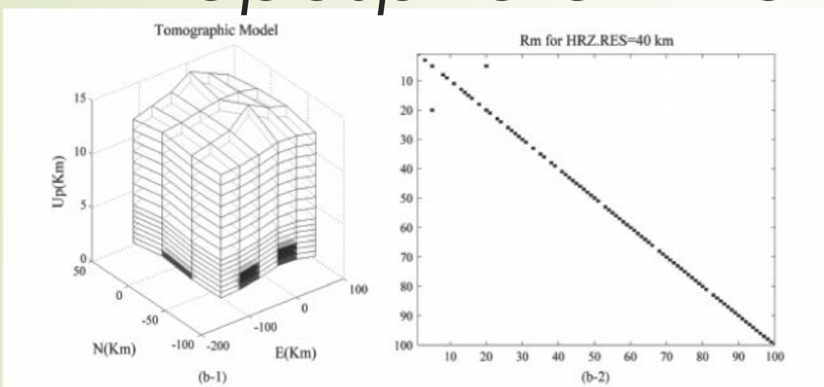


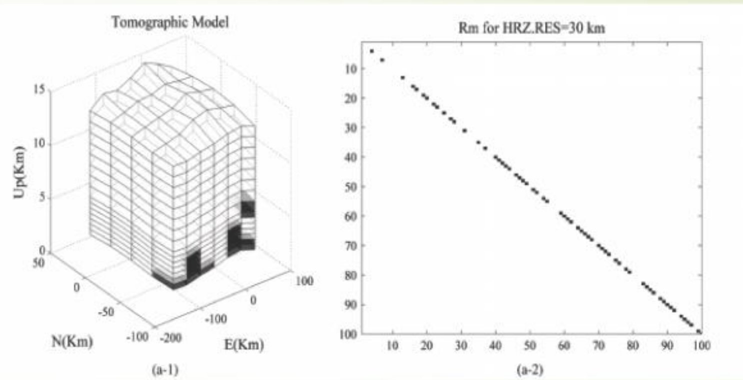
The **KNTU-1** model together with the GPS & GPS-R ground receivers as well as the topography of the study area in a local Cartesian coordinate frame

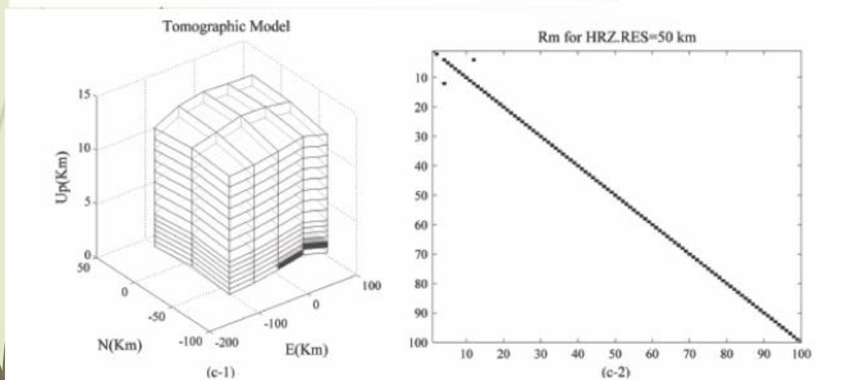


Rate of Gaussian curvature in Iran based on a mesh of triangular elements

Model space resolution Troposphere monitoring

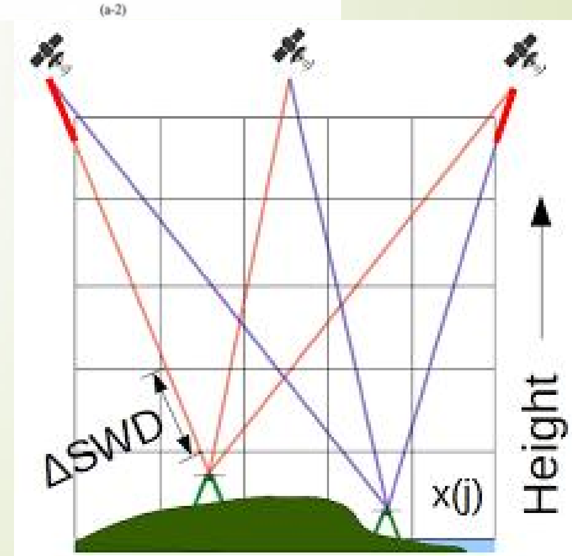






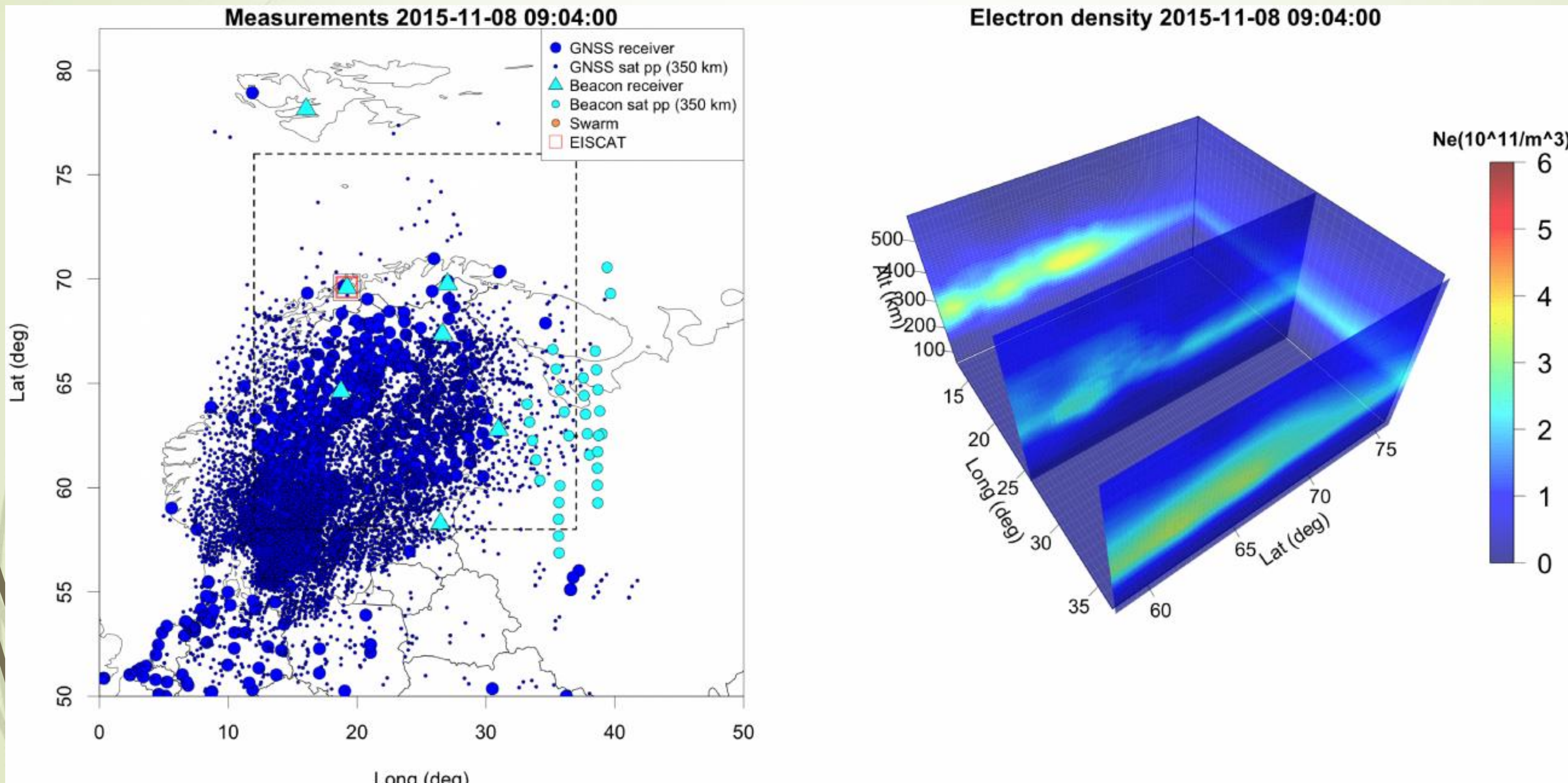
$$\mathbf{d} = \mathbf{A}\mathbf{m}$$

$$\mathbf{R}_m = \mathbf{A}_{\dagger}\mathbf{A}$$



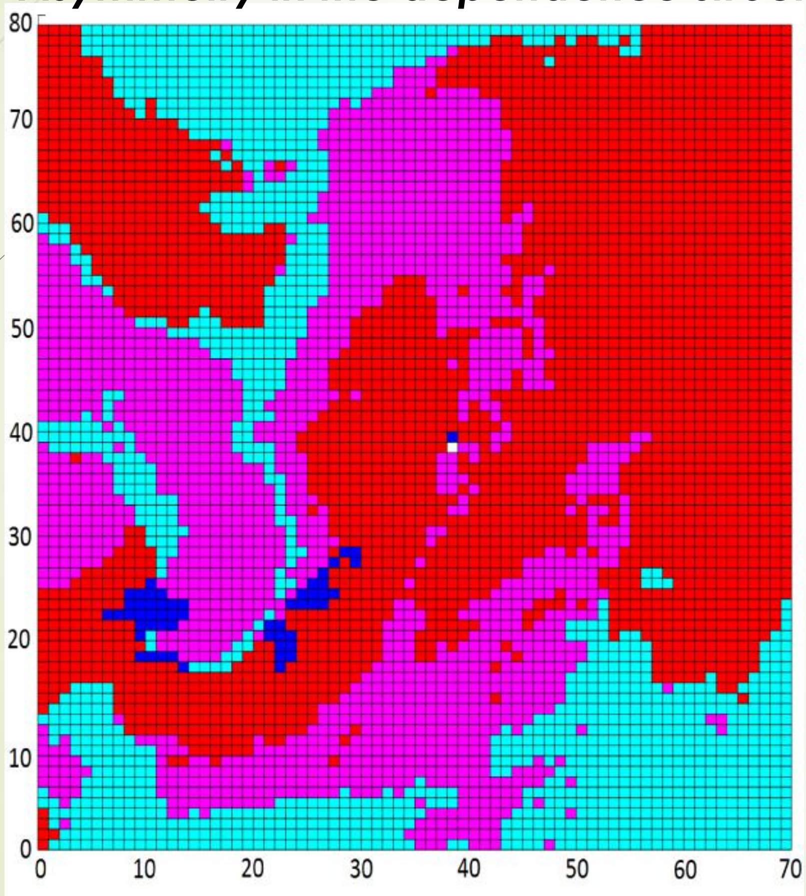
*The **KNTU-1** Tomographic model for troposphere monitoring (developed at the department of Geodesy, K. N. Toosi University of Technology)*

Dynamics of the problem
Ionosphere monitoring

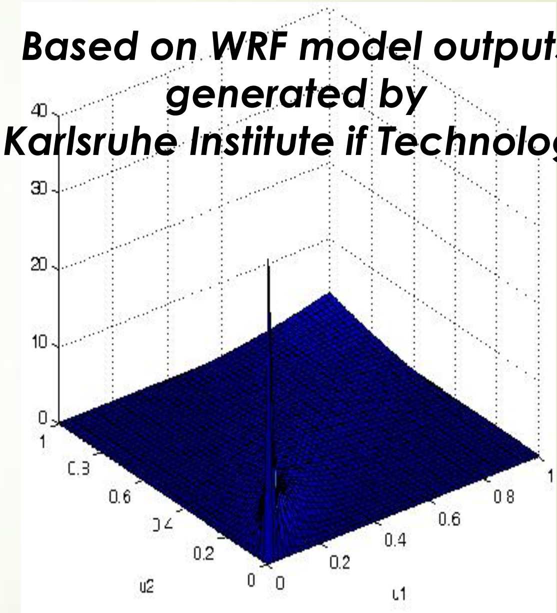


Dynamics of the problem
Wet refractivity monitoring

Asymmetry in the dependence structure of wet refractivity in Central Europe



Based on WRF model outputs generated by Karlsruhe Institute if Technology

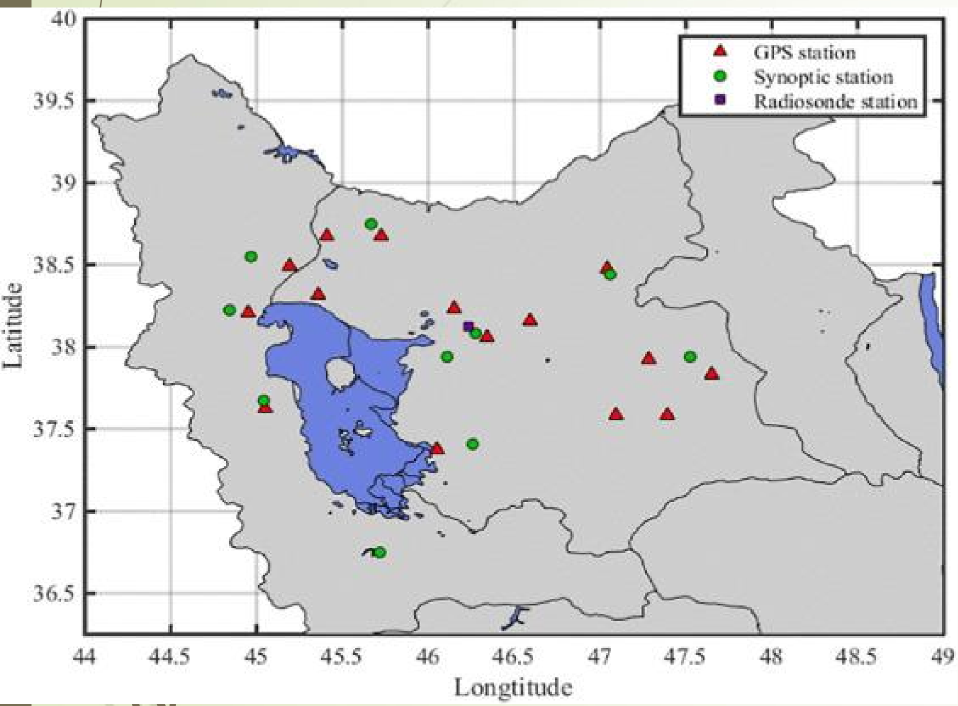


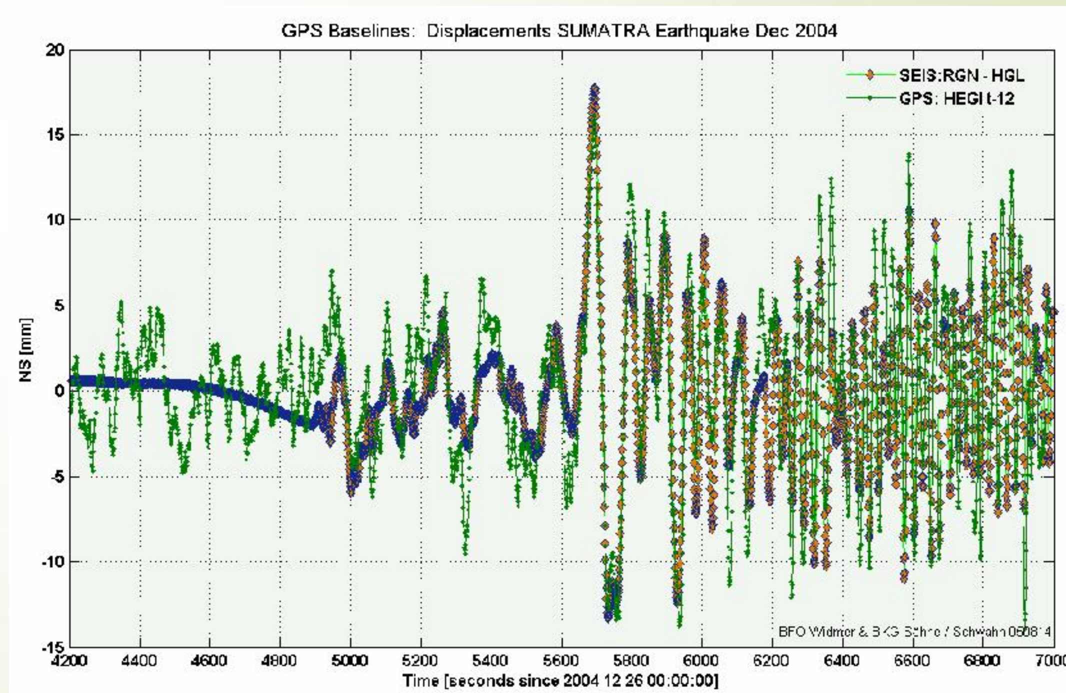
- ❑ **Gaussian Copula is not suffcient.**
- ❑ **Pearson's correlation is not sufficient to describe the full**

Challenges: Modeling- Validation

- Modeling data is different from validation data
  - Example 1: GNSS Seismology
    - Seismic records versus the GNSS position time series
  - Example 2: Troposphere Tomography
    - Radiosonde profiles versus SWDs
- Spatial distribution of validation data is usually poor as compared to the modeling data
  - It is not possible to simply extend the validation results to the whole test area!
  - Example: Troposphere Tomography

Validation: Radiosonde & synoptic versus GPS stations in Iran



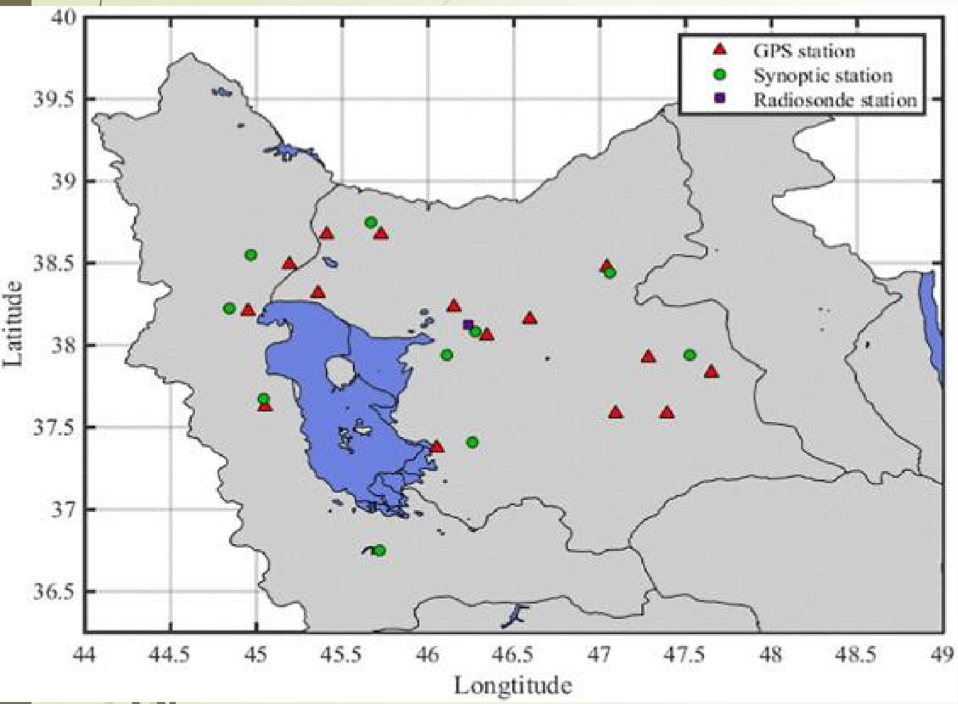


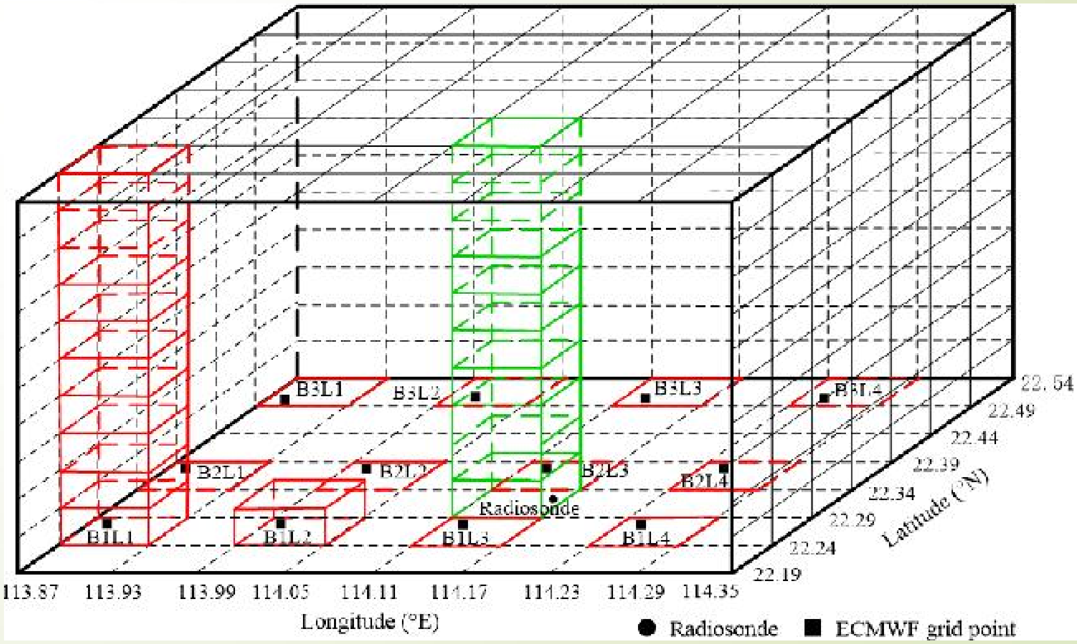
Challenges: Modeling- Validation

- Challenge: Is the accuracy and precision of proposed model similar or at least comparable everywhere within the model (test) area?
- Sensitivity of model to perturbations of input parameters
  - Time response of the model
  - Size or the model elements

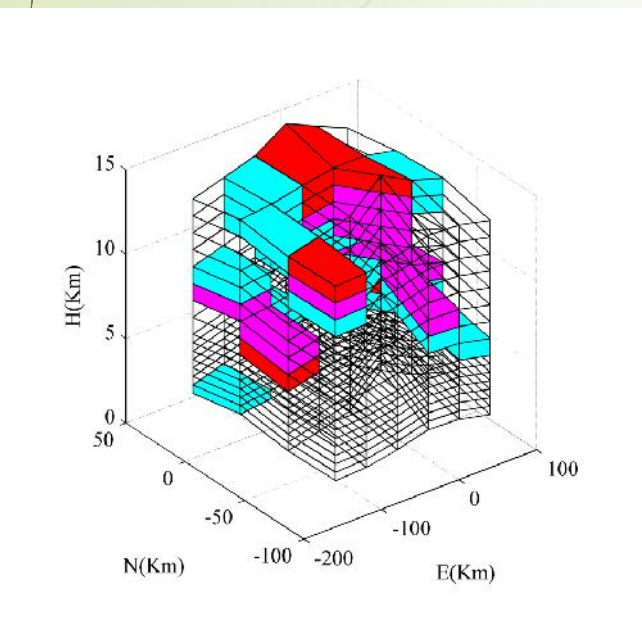
  How the continuous inverse problem is discretized both in space and time
  - Dynamics of the model parameter
  - How the model is constrained in order to compute a unique solution
  - ?!

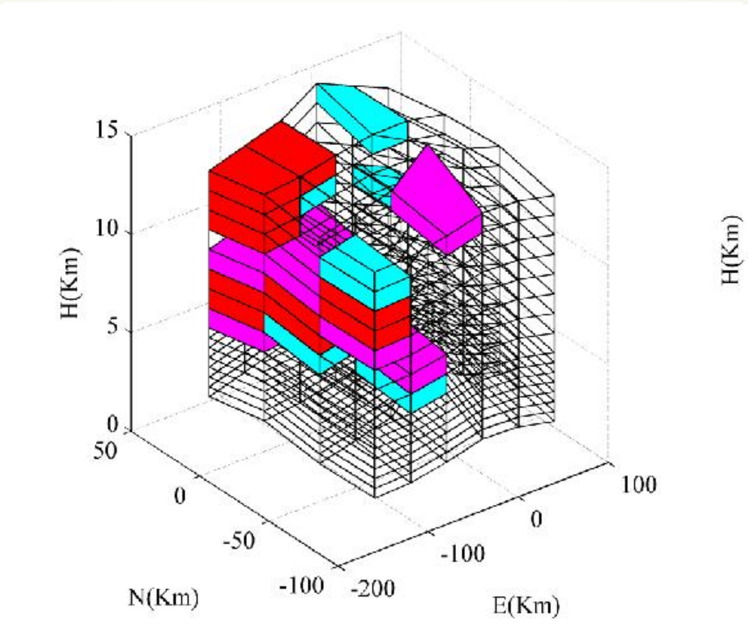
Validation: Radiosonde & synoptic versus GPS stations in Iran

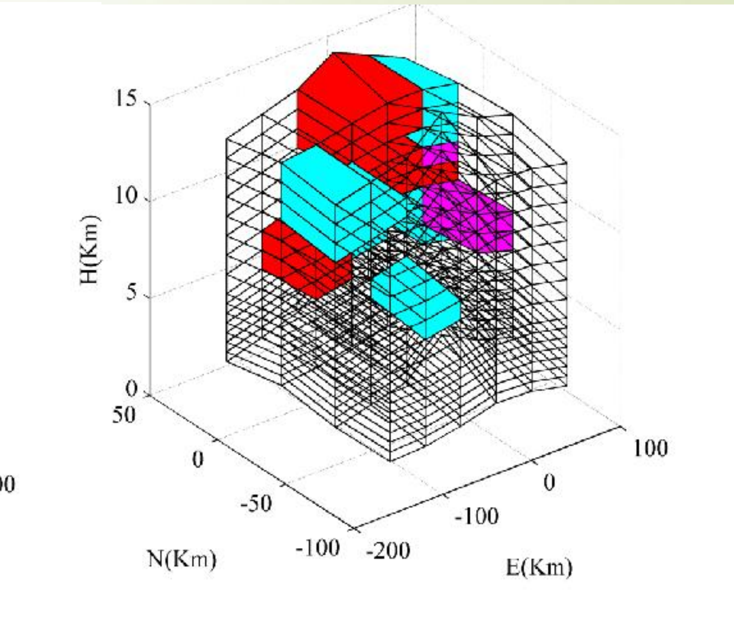




Sensitivity of model
Troposphere monitoring







VRS-constraints, Epoch 6, DOY: 202

NWP-constraints, Epoch 6, DOY: 202

Gaussian-constraints, Epoch 6, DOY: 205

Thank you