Geodetic Reference Frame and Its Dynamics

Case in Japan

Basara Miyahara, Koji Matsuo, Masahiro Nakashima, Shuntaro Fukaya, Yu Takagi
Geospatial Information Authority of Japan (GSI)

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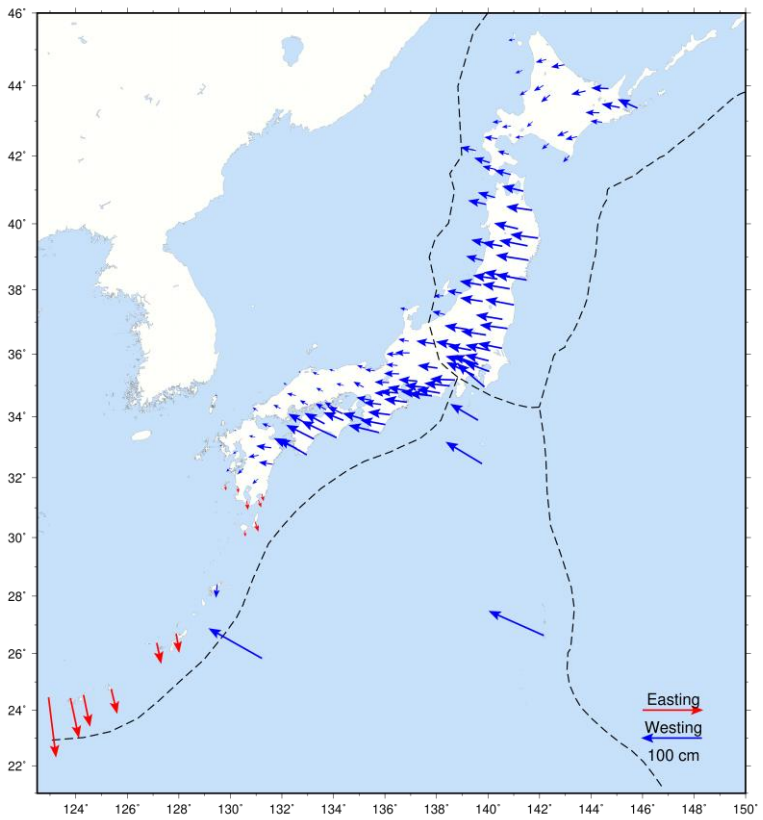
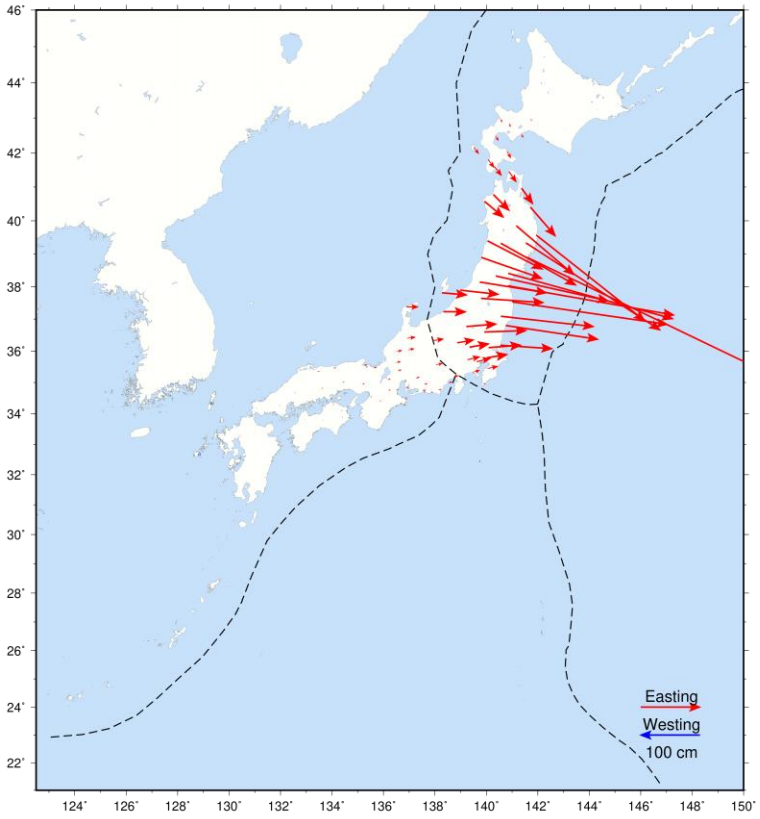
Crustal deformation

Crustal deformation detected by GNSS CORS Network in Japan

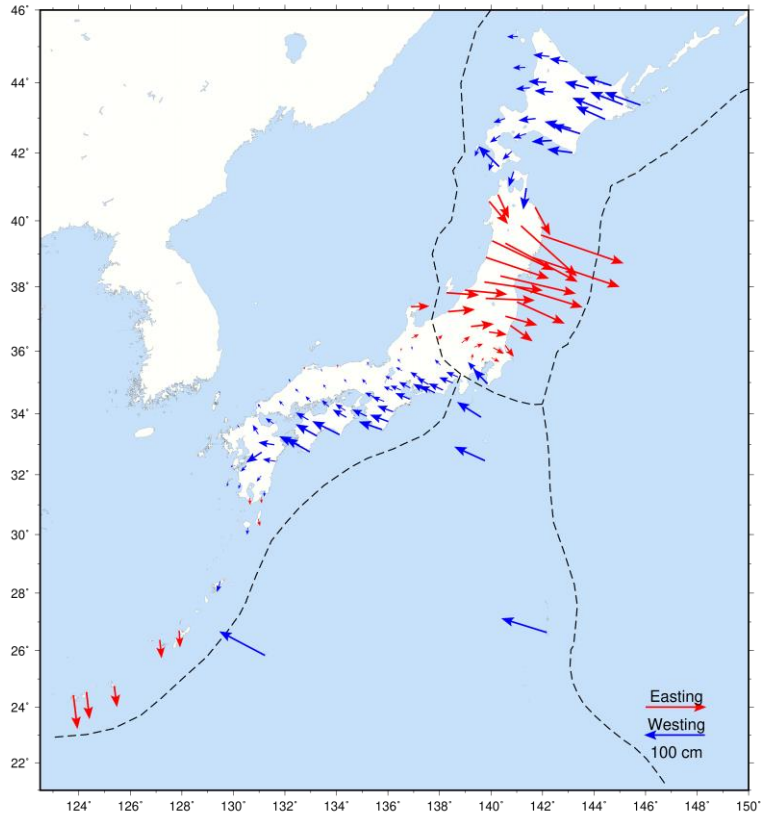
1997-01-01 − 2011-03-10



Co-seismic deformation



2011-03-12 − 2022-01-01



Crustal deformation detected by GNSS CORS Network in Japan

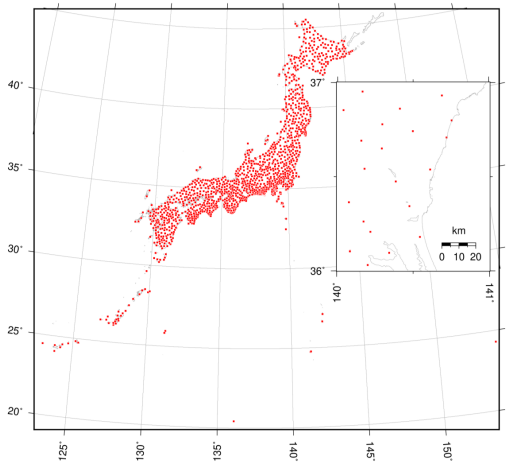
Current Japanese Geodetic Datum

- Current Japanese Geodetic Datum is referred to as JGD2011
- Released after the 2011 off the Pacific coast of Tohoku earthquake (Revision of JGD2000)
- Horizontal and vertical reference frames are mainly maintained by different techniques

Current Horizontal Datum

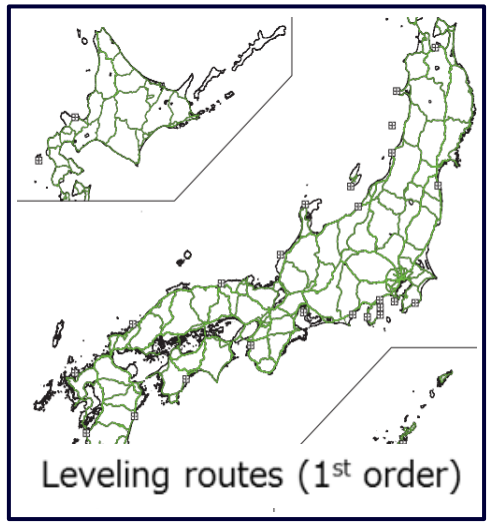
Maintained by space geodetic technique

GNSS CORSs + VLBI



Current Vertical Datum

Maintained by leveling survey



Benchmark

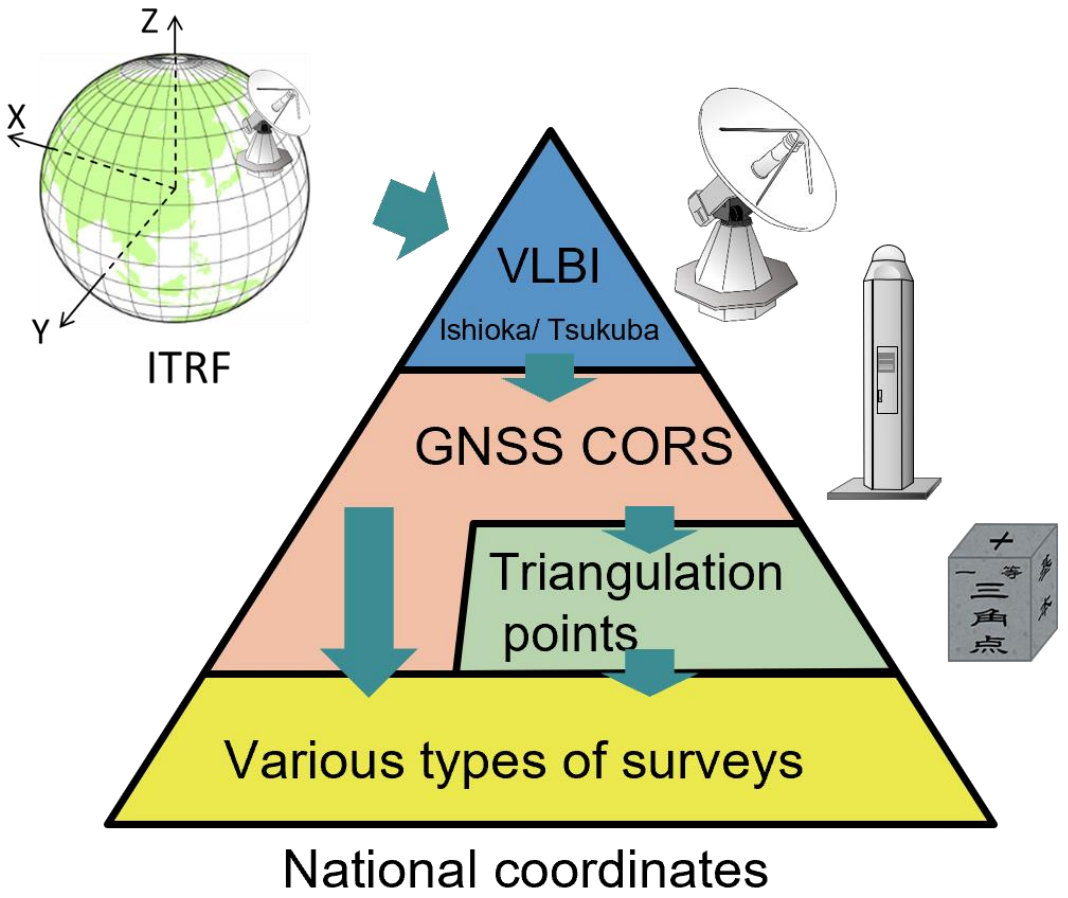
Horizontal Datum of Japan

- GRS80 & ITRF

  (Adopted based on Survey Act, Article 11)

- Official coordinates or “the survey results” are fixed at the reference epoch

- Realized and maintained by VLBI, GNSS CORSs and passive markers



VLBI operated by GSI

- GSI has been operating VLBI stations
  - Tsukuba 32 m at GSI: 1991-2016
  - Ishioka 13 m, a VGOS antenna, at Ishioka Geodetic Observing Station: 2015-
- Ishioka Geodetic Observing Station, where an IGS station is also located, is a GGOS station
- Participating in international observations and monitoring crustal deformation & Earth's rotation

Tsukuba 32m

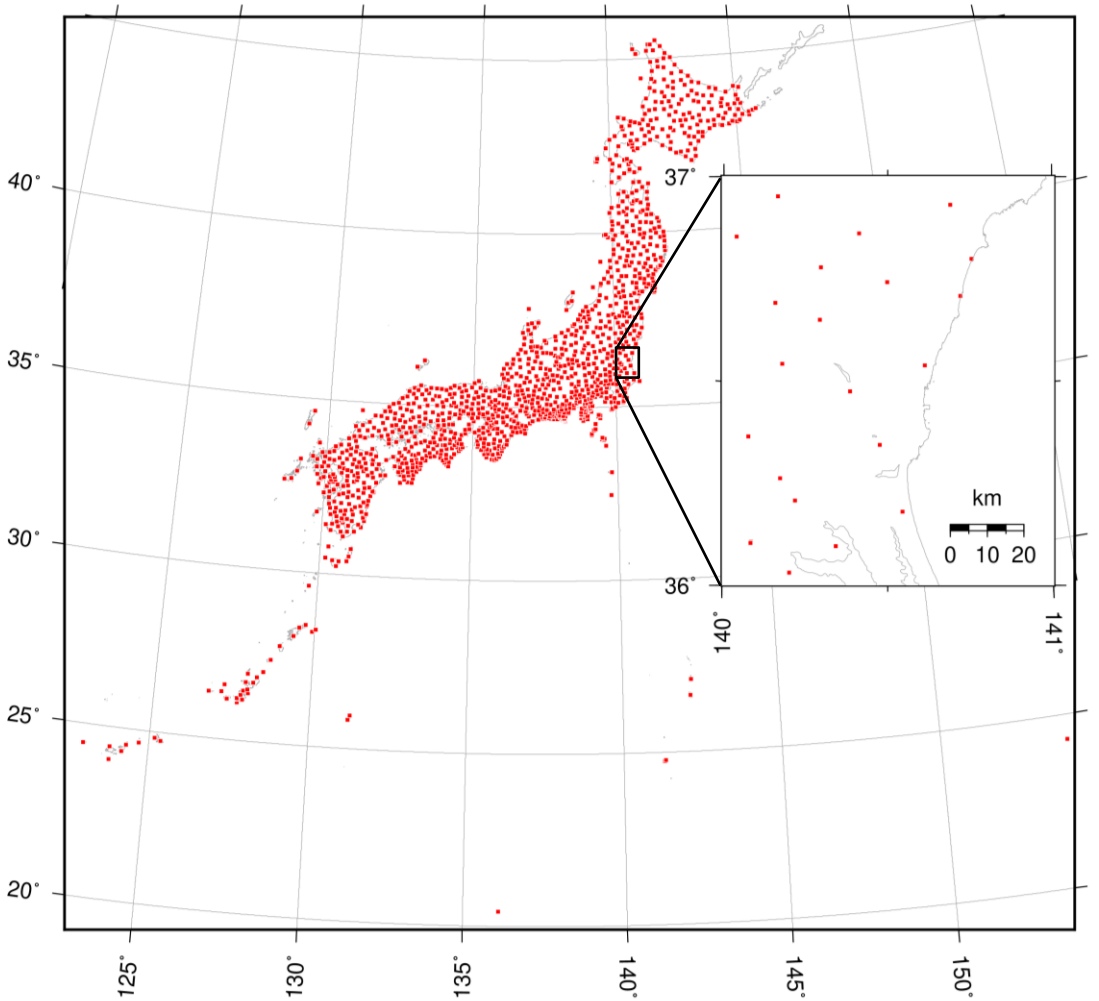
Ishioka 13m

IGS station ISHI

GNSS CORS Network in Japan

- About 1,300 stations in throughout Japan
  Spacing is 20-30 km
- Used in survey as reference points
- Monitoring crustal deformation

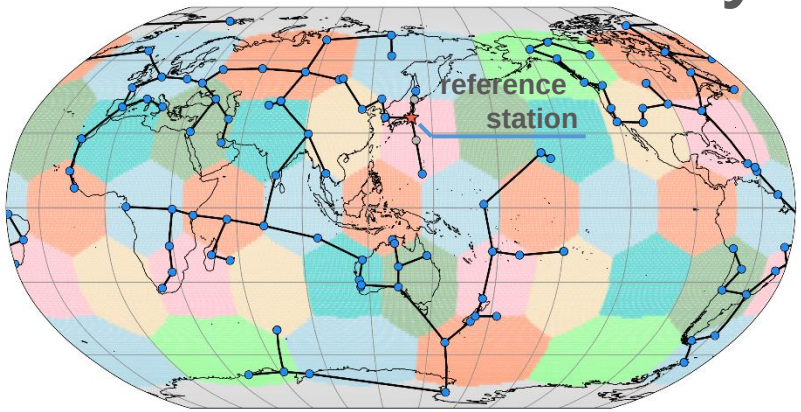
Distribution of GNSS CORSs in Japan



F5 solution: Daily coordinates of GNSS CORSs

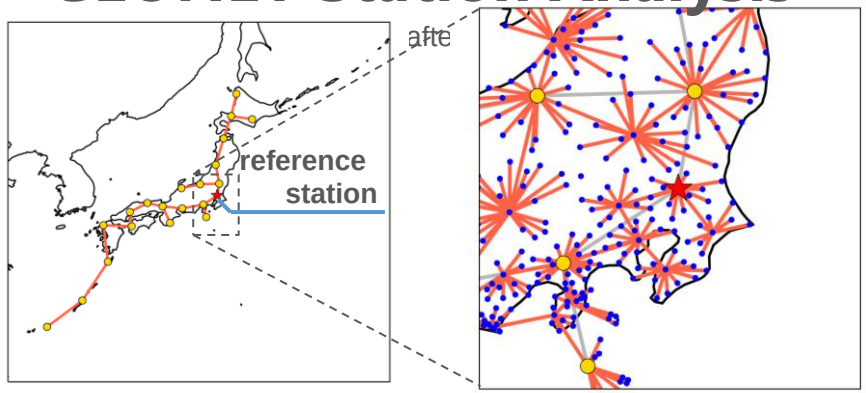
- Daily coordinates of nationwide GNSS CORSs in Japan, GEONET
- Realize the ITRF with a minimum constraint approach
- Objective : to monitor co-seismic and secular deformation field to build the deformation model
- Accuracy : several mm

Step1 :
Reference Station Analysis



Estimate reference station coordinate by global network processing

Step2 :
GEONET Station Analysis

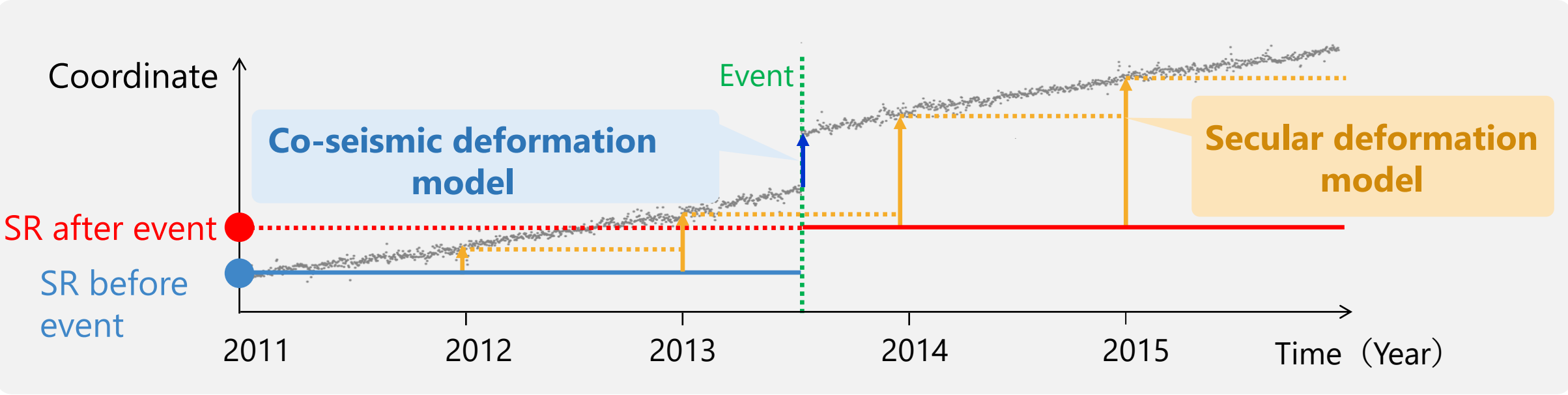


modified after Takamatsu et al. (2023)

Fixing the reference station, estimate every GEONET station coordinates.

How to deal with the crustal deformation

- Survey Results (SRs) are fixed at the reference epoch
- Two models to handle the crustal deformation
  - ✓ Co-seismic deformation model — Update the survey results after events
  - ✓ Secular deformation model — Transform between the survey results and the coordinates at observation epoch



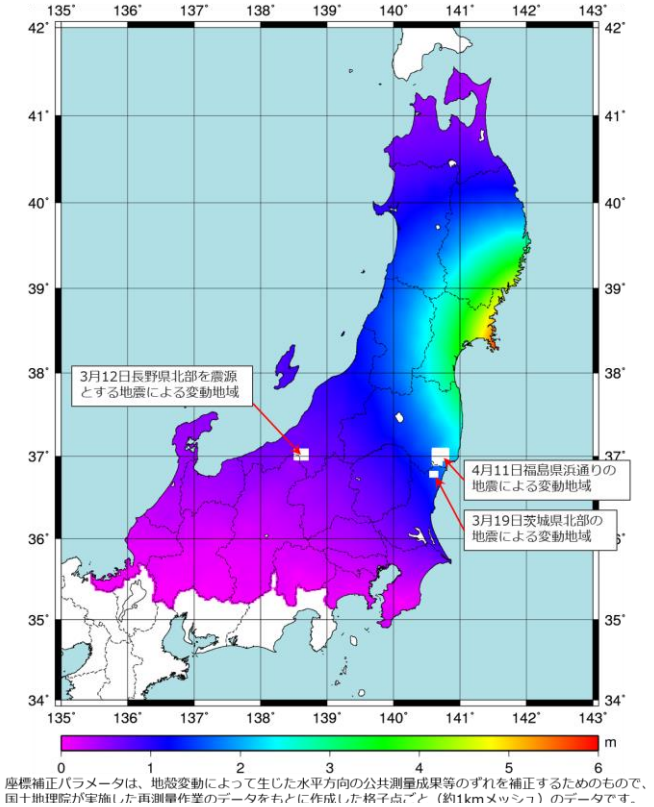
Co-seismic & Secular Deformation models

- Grid models
- GSI derives the models and provide them on its website

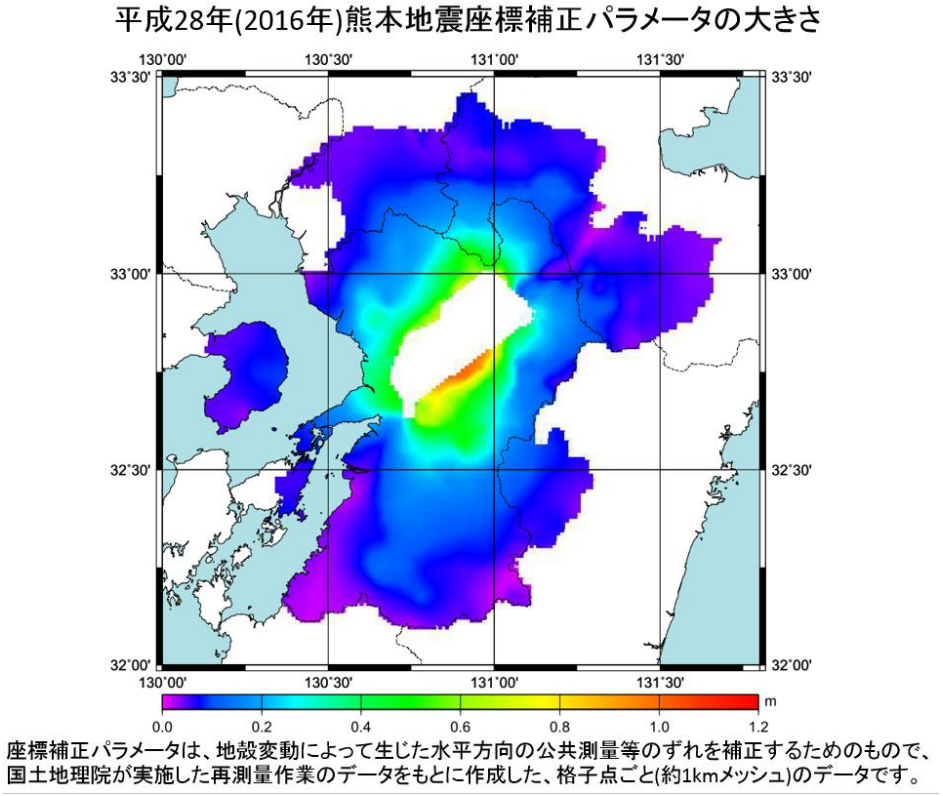
		Co-seismic deformation	Secular deformation
Input data		✓ GNSS CORSs ✓ GNSS campaign obs. after events	✓ GNSS CORSs
Model	Area	Affected area	Japanese territory (Only land)
	Updating Intervals	After events	Every year
	Spacing	~ 1 km	~ 5 km

Co-seismic deformation models

2011 off the pacific coast of Tohoku earthquake (Mj 9.0)



2016 Kumamoto earthqaukes (Mj 6.5, 7.3)

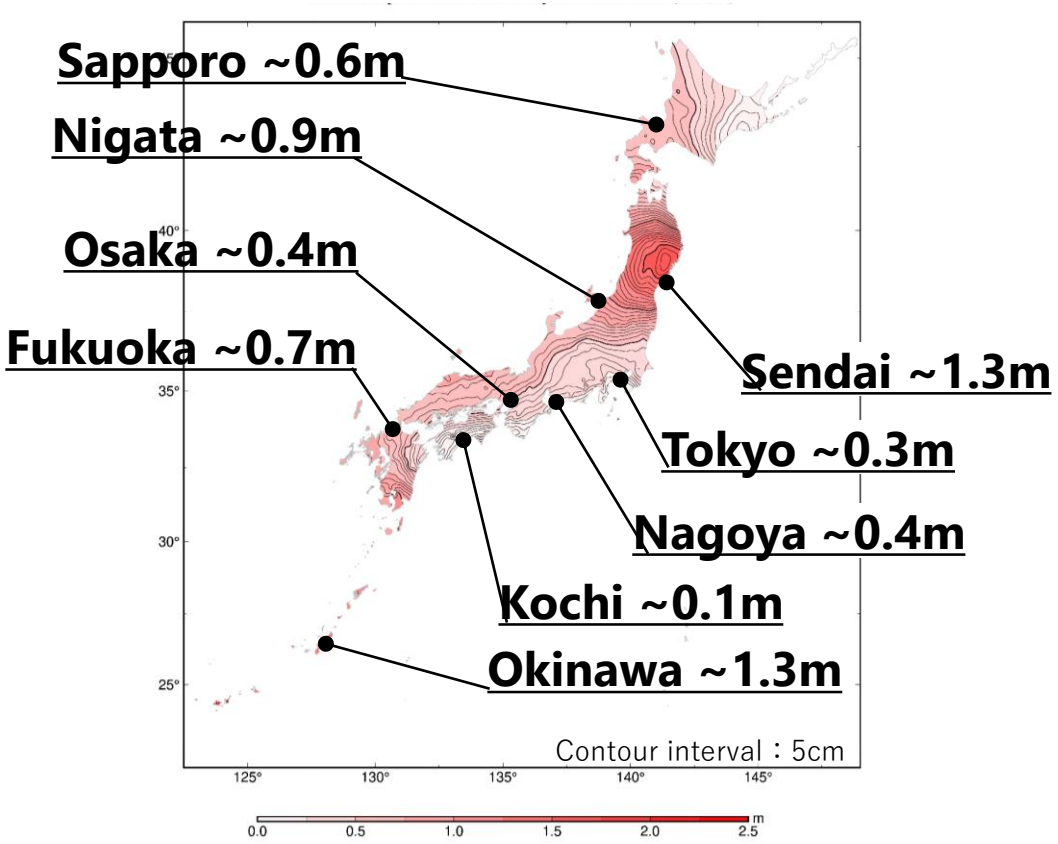


After this event, the datum was revised from JGD2000 to JGD2011

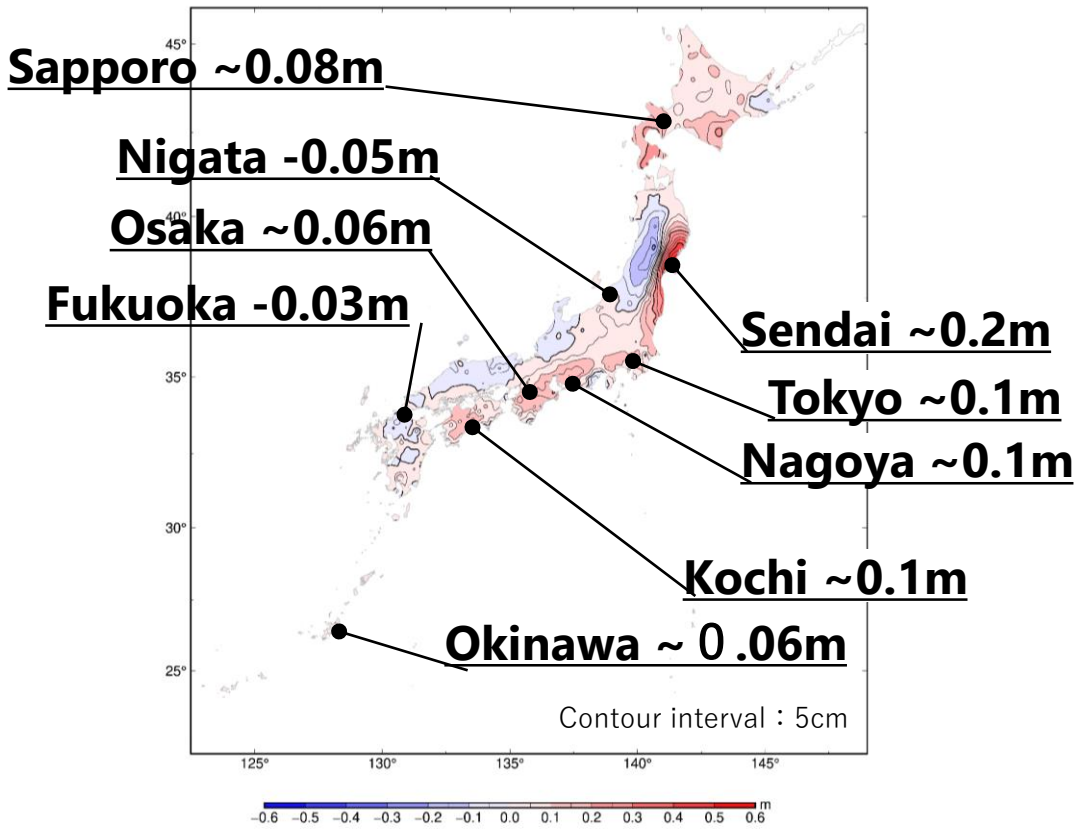
Secular deformation model

- Transform coordinates between at the reference epoch and at the observation epoch
- Derived by using about 1,300 GNSS CORSs' time series data

Deformation model (horizontal)

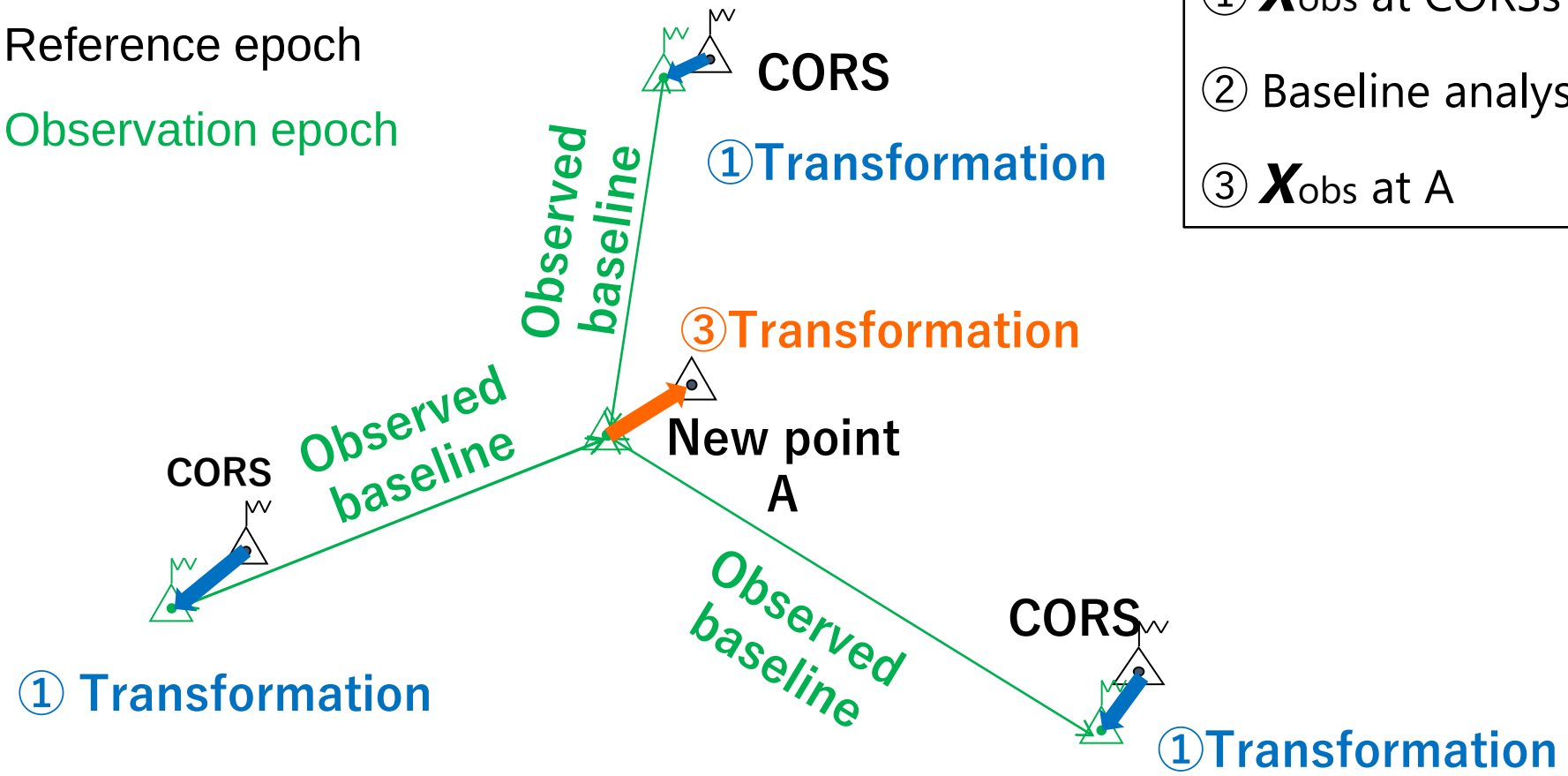


Deformation model (vertical)



Applying secular deformation model to surveying

Secular deformation model is used to obtain the survey results of a newly installed point in survey



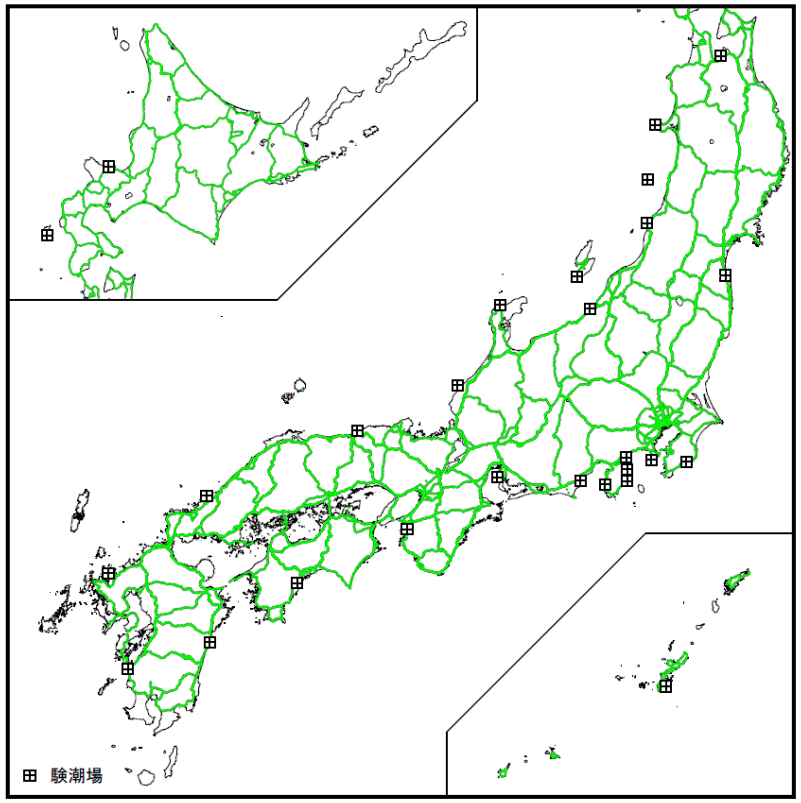
① $\boldsymbol{X}_{obs}$ at CORSs → $\boldsymbol{X}_{ref}$ at CORSs

② Baseline analysis to calculate $\boldsymbol{X}_{obs}$ at A

③ $\boldsymbol{X}_{obs}$ at A → $\boldsymbol{X}_{ref}$ at A

Vertical datum in Japan

- Defined in reference to elevation from the mean sea surface of Tokyo-Bay
- Realized by the Vertical Control Network and leveling survey



Japanese Vertical Control Network

Origin of the Japanese
Vertical Control Network

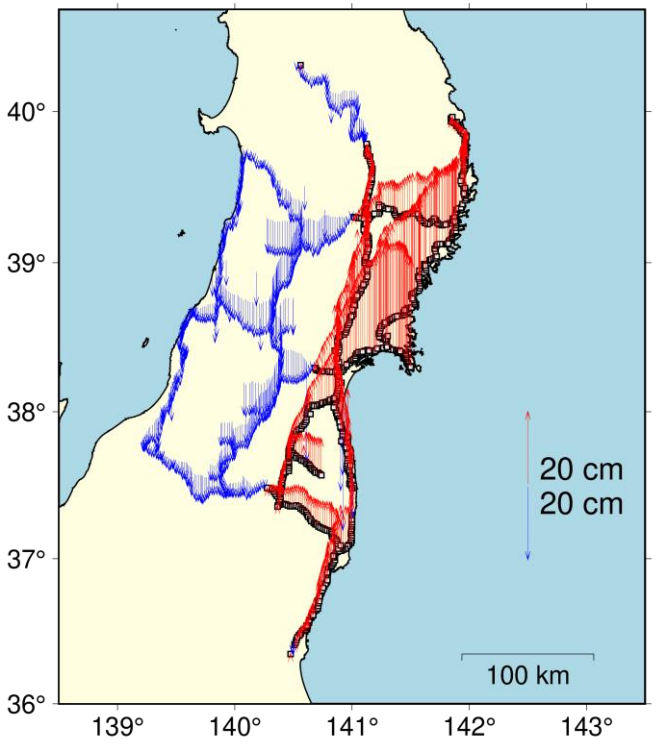
How to handle the crustal deformation

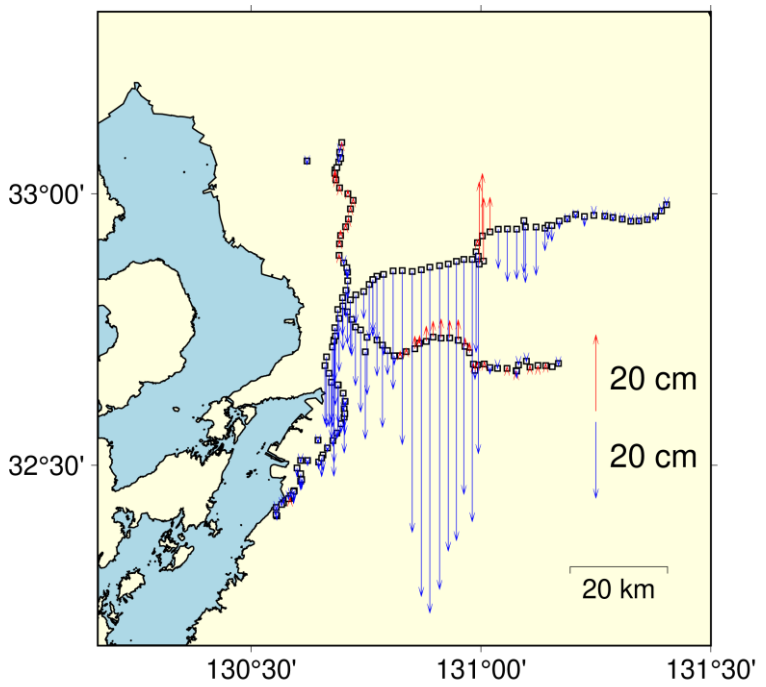
- Cyclic leveling survey all over Japan
  → Leveling survey in the area where the deformation is significant
- Leveling survey campaign after events

2011 off the pacific coast Tohoku earthquake

2016 Kumamoto earthquakes

New – Old



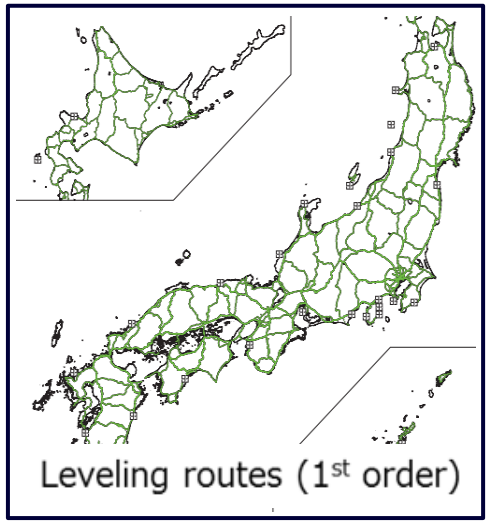


Hight modernization plan

Current vertical datum

Level-based system

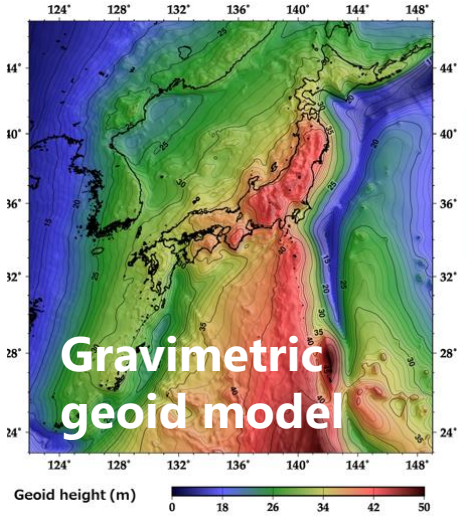
- High precision in short distance
- Time & cost consuming, labor intensive, low resilience, user unfriendly …



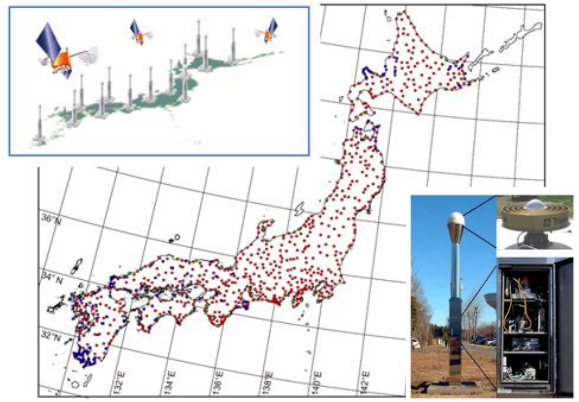
Future vertical datum

Geoid-based system

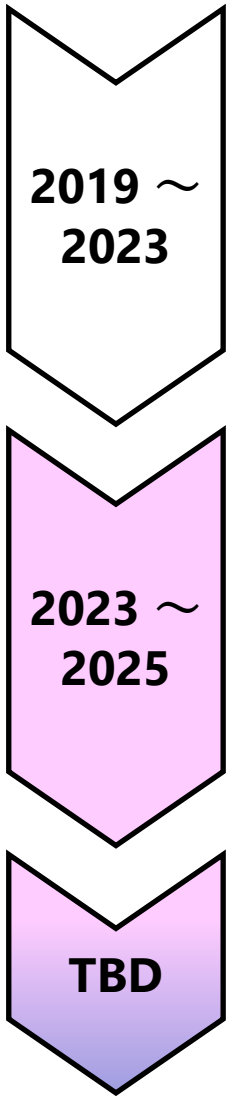
- Time & cost effective, efficient, high resilience, user friendly …
- Precise geoid model is required



GNSS CORS (~1,300 stn.)

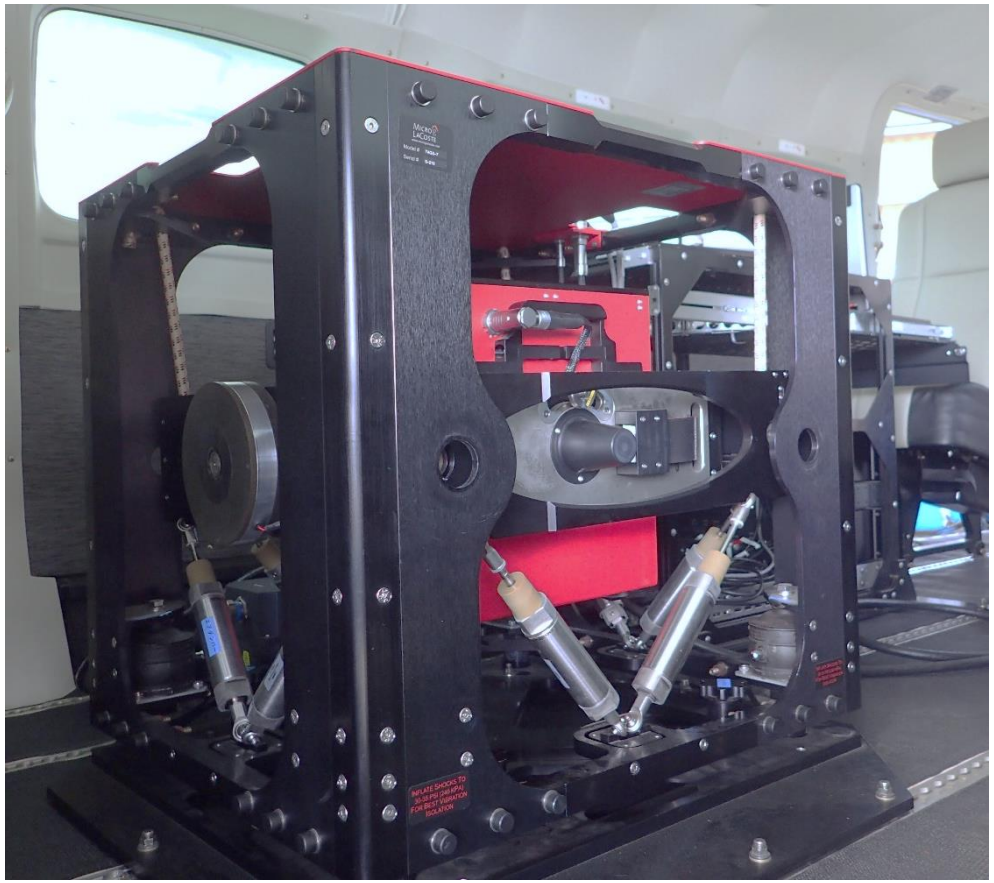


Airborne gravity survey project: plan



- Airborne gravity survey started
- Airborne gravity survey completed
- Development of a new gravimetric geoid model
- Introduction of a new gravimetric geoid model to surveying system
- Implementation of geoid-based geodetic datum

Airborne gravimetry & Aircraft



▲ Micro-g Lacoste TAGS-7

(Accuracy in catalog: <0.7mGal)

▲ JA889N

(Textron Aviation 208)

◀ Checking a log

Airborne gravity survey

Flight altitude

- 5000 m at Tokyo and mountainous areas
- 3000 m at other

Flight velocity

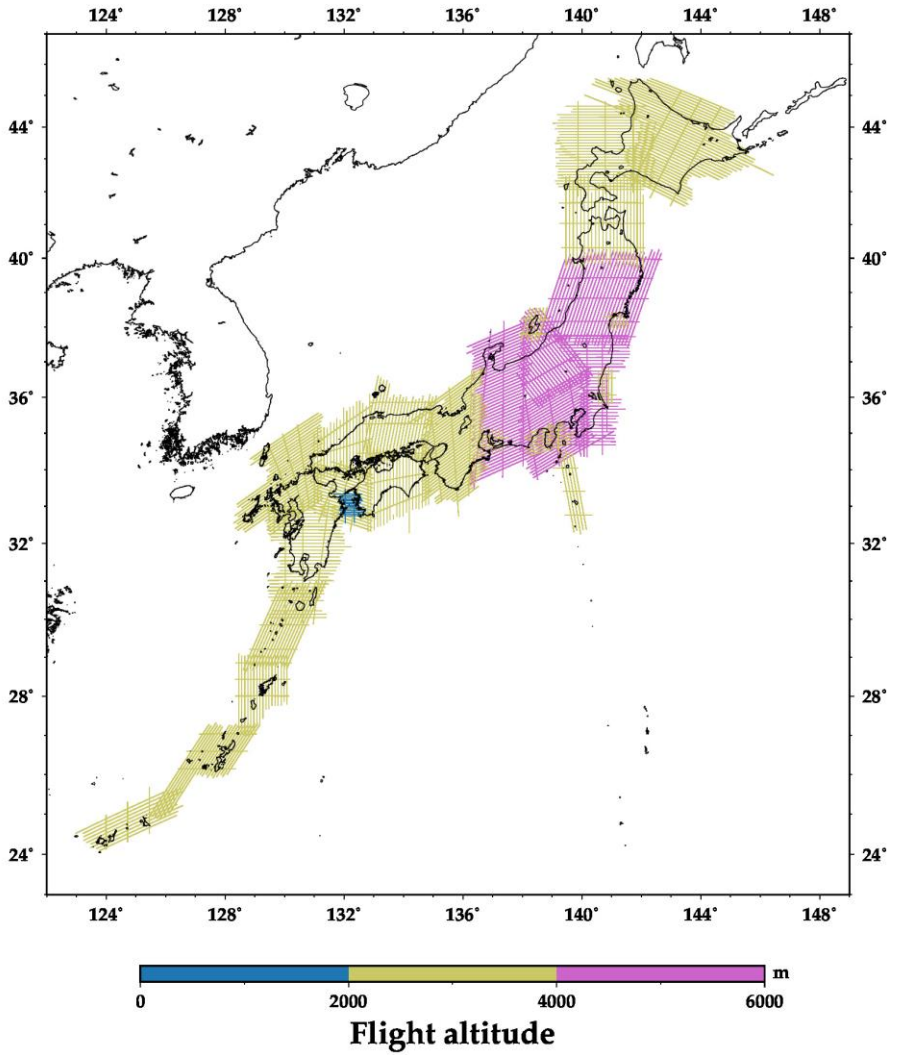
- 300 km/h

Data sampling

- 20 Hz (≈ 4.2 m)

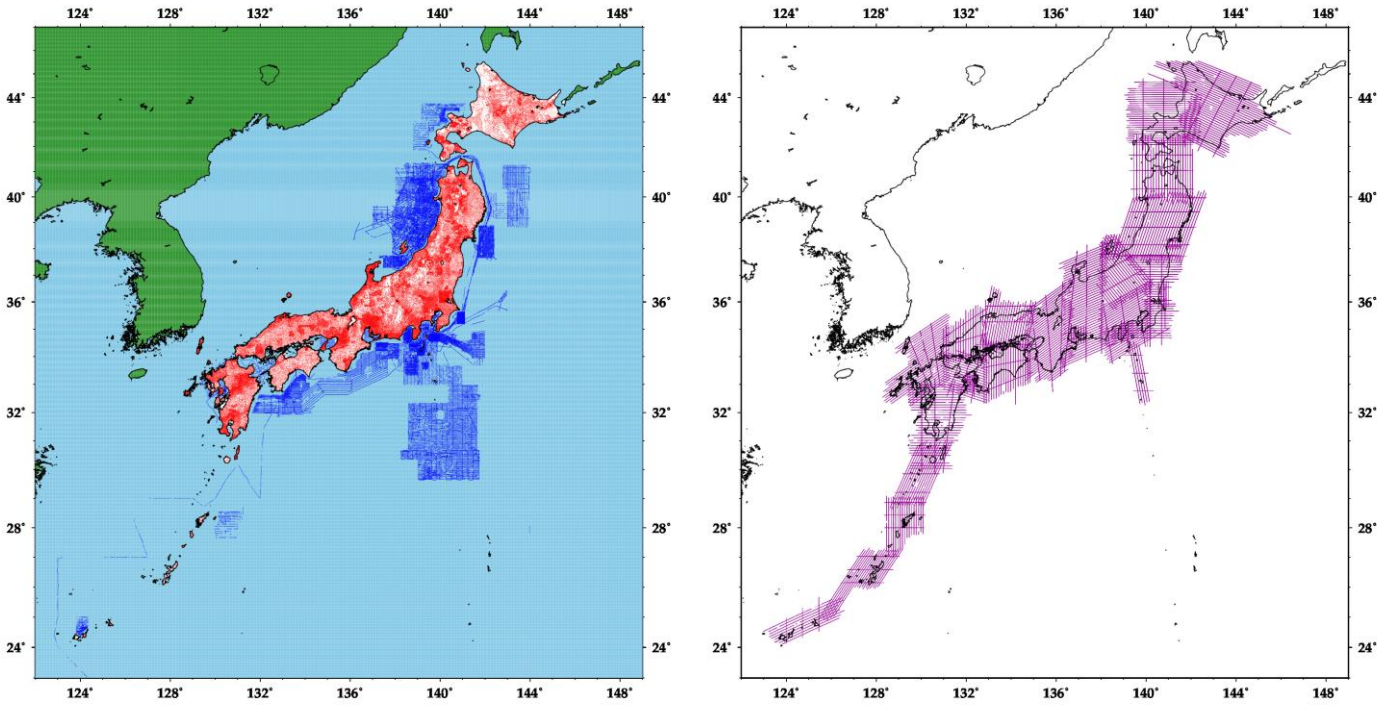
Survey line spacing

- 10 km at data lines
- 20~80 km at validation lines



Geoid computation using airborne gravity data

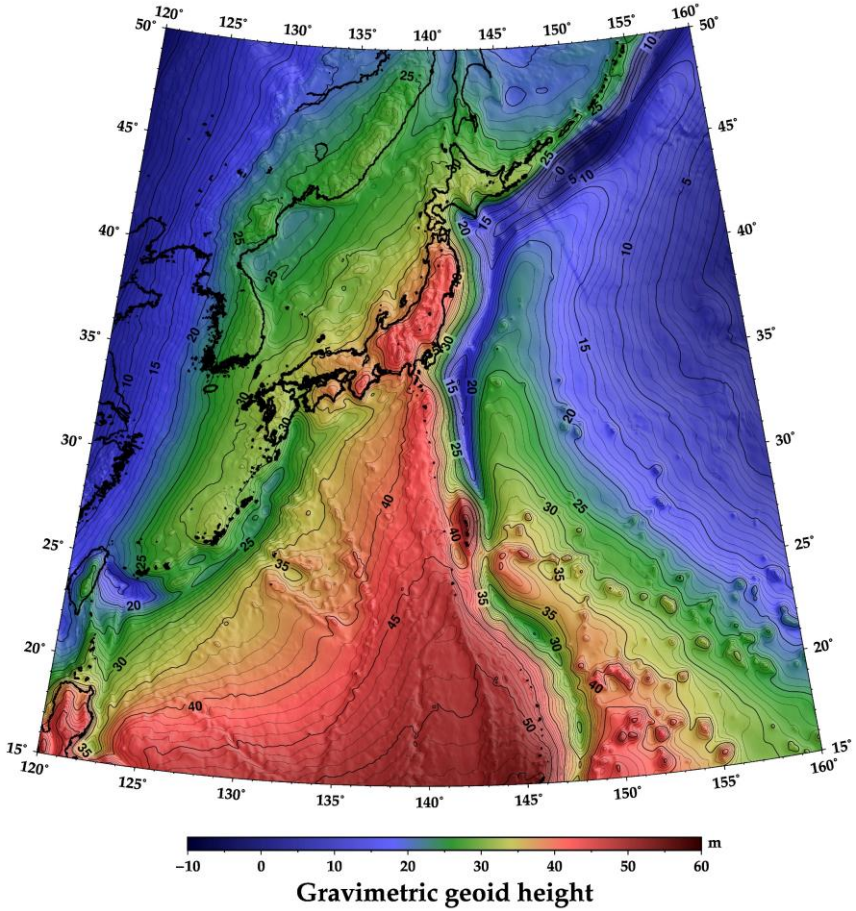
Gravity data distribution



- Land gravity data (326,116 pnt.)
- Ship-borne gravity data (443,338 pnt.)
- Scripps V32.1 model (1 min grid)
- EGM2008 + RTM (1 min grid)

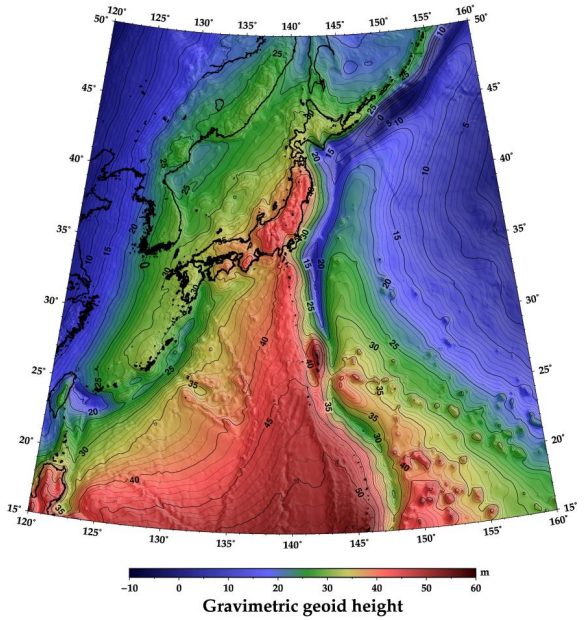
- Airborne gravity data (1.0 mGal accuracy by cross-over evaluation)

JGEOID2023

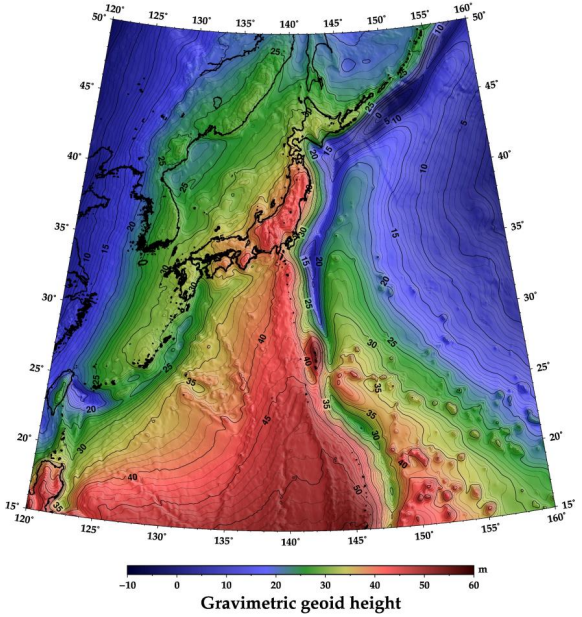


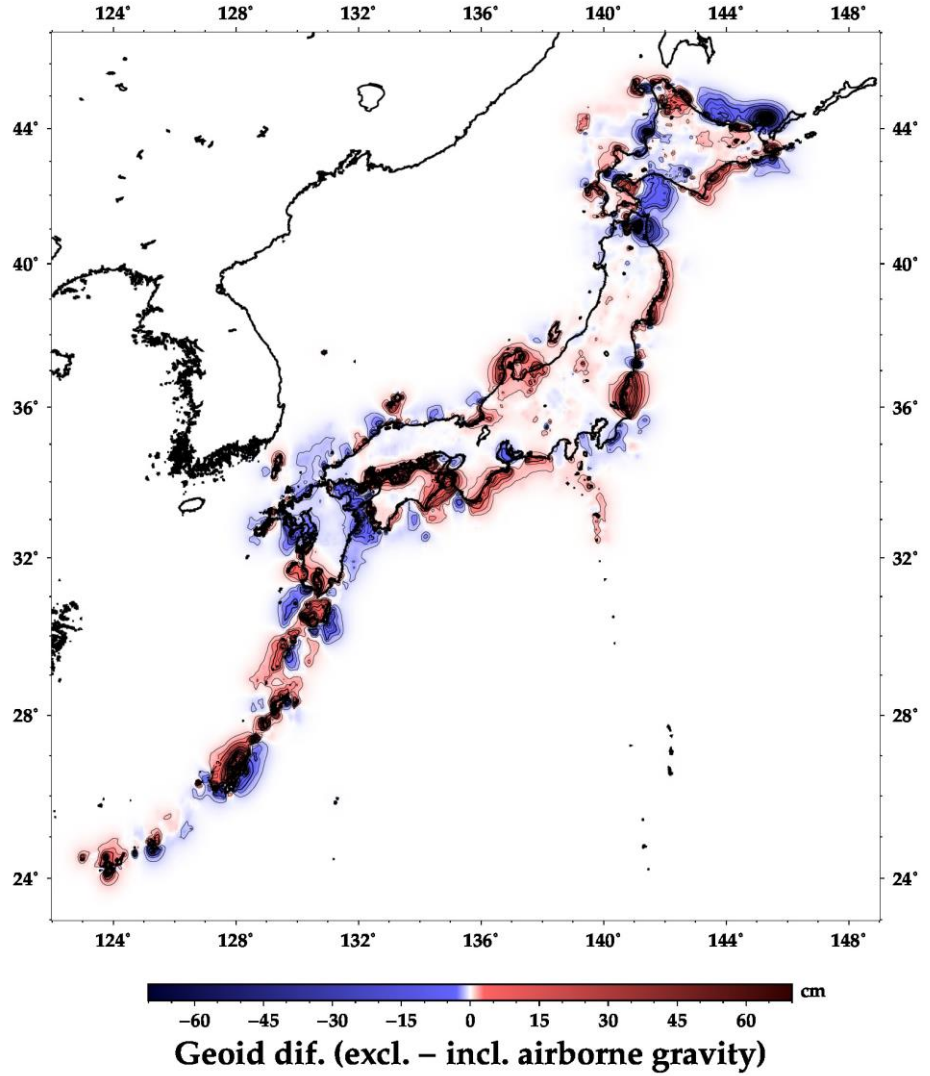
Contribution of the airborne gravity data

Geoid model excluding the airborne gravity data



Geoid model including the airborne gravity data

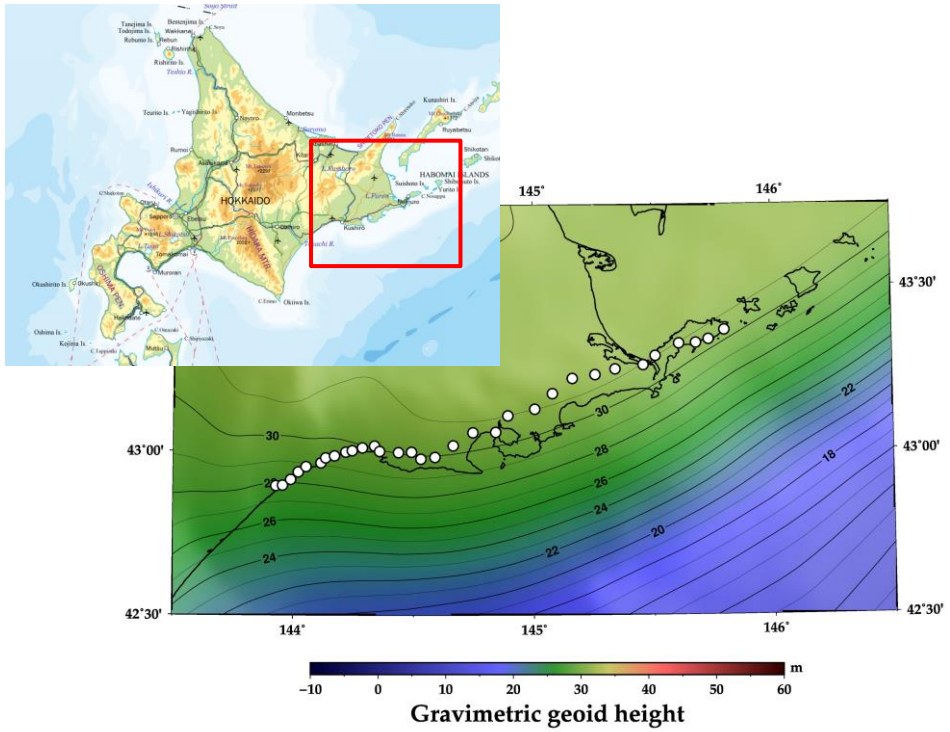


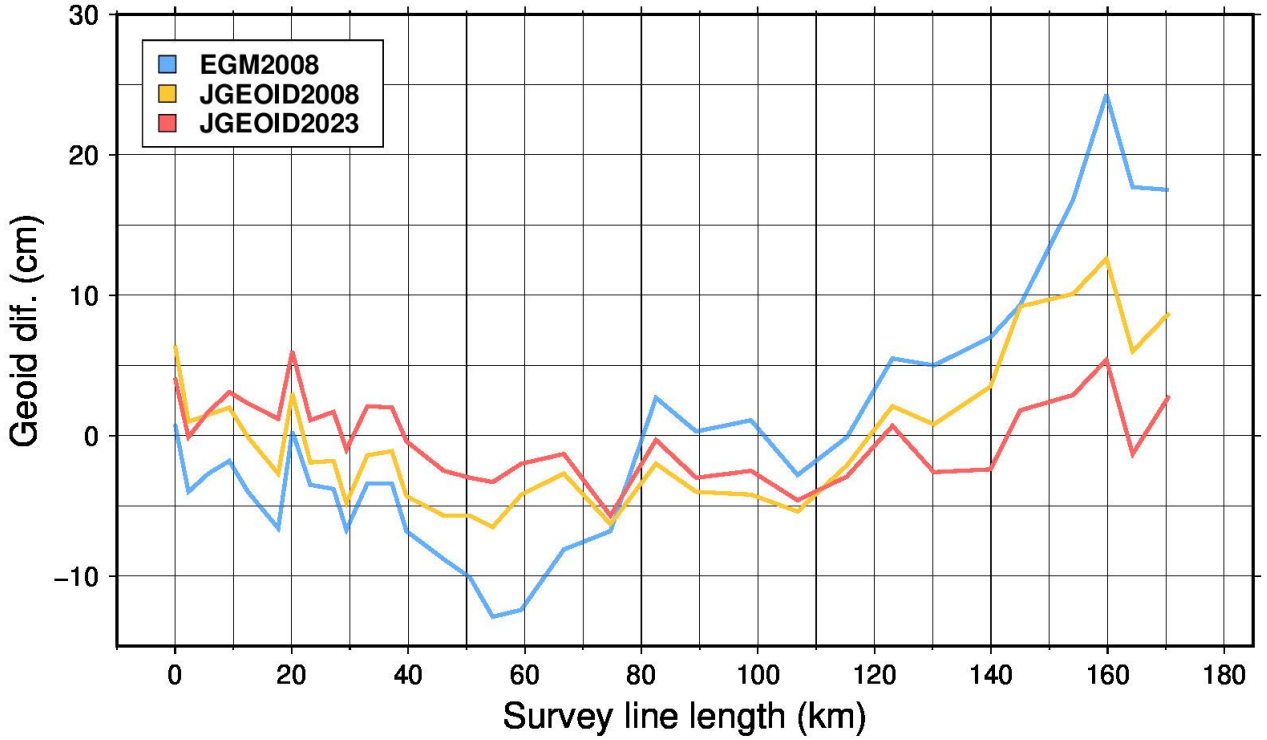


Geoid difference of -69.3 cm to +24.4 cm

Validation of geoid model

Geoid difference between models and results of GNSS/leveling survey



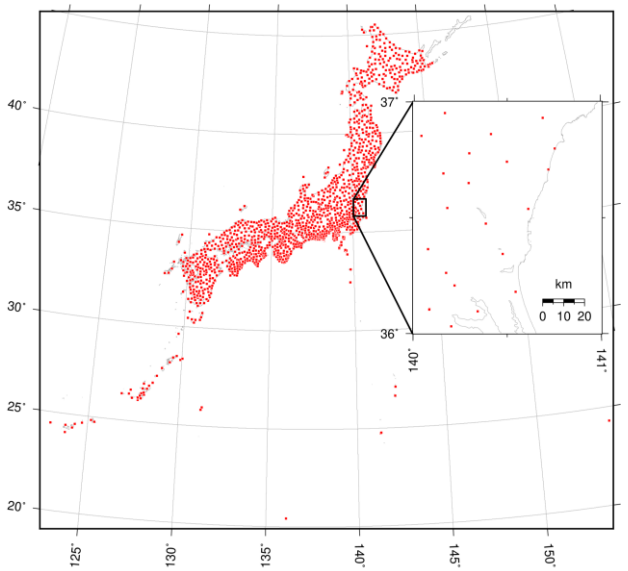


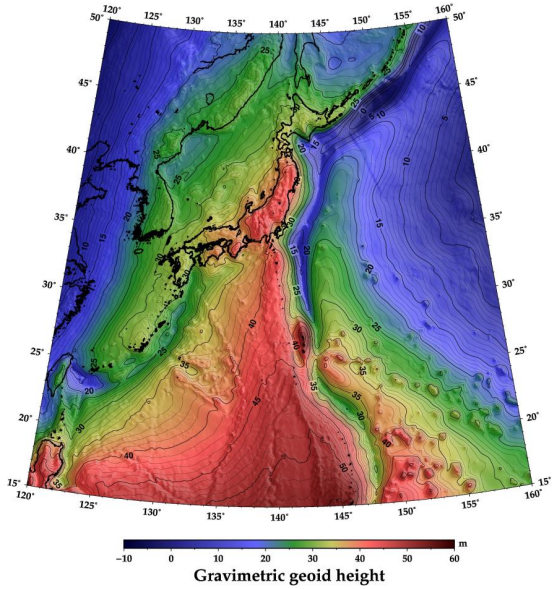
	EGM2008	JGEOID2008	JGEOID2023
STD (cm)	8.9	5.1	**2.5**

Revising the heights based on the geoid model

- Heights at GNSS CORSs are recalculated using their ellipsoidal heights and geoid heights
- Heights of benchmarks are revised based on the heights of GNSS CORSs
- The official heights are fixed at the reference epoch

- Both GNSS observation and leveling survey are available to measure heights in public survey





Summary

Current Horizontal Datum

- Maintained by space geodetic techniques
  GNSS CORSs + VLBI
- Two models for crustal deformation

Current Vertical Datum

- Maintained by leveling survey
- Remeasurement and revision for crustal deformation

- Airborne gravity survey project
- New gravimetric geoid model

Future Datum (20XX~)

- Mainly maintained by GNSS CORS network and the newly developed gravimetric geoid model
- Dealing with the crustal deformation using the deformation models