Case Study of Japan: Current situation and challenges in Vertical Reference Frame of Japan

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Introduction

- Geospatial Information Authority of Japan (GSI) has been maintaining Japanese geodetic reference frame from the beginning of Meiji era, 120 years ago.
- The 3D reference frame was realized from triangular surveys on triangular control points and the vertical frame has been realized from leveling surveys on benchmarks.

- Total number of the points reached 100,000 and the total benchmarks reached 17,000 by the end of 20th century.

- Considering performance of GNSS and needs for more accurate and efficient surveying, GSI decided to switch main geodetic control points from triangular control points to Continuously Operating Reference Station (CORS).
- However, GSI still maintains benchmarks because of continued demands from land surveyors.

Introduction

- Vertical datum of Japan has no reference epoch. However, heights of the benchmarks are gradually changing because of crustal deformation mainly by plate motions. The datum is realized from leveling data of over 10 years and the deformation reaches 10cm over the decade especially along the Pacific coast. This means the datum contains internal inconsistency up to 10cm. Therefore, the accumulated crustal deformation have to be considered.
- Coseismic displacements also have to be considered to the vertical datum.
- GSI also developed a hybrid geoid model of Japan, "GSIGEO2011", which enables orthometirc height determination by GNSS surveying. The model has been available for land surveys since April 1 2014.

Outline

1. *Introduction*
2. *Current vertical datum of Japan*
3. *Challenges in Maintenance of vertical datum*

- Crustal deformation

Accumulated deformation by plate motions

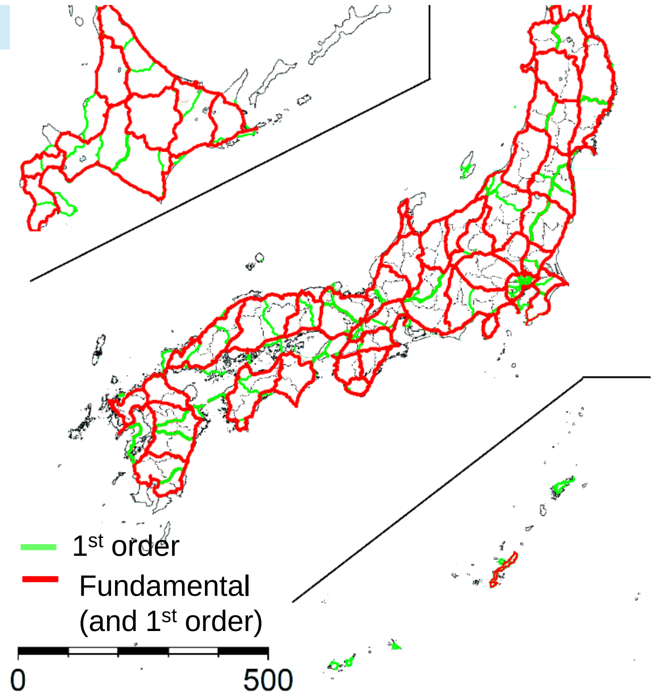
Coseismic deformation

- Hybrid geoid model of Japan

Vertical Datum of Japan

- Vertical datum of Japan has been realized from leveling surveys and gravity measurements on benchmarks. Height of Japan is orthometric height.
- The first-order leveling routes cover all over Japan and the total length is 24,000km.
- Fundamental routes are basic frame and surveyed every 10 years. The length is 14,000km.
- The datum contains internal inconsistency because the leveling data contain cumulative crustal deformation over 10 years.

1st order and fundamental leveling network



Category	Number	Sub-category		Ave. Int.
Bench marks 	17,050	Fundamental bench marks	84	150km
		First order bench marks	13,825	2 km
		Second order bench marks	3,141	2 km
Total	126,816	(As of April 1 2015)		

Vertical Datum of Japan

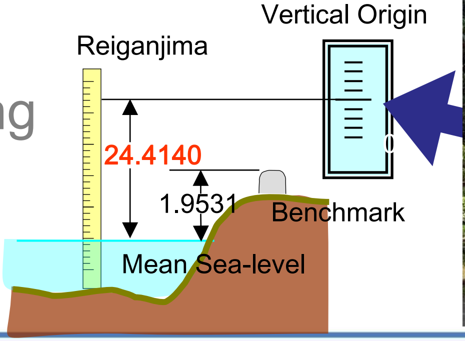
- Vertical “0” in Japan is defined from mean sea-level in Tokyo Bay. The mean was calculated from tidal observation of 6 years from 1873 to 1879.
- The mean sea-level is monitored through continuous tidal observation at Aburatsubo tidal station. Leveling survey once a year is conducted between the station and vertical origin in Tokyo.
- First order leveling survey was conducted 4,000km a year. It took 10 years to cover the fundamental leveling routes.
- Current vertical datum was realized in 2000 by network adjustment of leveling data from 1986 to 1999 with only one station, the vertical origin, fixed.

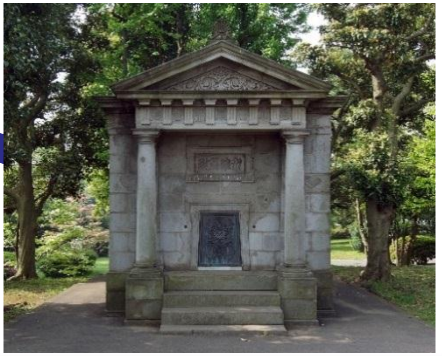
Vertical origin

Tidal Station at Aburatsubo

Mean Sea-Level in Tokyo Bay

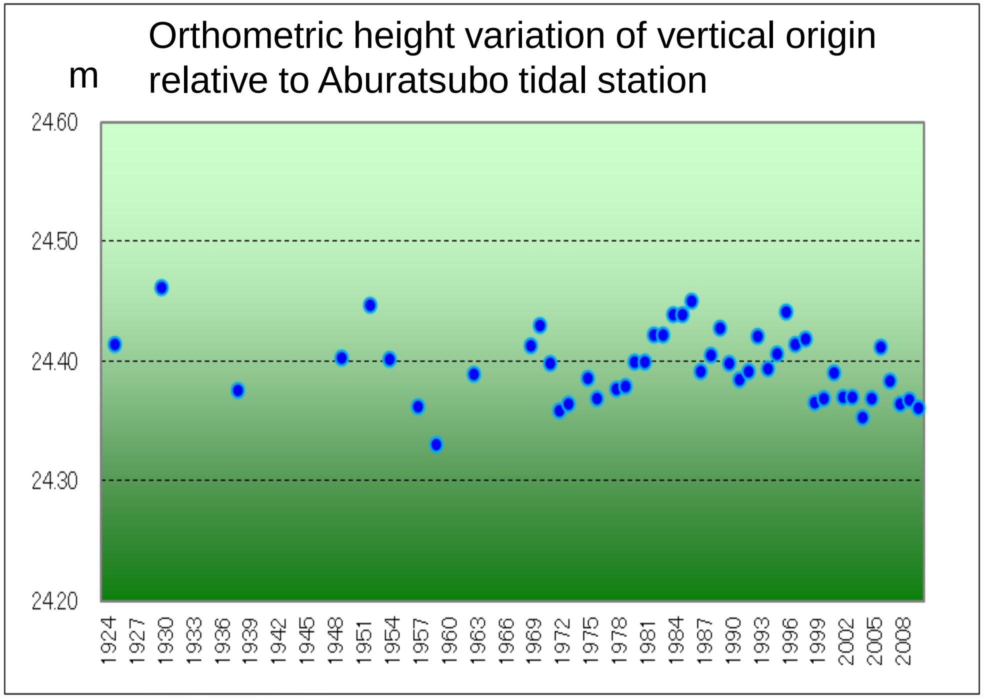
- Vertical "0" in Japan was calculated from tidal observation of 6 years from 1873 to 1879 at Reiganjima in Tokyo Bay.
- The mean was evaluated by comparing with continuous tidal observation data from 1900 to 1923 at Aburatsubo tidal station. The values are consistent within 3mm.
- The height of the origin was revised -8.6cm in 1928 after the Great Kanto earthquake occurred in 1923.
- The height is monitored through leveling once a year.

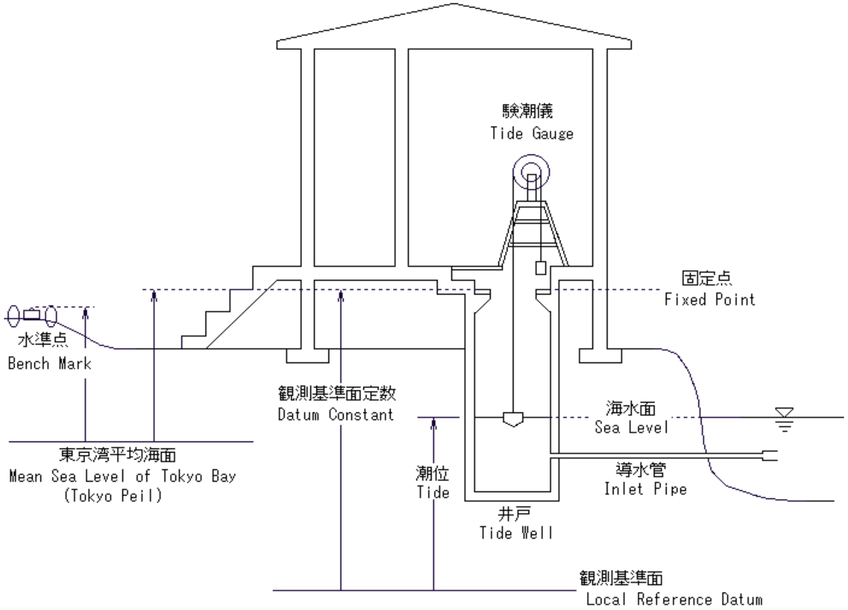




Monitoring mean sea-level

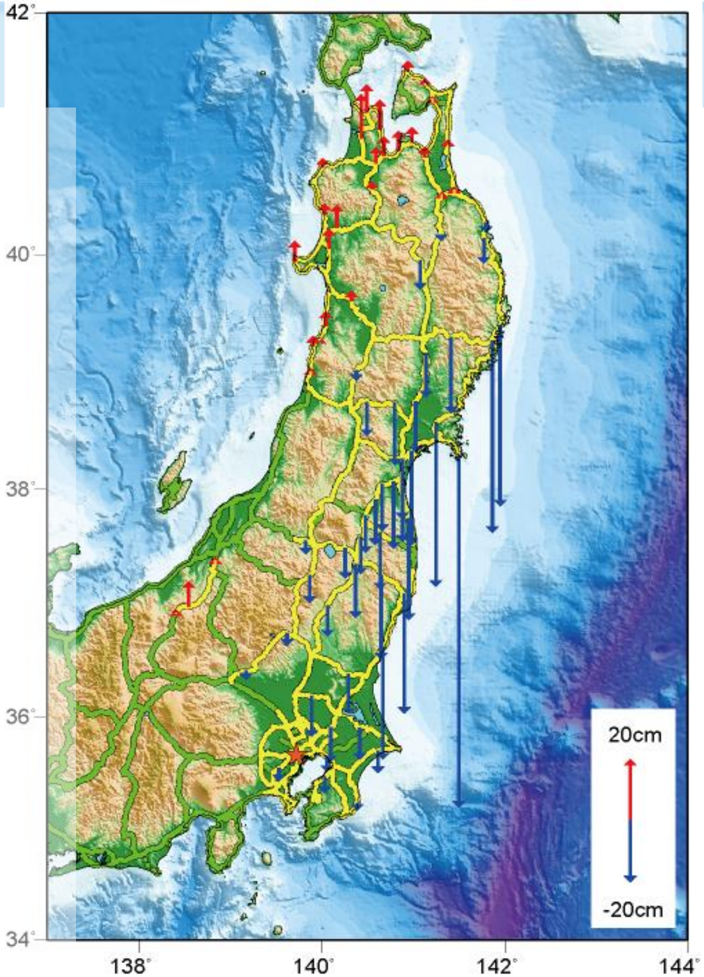
- Orthometric height of vertical origin measured by leveling survey is not changing relative to Aburatsubo tidal station from 1924.





Geodetic Coordinates 2011

- After the 2011 Off the Pacific coast of Tohoku Earthquake (March 11, 2011), GSI re-surveyed orthometric heights of almost all leveling routes in Tohoku region. About 55% of benchmarks at GEONET stations also re-surveyed.
- As a result of the leveling survey, vertical displacements up to 1.1m were detected. Orthometric heights were calculated from network adjustment. The result was opened two months after the earthquake.
- Height of the vertical origin was also revised from the result of leveling survey between the origin and Aburatsubo tidal station. The amount is -2.4cm.



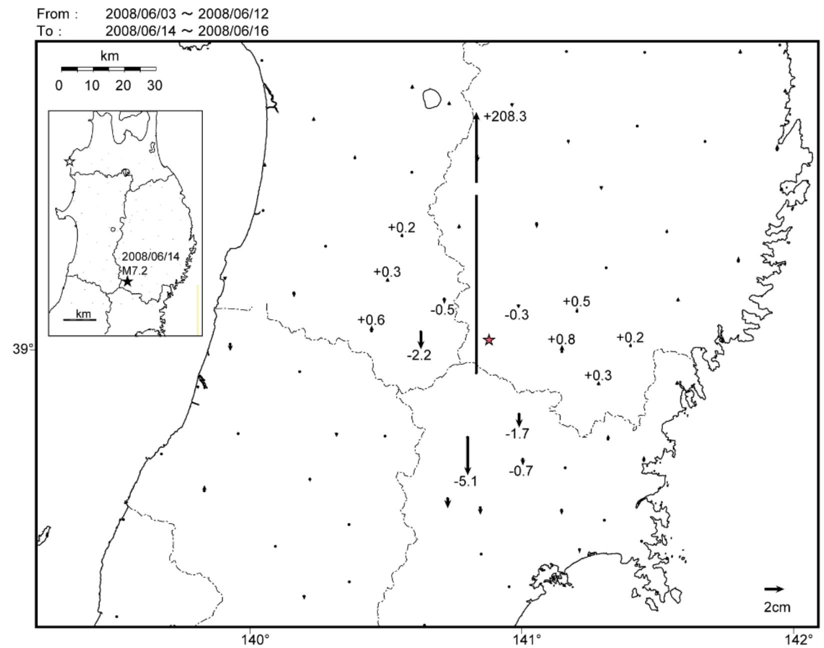
First order leveling routes and amounts of revision
Yellow lines indicate re-surveyed leveling routes

Challenges

- Japan is located on an area where four active plates are colliding. This makes the country continuously deforming and prone to earthquakes and volcanic activities.
- The amount of crustal deformation is accumulated over time. Therefore, the deformation, both cumulative and coseismic, have to be considered in realizing vertical datum of Japan.
- Accumulated crustal deformation by plate motions can be modelled by utilizing dense CORS network. GEONET of Japan has 20km average spacing between the stations. This means vertical displacement field longer than 20km can be modelled from GEONET data.
- Coseismic crustal deformation commonly has shorter wavelength. Therefore, it is difficult to express the detailed deformation by CORS network. Areas affected by coseismic deformation have to be re-surveyed after the earthquakes.

Coseismic Crustal Deformation

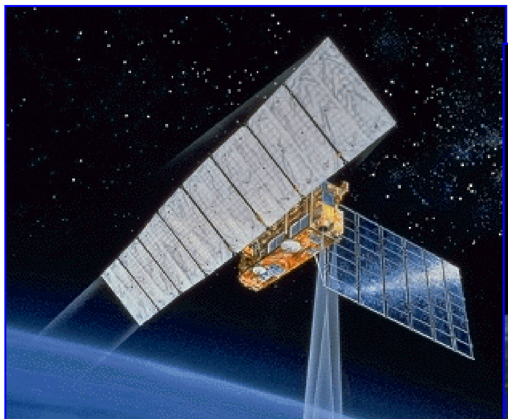
- Coseismic crustal deformation usually has relatively large displacement gradient and its spatial pattern is complicated.
- GEONET is useful to detect coseismic deformation. However, its spatial density is not enough to detect detailed distribution of the displacements. Displacements between GEONET stations need to be measured by leveling.
- InSAR is very useful to identify an area of coseismic crustal deformation. If the area can be identified by InSAR, planning of efficient re-surveying becomes possible.



Coseismic vertical displacements at GEONET stations caused by the Iwate-Miyagi Nairiku Earthquake in 2008.

Deformation Monitoring by InSAR

- Japan has been operating L-band SAR satellites. Current operational satellite is ALOS-2 (Advanced Land Observation Satellite).
- GSI has been utilizing InSAR for monitoring crustal deformation.



Research & development
JERS-1
Feb. 1992 ~ Oct. 1998

Deformation monitoring
ALOS
Jan. 2006 ~ May 2011

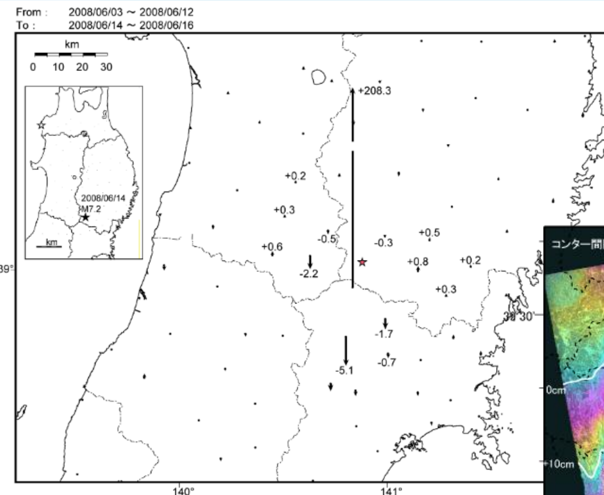
Enhance deformation monitoring
ALOS-2 May 2014 ~

Image：JAXA

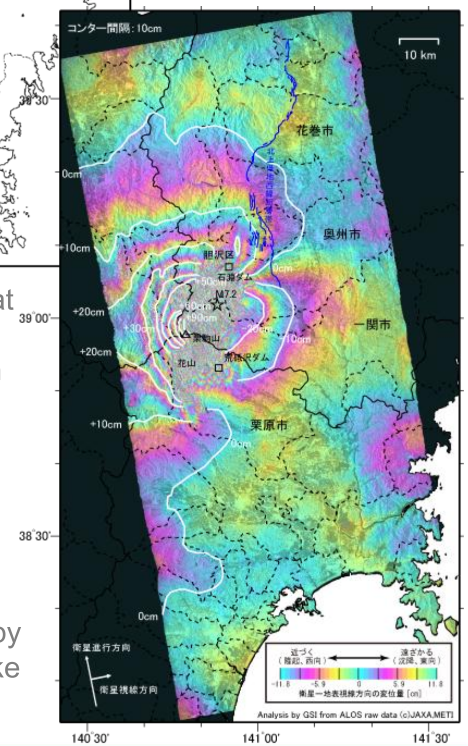
ALOS: Advanced Land Observation Satellite

Identify Area of Coseismic Deformation by InSAR (ALOS)

- InSAR is useful to identify area of coseismic deformation.
- For example, large crustal deformation occurred by the Iwate-Miyagi Nairiku Earthquake in 2008, GEONET detected large vertical displacement over 2m. InSAR image of ALOS satellite was also critical to detect spatial distribution of the displacements.
- The InSAR images were utilized for identifying area of displacement. Plan for re-surveying was established based on the information of InSAR.

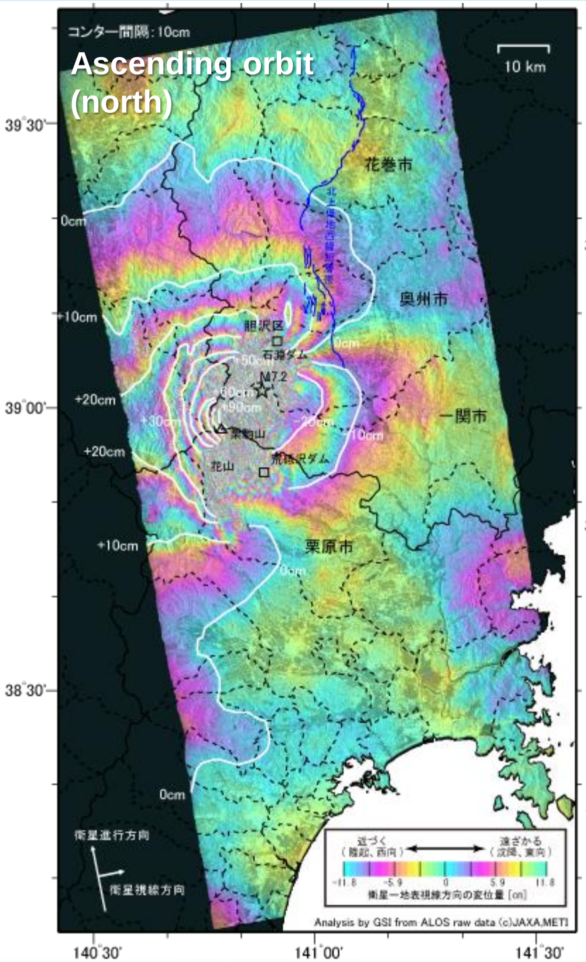


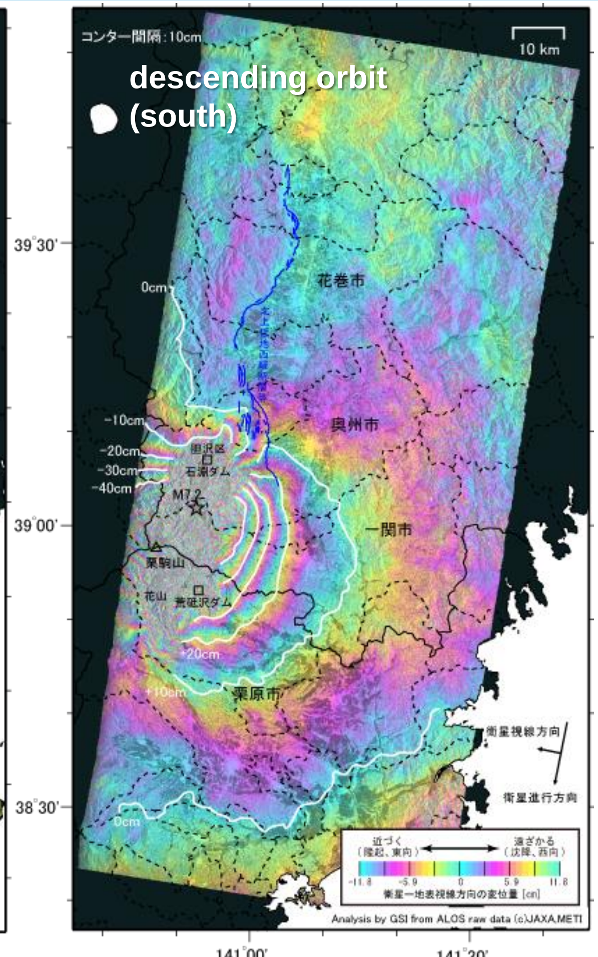
Coseismic vertical displacements at GEONET stations caused by the Iwate-Miyagi Nairiku Earthquake in 2008.

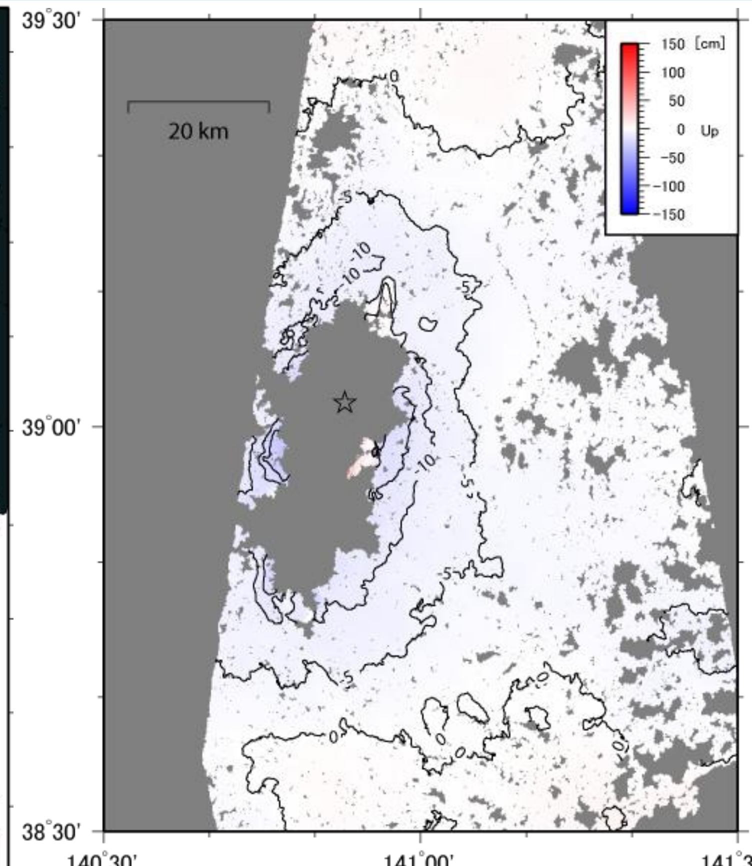


Coseismic displacements detected by InSAR image of ALOS caused by the Iwate-Miyagi Nairiku Earthquake in 2008.

Identify Area of Coseismic Deformation by InSAR (ALOS)



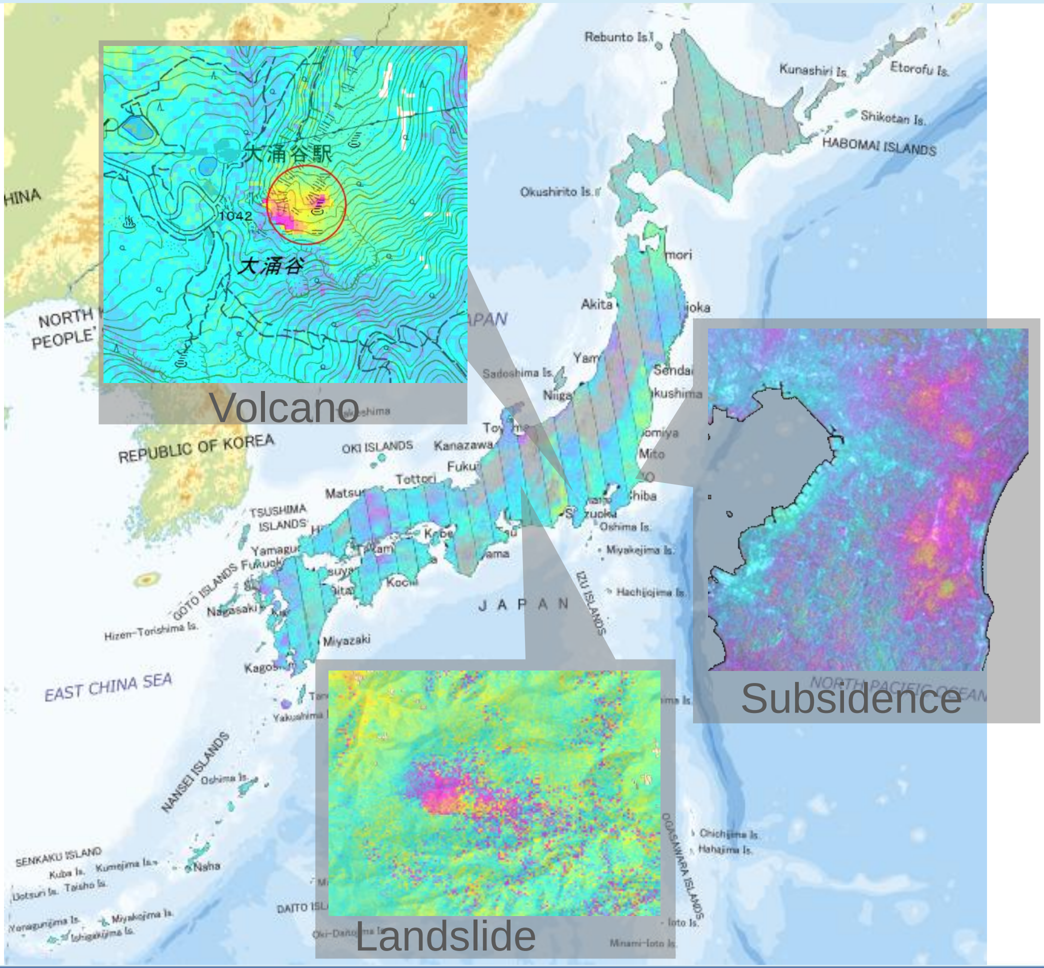




Quasi-vertical displacement derived from two InSAR images

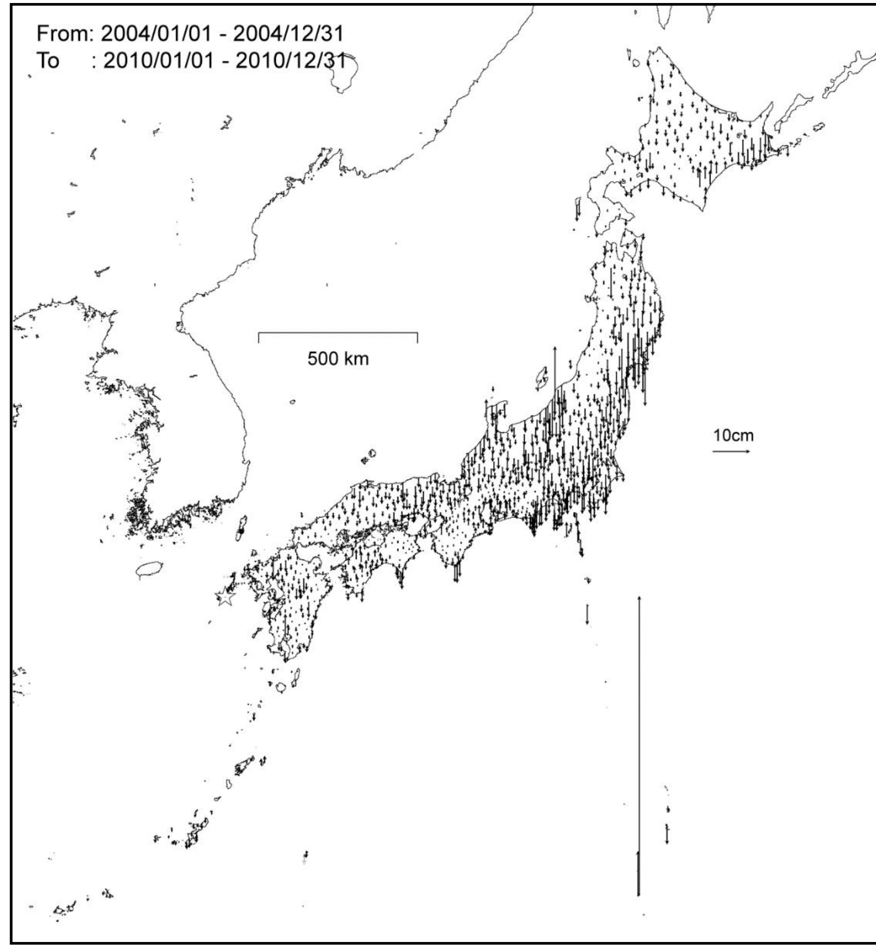
Identify Area of Local Deformation by InSAR (ALOS-2)

- GSI is monitoring Japan with InSAR of ALOS-2.
- The monitoring is useful to detecting local deformation such as volcanos, local subsidence, landslide and etc.
- GSI provides the information to related organizations such as municipalities. The municipalities utilize the information to make plans for most efficient and effective leveling.



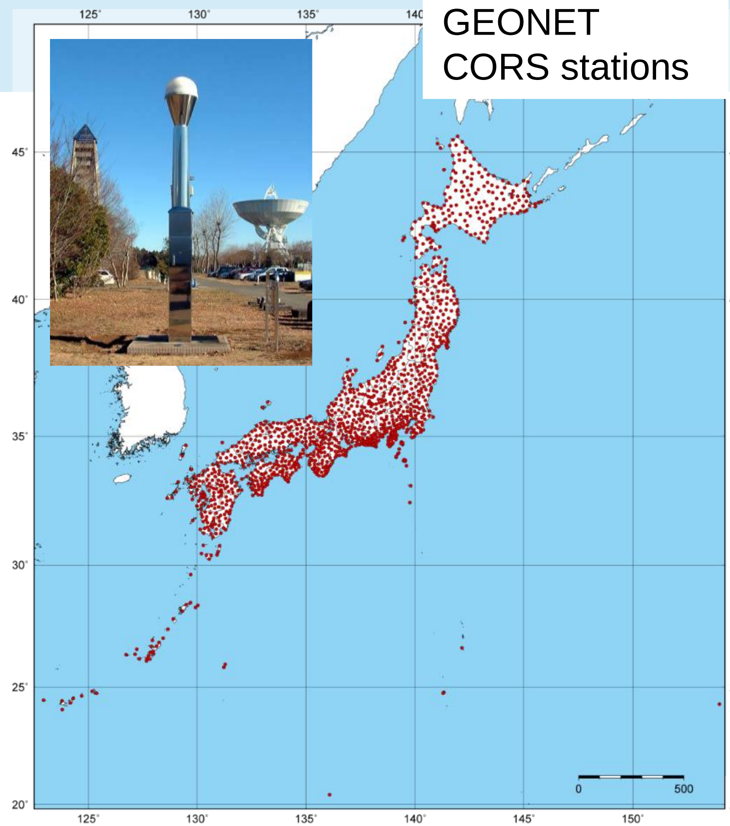
Accumulated Crustal Deformation

- Japan is located on an area where four active plates are colliding . This makes the country continuously deforming.
- The accumulated crustal deformation is up to 10cm over a decade. This makes vertical datum of Japan contain internal inconsistency up to 10cm.
- CORS network of Japan, GEONET, has 20km average spacing and useful to estimate vertical displacement field of Japan.
- The estimated field can be utilized for converting leveling data into certain epoch.



GEONET

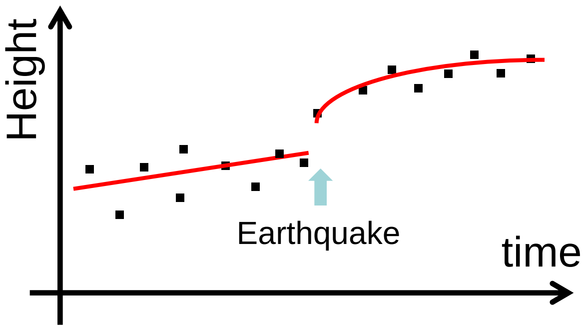
- GSI started GNSS continuous observation from the middle of 1990's.
- The system, GNSS Earth Observation Network System (GEONET), has been gradually enhanced and covers Japan with over 1,300 stations with 20 km spacing.
- Daily solutions are utilized for monitoring crustal deformation.
- Observation data and station coordinates are also utilized for various location based services.



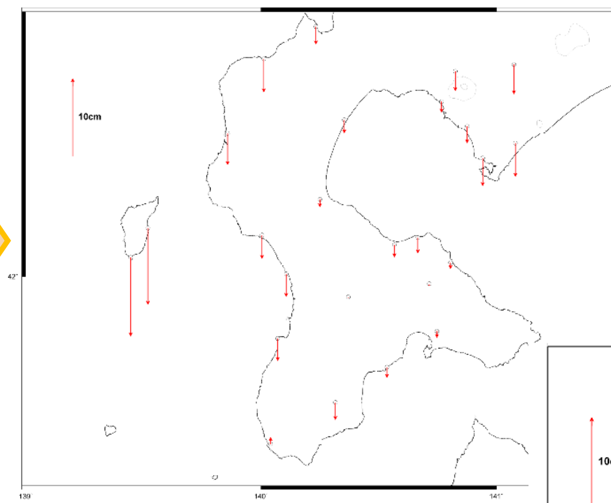
Category	Number	Sub-category	Ave. Int.
GEONET CORS (GNSS-based control stations)	1,318	(As of April 1 2015)	20 km

Vertical Displacement Field Estimated from GEONET

Vertical coordinate time series of GEONET stations

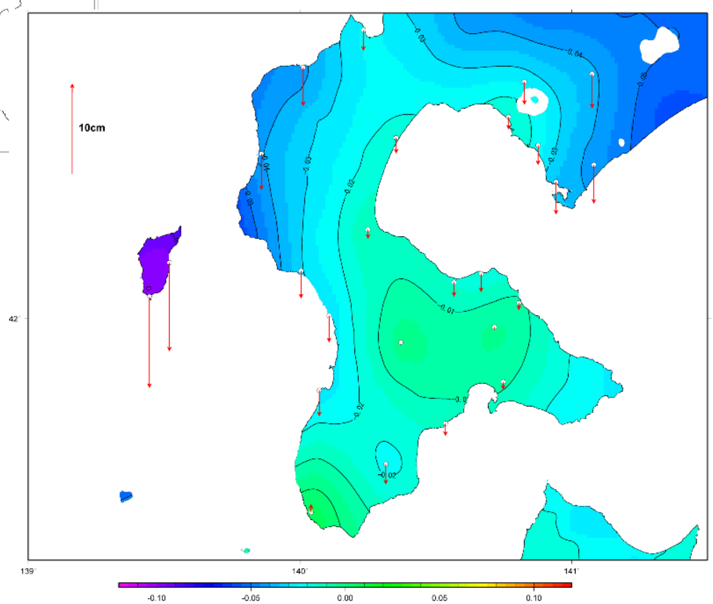


1. Modelling velocity at GEONET station by fitting coordinates to linear trend , coseismic displacement and postseismic movement (logarithmic function)



○ Distribution map of Vertical displacement at GEONET stations

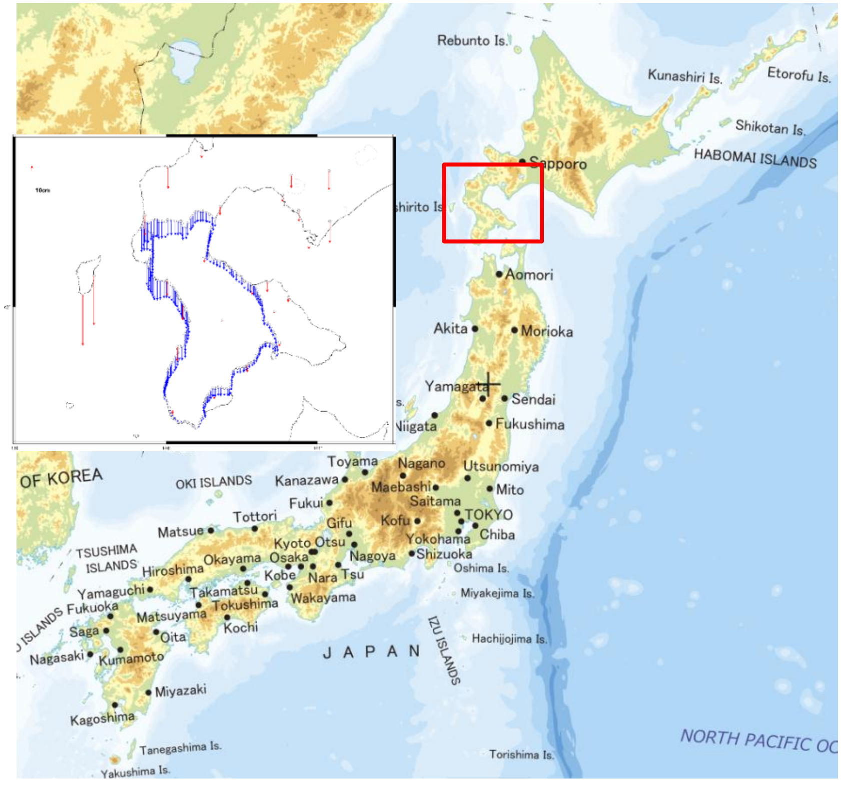
2. Interpolation by kriging method



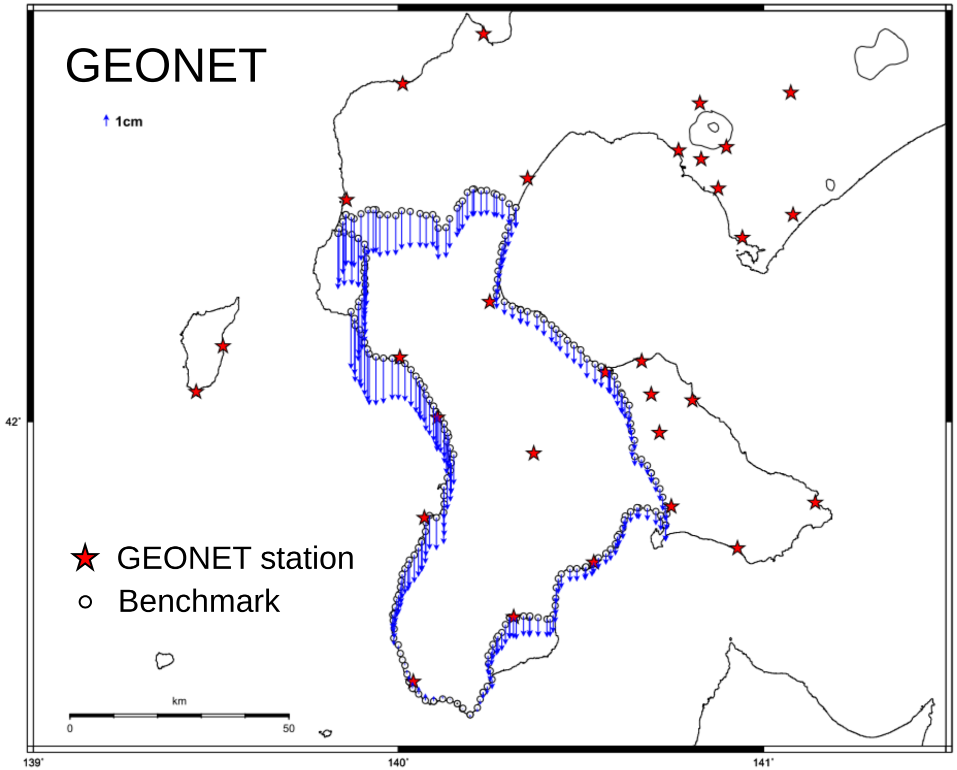
○ Vertical displacement model estimated from GEONET

Evaluation by Leveling Data

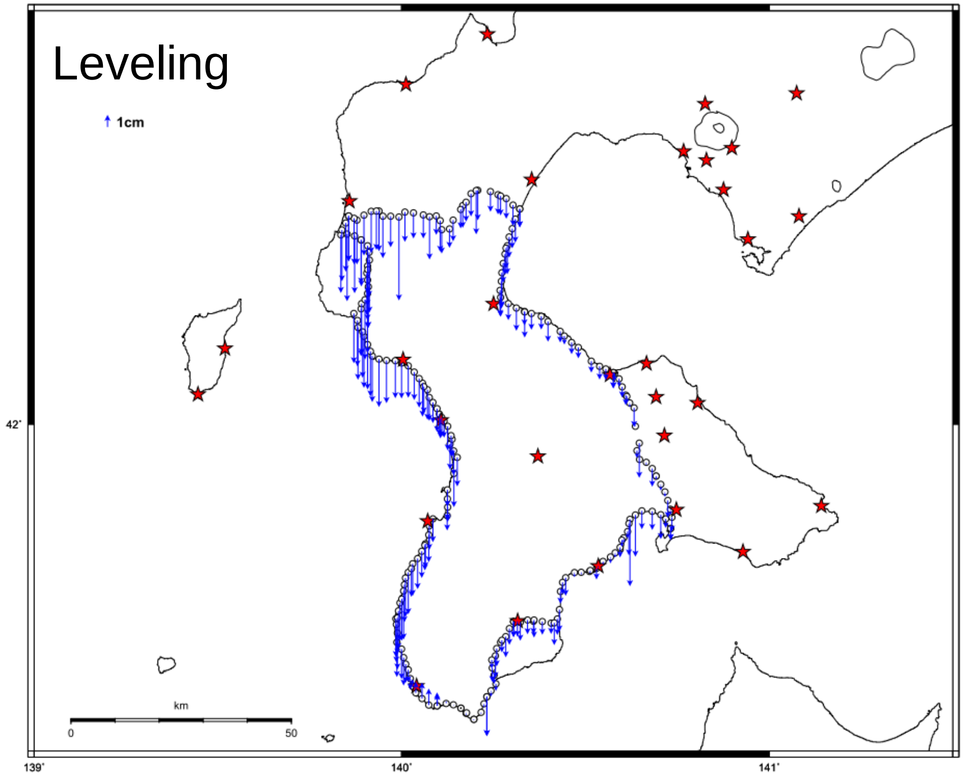
- Accuracy of vertical displacement model is estimated by comparing the model with leveling surveys.
- The model estimated from GEONET can provide displacements anywhere in Japan including on benchmarks along first order leveling routes.
- First order leveling survey was conducted at Oshima peninsula in Hokkaido both on 2003-2004 and 2014.
- The displacements estimated from the model and measured by leveling can be compared along the leveling route at Oshima peninsula.



Evaluation by Leveling Data



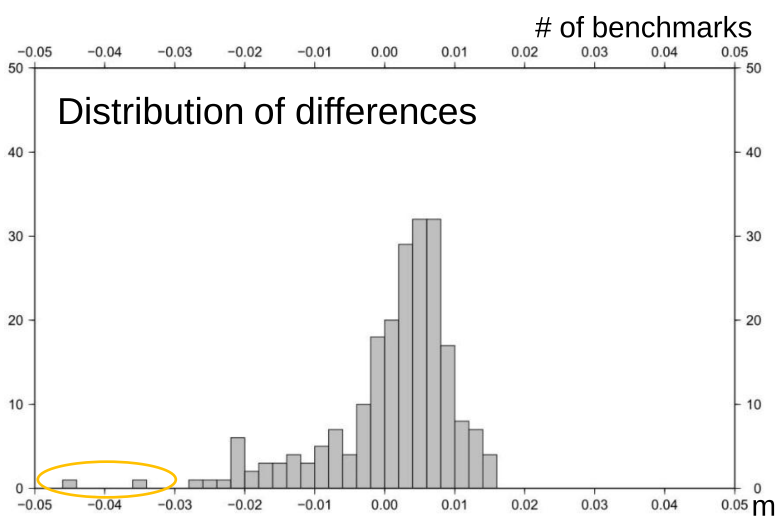
Vertical displacements on benchmarks from 2003-2004 to 2014 estimated from GEONET coordinate time series

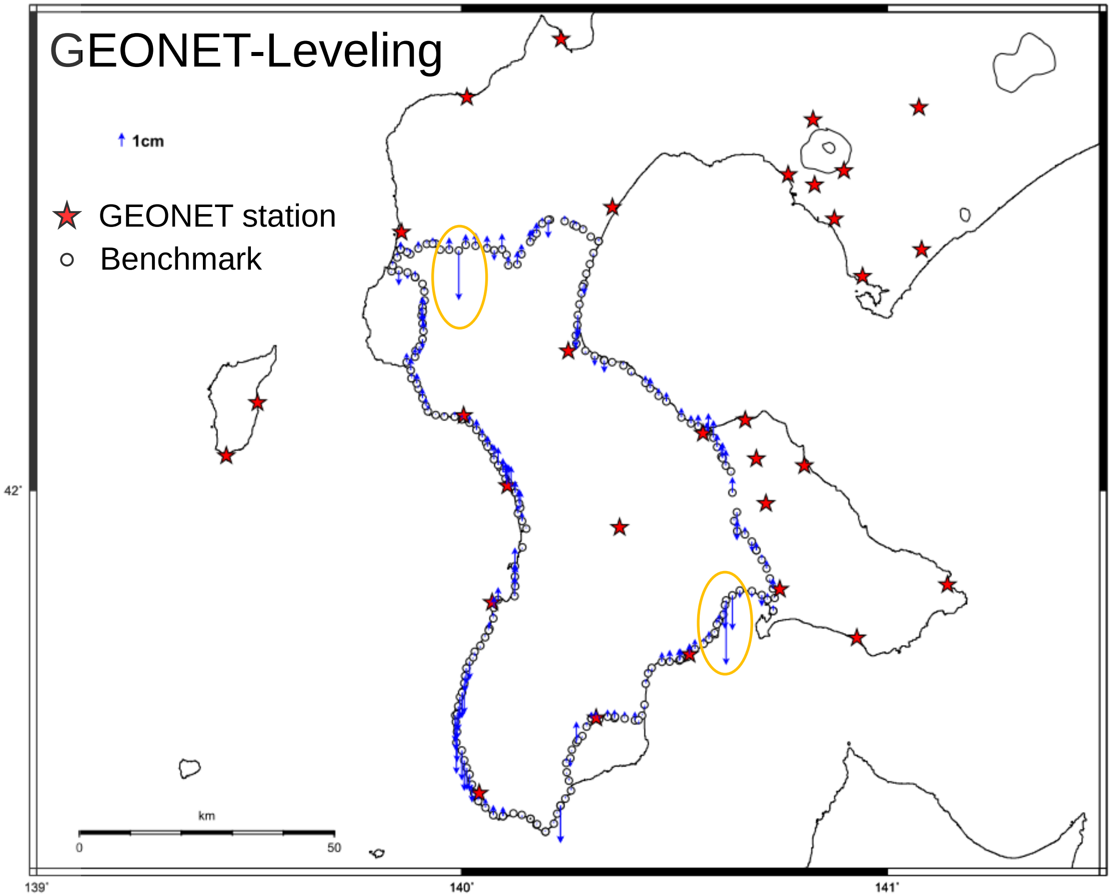


Vertical displacements on benchmarks from 2003-2004 to 2014 measured by leveling survey

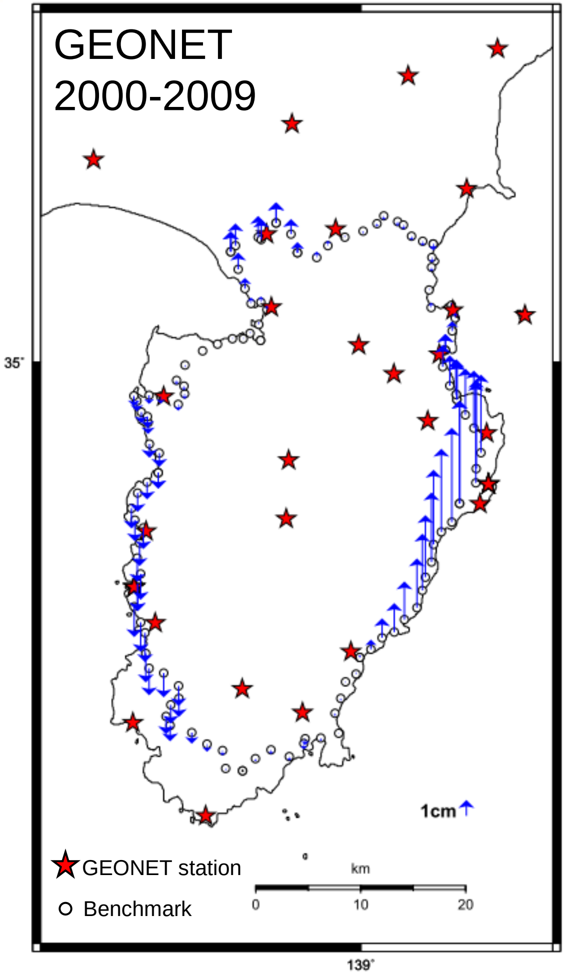
Evaluation by Leveling Data

- Differences between displacements estimated form GEONET and measured by leveling is 9.24mm in standard deviation and 0.64mm in average.

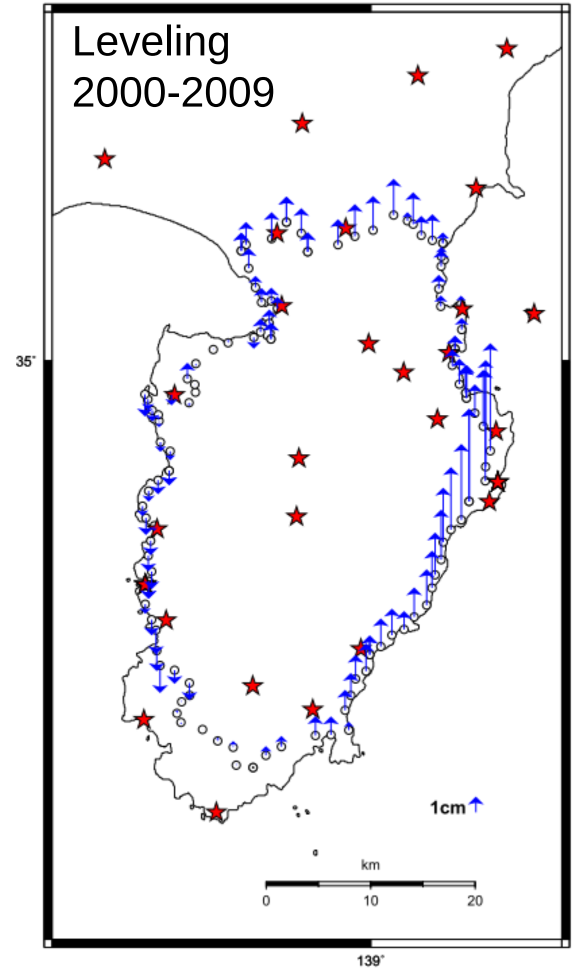




Difference between estimated displacement and leveling



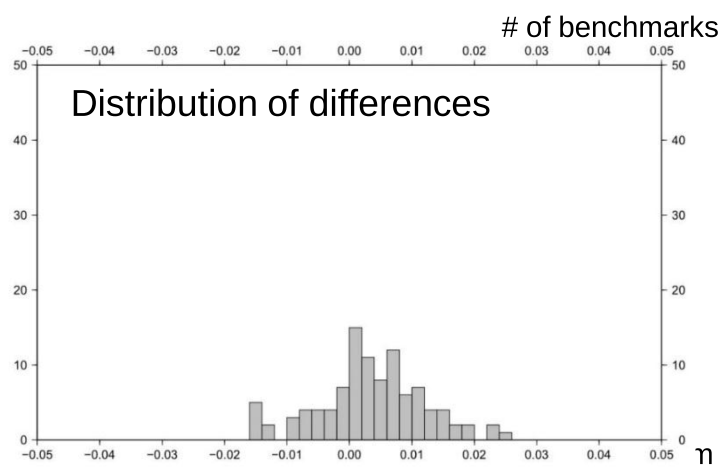
Vertical displacements on benchmarks from 2000 to 2009 estimated from GEONET

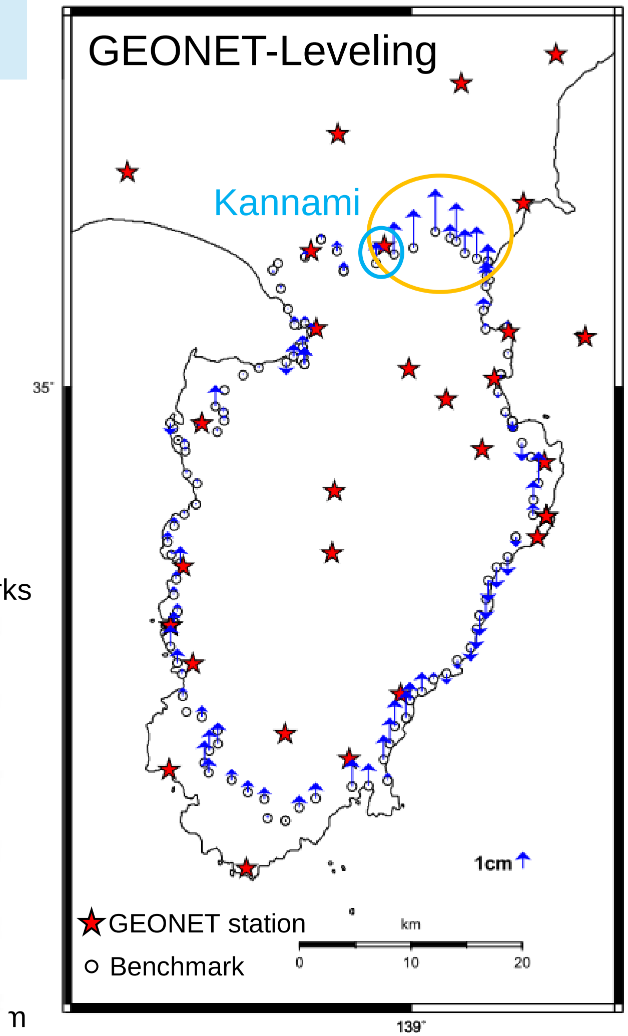


Vertical displacements on benchmarks from 2000 to 2009 measured by leveling

Evaluation by Leveling Data

- Izu peninsula is active region of volcanic activity and crustal deformation is accumulated over time.
- Difference is 8.53mm in standard deviation and 3.44mm in average. Length of the route is shorter than Hokkaido. However, the difference is larger.
- Relatively large differences shown in northern part are derived from bad data of one GEONET station.



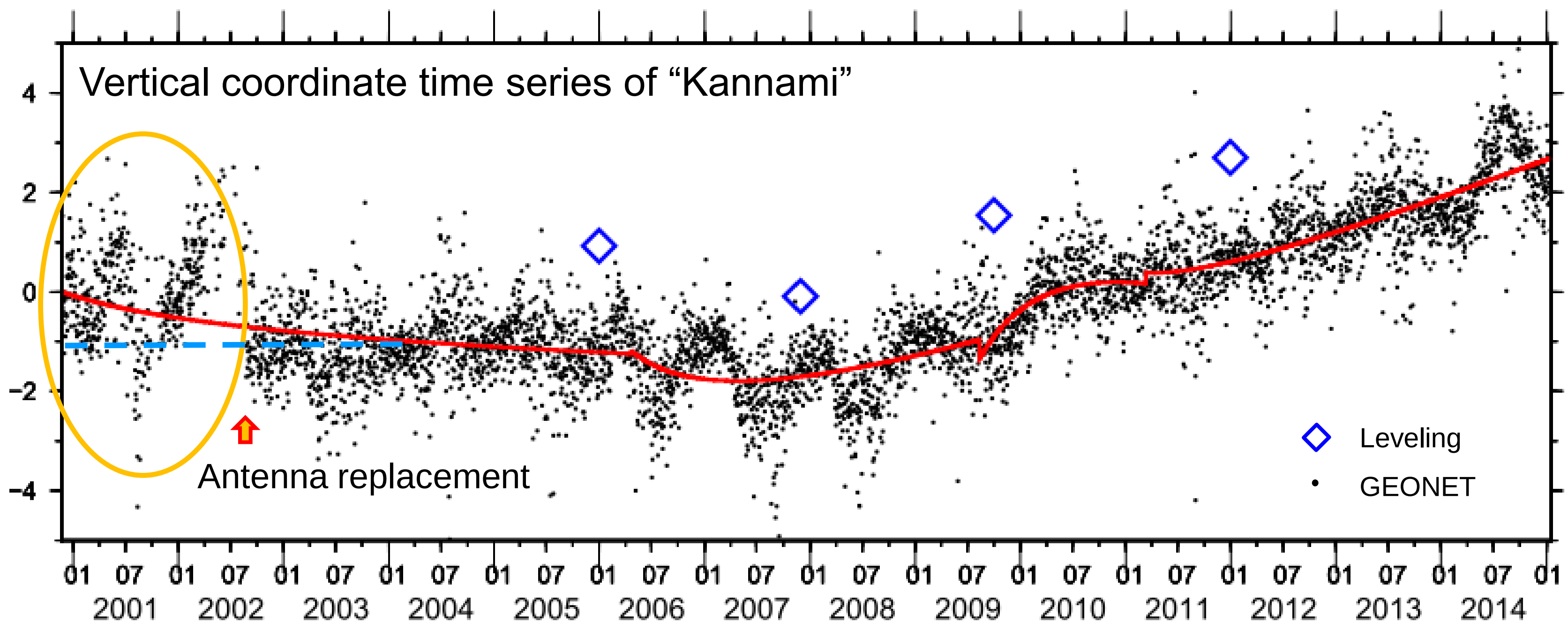


n

een estimated displacement and leveling

Importance of CORS data Quality

- An antenna installed at GEONET station, “Kannami”, was changed from ground-plane to chokering in 2002. Quality of the data was greatly improved after the replacement and coordinate time series also became stable.

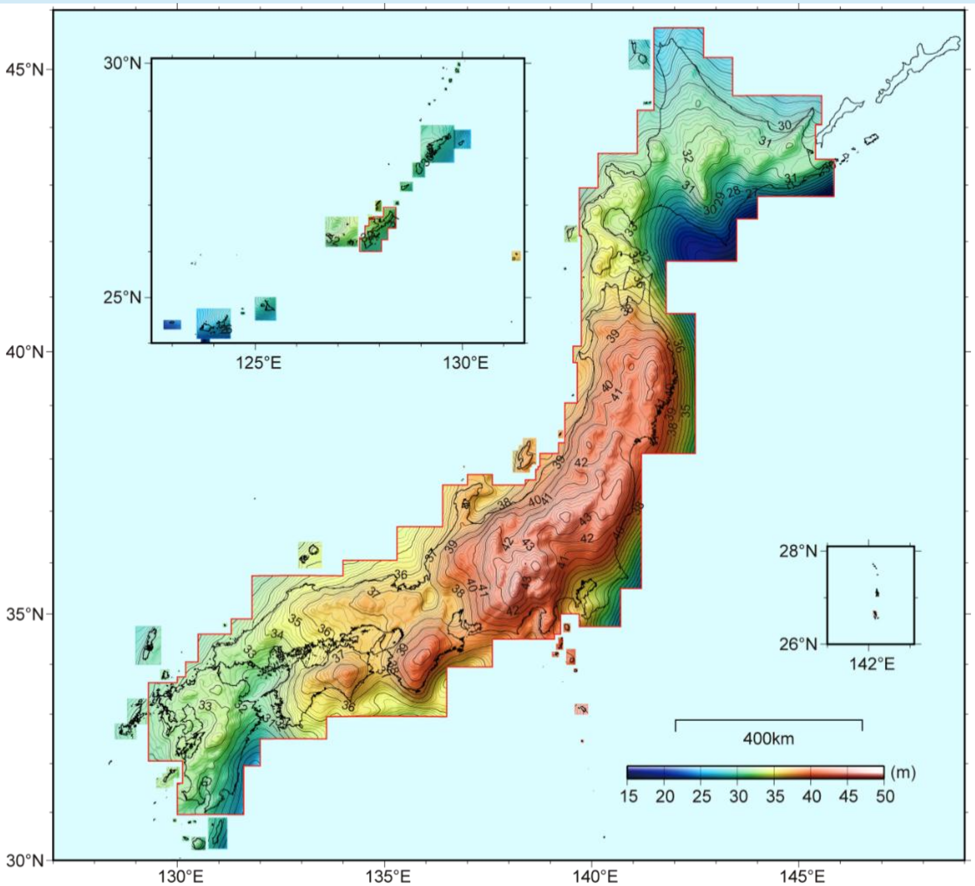


Utilization of CORS for Vertical Reference Frame

- CORS network is useful for monitoring and realizing not only 3D reference frame but also vertical reference frame.
- In order to estimate appropriate vertical displacement field from CORS network, appropriate spatial distribution of CORS is important.
- Data quality and continuity of CORS are also extremely important because bad quality directly degrades the accuracy of the estimation.
- GSI will develop vertical displacement field model of Japan from GEONET data. GSI will also utilize the model for revising vertical datum of Japan.

Hybrid Geoid Model of Japan

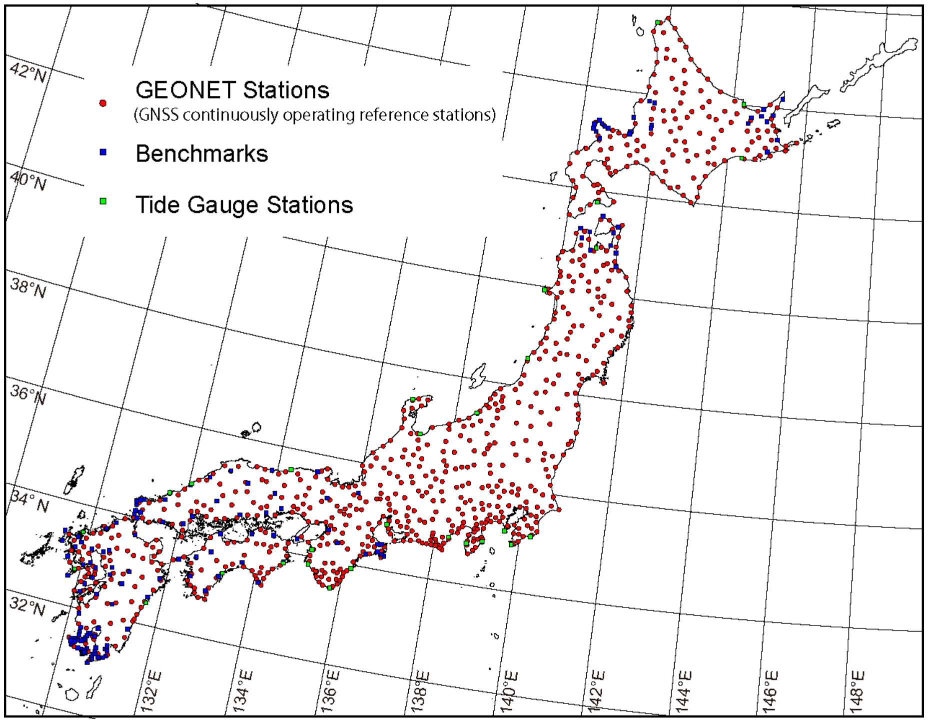
- GSI developed hybrid geoid model of Japan, “GSIGEO2011” in order to enable orthometric height determination by GNSS surveying.
- The model is established by fitting gravity geoid model of Japan, “JGEOID2008”, to geoid heights determined from GNSS/Leveling at 796 GEONET stations, 29 tidal stations and 197 benchmarks.
- The model was open on April 1 2014 and available for land survey in Japan.



Counter interval is 20cm and numerals in meters

Hybrid Geoid Model of Japan -Geoid Height-

- First order leveling survey was conducted from first order leveling routes to 796 GEONET stations and 29 tidal stations. GNSS observation was also conducted at 197 benchmarks.
- GNSS observation at benchmarks was mainly conducted in areas which have bad or sparse gravity data.
- Density of geoid undulation points is relatively low in Tohoku area. Data in the area became not available because of the 2011 Off the Pacific coast of Tohoku Earthquake.

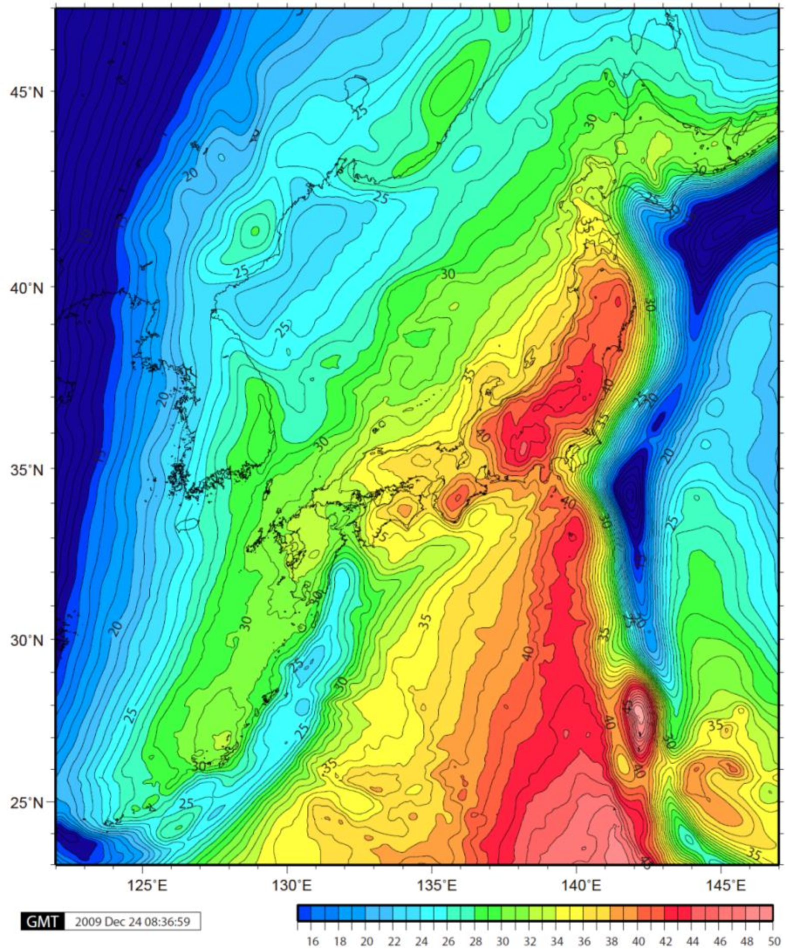


Distribution map of geoid undulation points for hybrid geoid model of Japan, "GSIGEO2011"

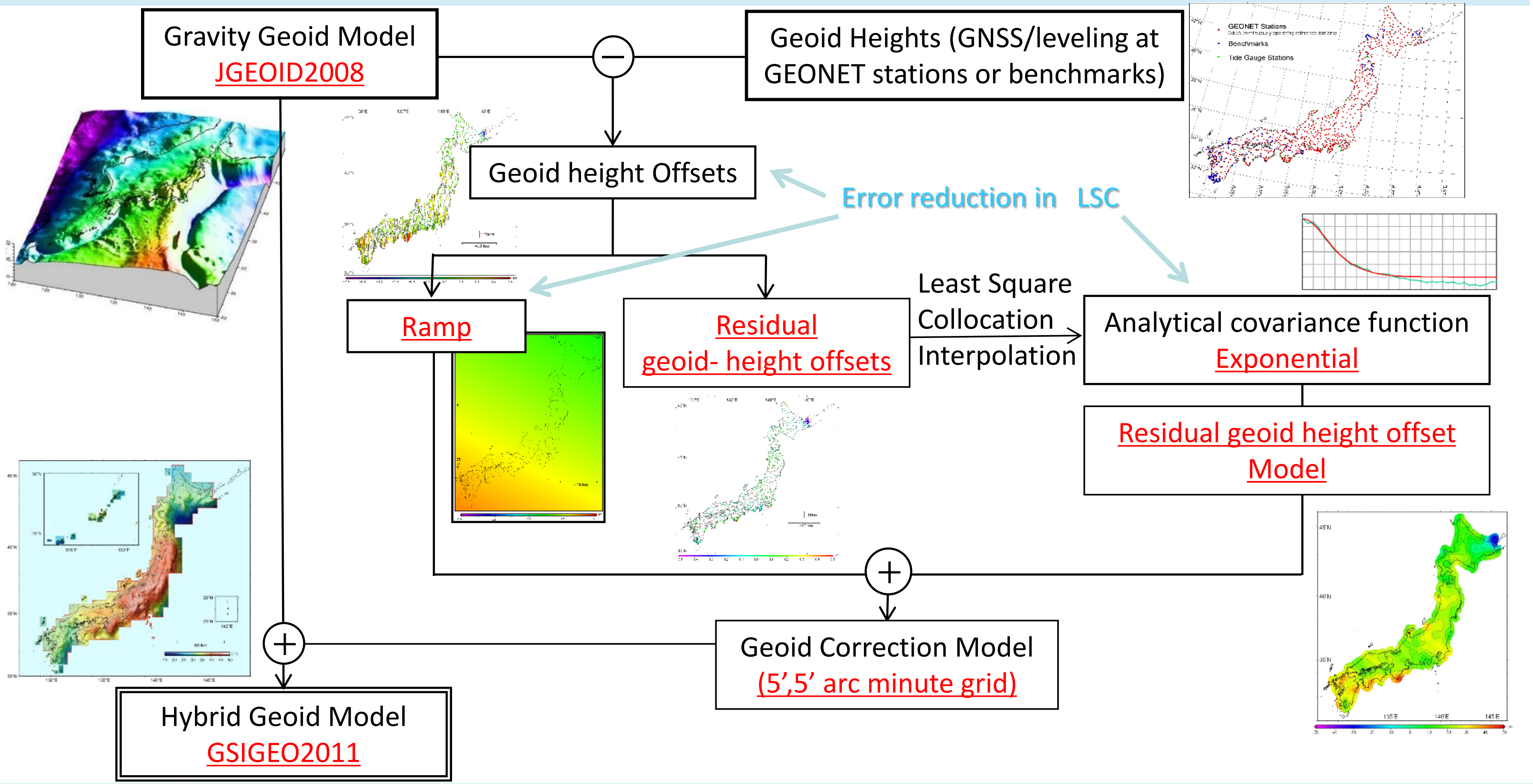
Hybrid Geoid Model of Japan -Gravity Geoid Model

- JGEOID2008 is the latest gravity geoid model of Japan developed by GSI.
- Combining
  - GGM02C/EGM96: global geopotential model
  - surface (land and ship-borne) gravity measurements
  - KMS2002: altimetry-derived marine gravity model
  - 250m mesh digital elevation model of Japan
- Model resolution is 1×1.5 arc-minute grid.
- According to comparison with GPS/leveling geoid heights on benchmarks, residual is 8.44cm in standard deviation and maximum difference is -20.22cm.

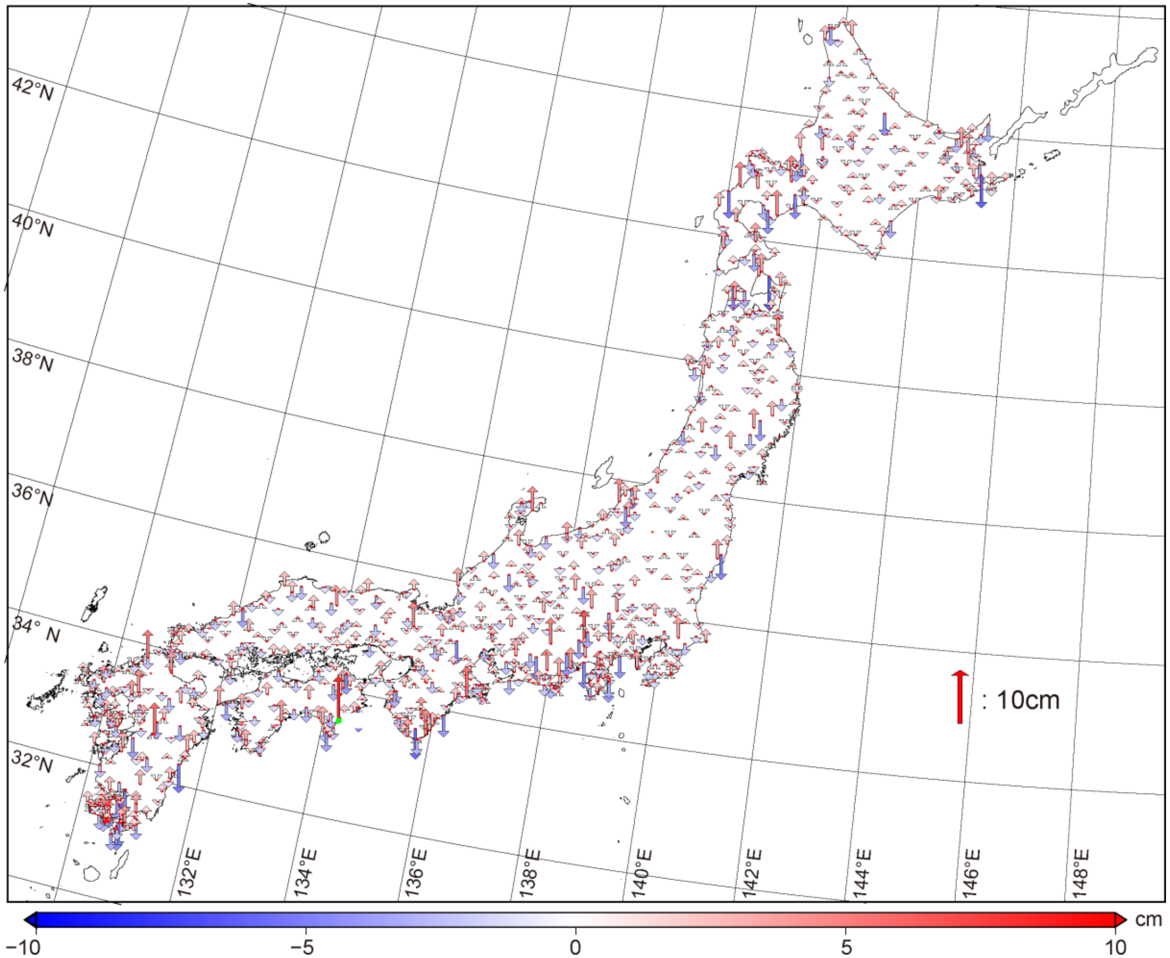
Kuroishi (2009) : Improved geoid model determination for Japan from GRACE and a regional gravity field model



Schematic flow of development of GSIGEO2011



Evaluation of hybrid geoid model of Japan



Reproduction errors (differences between GSIGEO2011 and GNSS/leveling).

	Reproduction error
Average	0 mm
SD	1.9 mm
Max Difference	8.3 mm(-6.2 mm)

Miyahara, B., T. Kodama and Y. Kuroishi (2014): Development of new hybrid model for Japan,"GSIGEO2011", Bulletin of the Geospatial Information Authority of Japan, Vol.62, 11-20.

Summary

- Vertical datum of Japan was realized and maintained by leveling survey of 14,000km fundamental leveling routes.
- For coseismic vertical crustal deformation caused by large earthquakes, GSI will re-survey benchmarks and revise orthometric heights of benchmarks.
- For accumulated vertical crustal deformation caused by plate motions, GSI will develop vertical displacement model of Japan from GEONET coordinate time series and utilize it for maintanance of vertical reference frame.
- In order to realize best mix of leveling, CORS and geopotential heights, GSI will continue to develop geoid model of Japan by combining latest satellite gravity data, improved land gravity data and etc..