Case Study of Japan Vertical Reference Frame Challenge and future plan

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Contents

Motivation

- Current vertical datum in Japan
- Issues of current system

Geoid model for a new height system

- Refine a gravimetric geoid model for Japan
- Issue for further improvement

Airborne gravity measurement in Japan

- Current situation
- Schedule of measurements

Current Vertical Datum in Japan

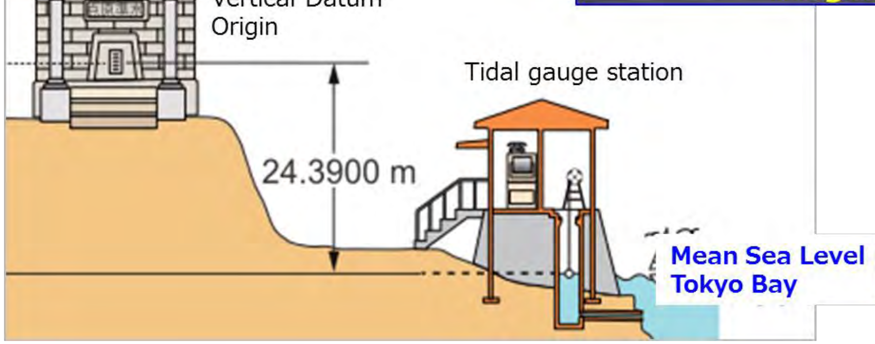
Definition of the height reference (0m) in Japan

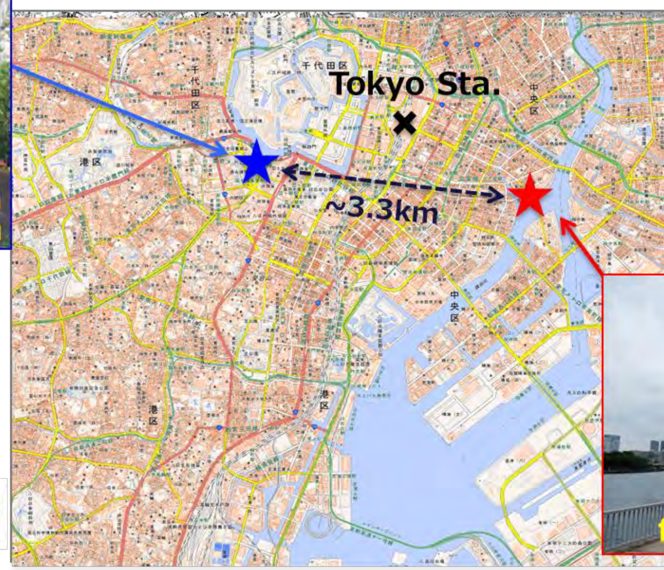
- Mean sea level of Tokyo Bay (tide data of 1873~1879)

Vertical Datum Origin of Japan

- Locates in the center of Tokyo. Built in May 1881.

Datum Value
24.500m (1881)
24.4140m (1923)
24.3900m (2011)



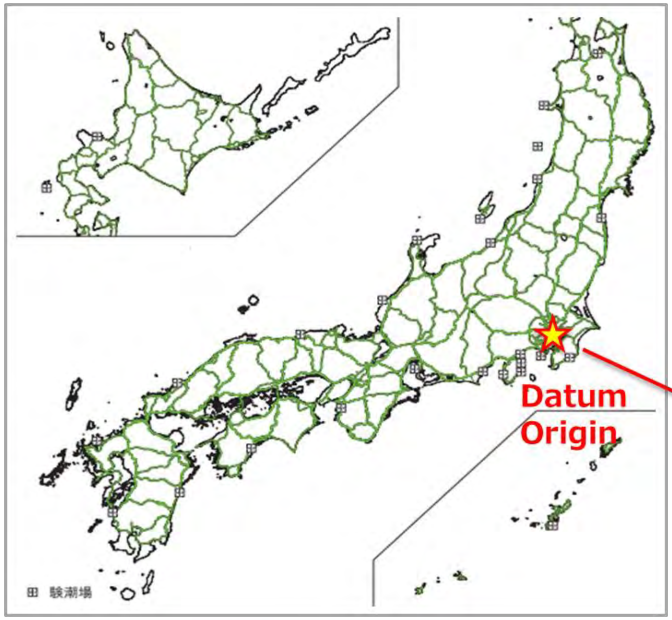


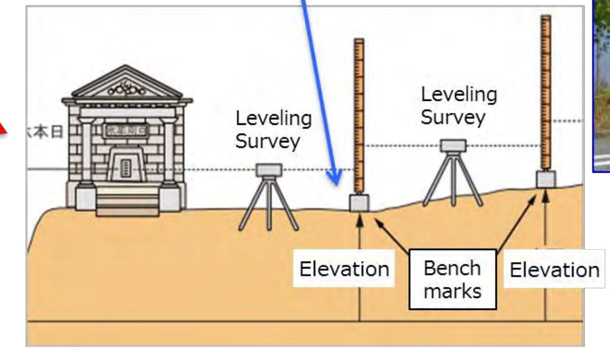
Current Vertical Datum in Japan

Realization of the Vertical Datum in Japan

- Maintained by conducting nationwide leveling survey routinely
- 17,000 benchmarks along 18,000km survey routes throughout Japan

Leveling routes (1st order)





Issues of Current Height System

1) Time consuming and expensive cost

- More than 10 years to cover the whole routes
- Costing $15M in total has been becoming a big burden for GSI

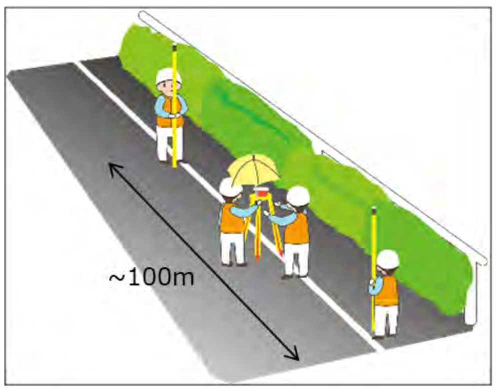
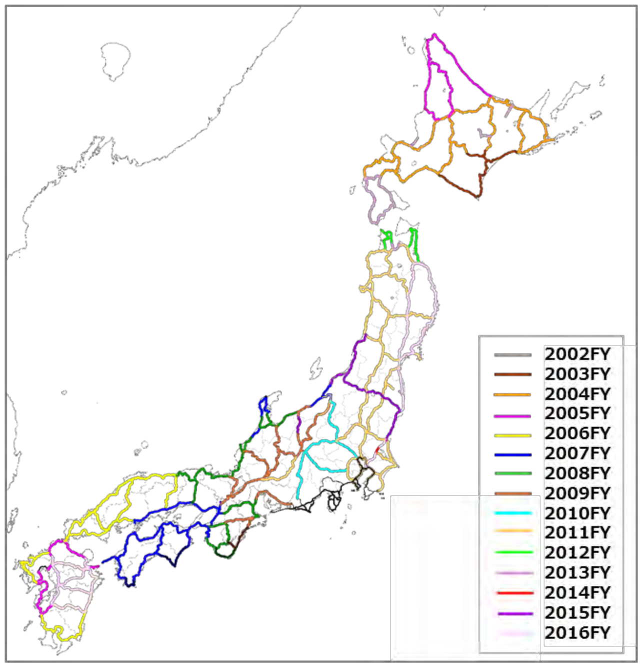
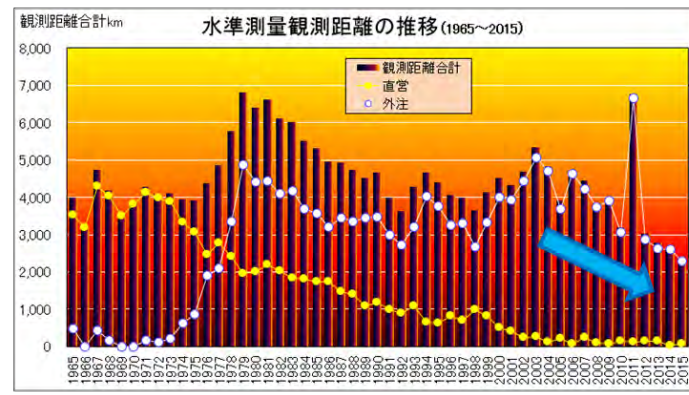


Image of leveling survey



Surveyed route in past year



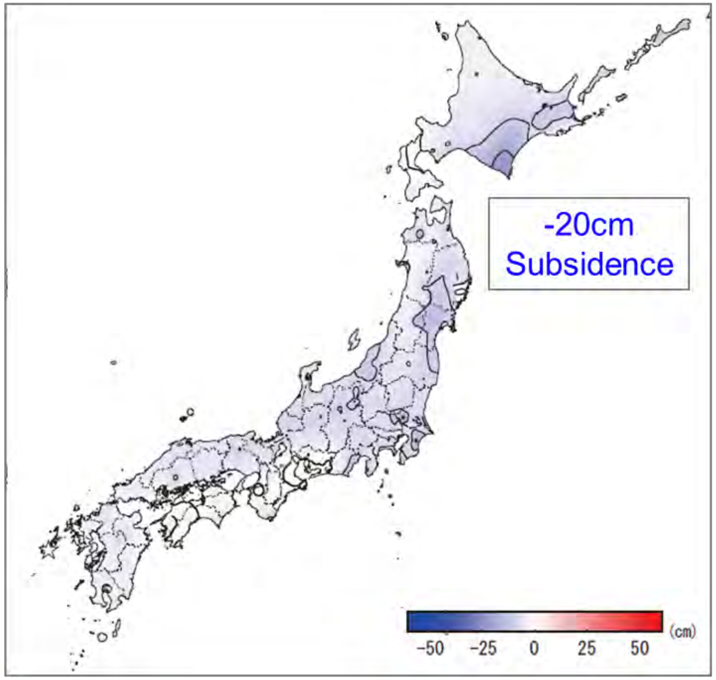
Survey distance for each year

Issues of Current Height System

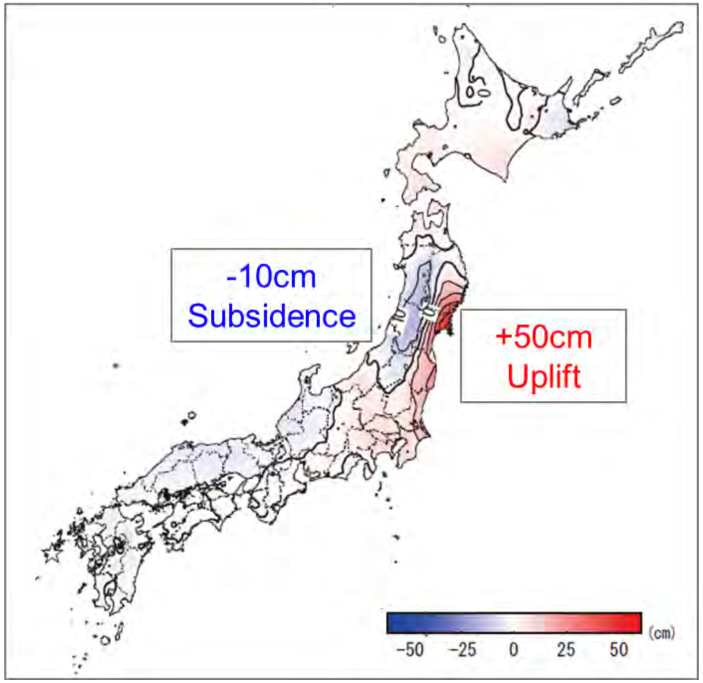
2) Effect of Crustal Deformation

- Crustal deformation is constantly occurring in Japan
- 10 years revision schedule is not enough to maintain accurate elevation

Vertical movement of **1997-2011**



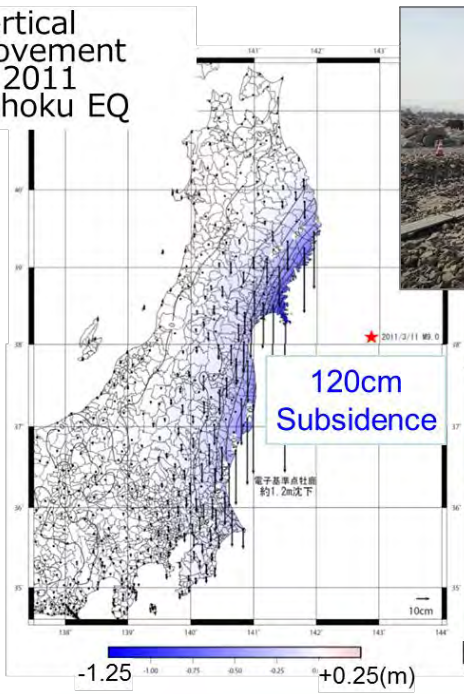
Vertical movement of **2011-2019**



Issues of Current Height System

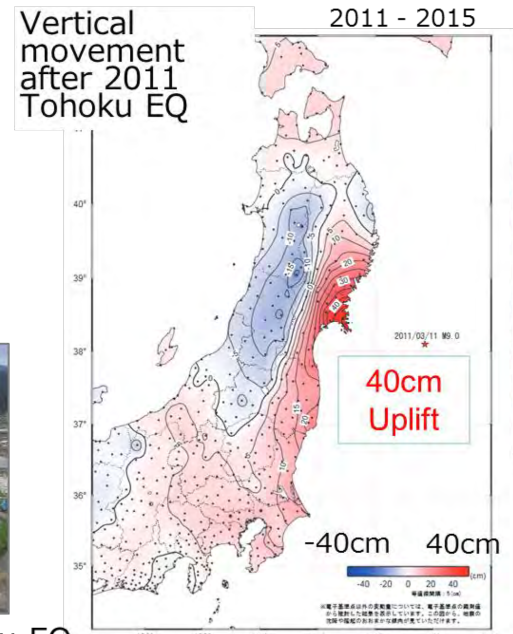
3) Difficulty of Quick Recovery from Disaster

- Elevation is very important for quick reconstruction after disasters
- Difficult to revise quickly by leveling (e.g. 7 mos. for 3,600km after 2011 Tohoku EQ)
- Post-seismic motion caused another issue (e.g. 40cm uplift 4 years after Tohoku EQ)



Destroyed embankment

Leveling after 2011 Tohoku EQ



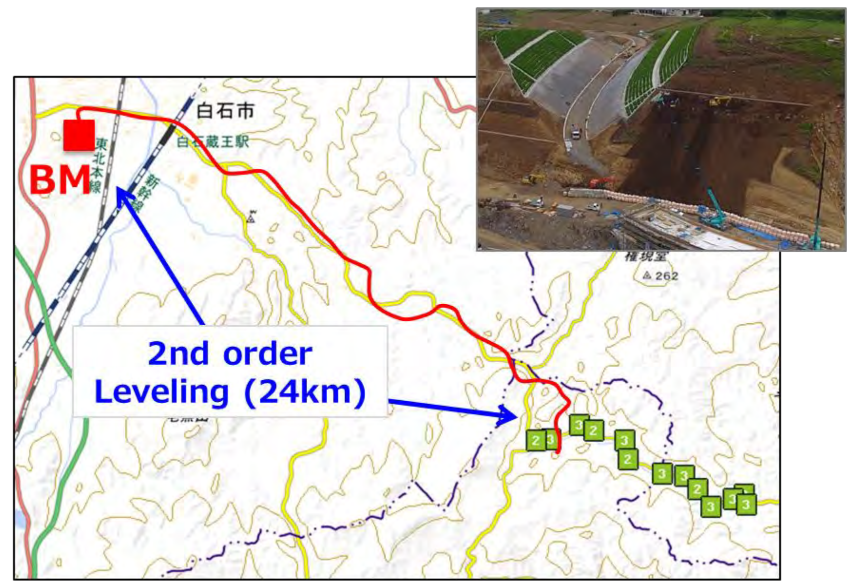
Quay at Miyagi Prefecture

Issues of Current Height System

4) Inconvenience of Users

- Users need an additional leveling survey for their purposes
- Large demand of utilize GNSS for determining the elevation

Altitude determination for dam construction



Altitude determination for road reconstruction

Vision of New Height System

Current Japanese height system (since 1883)

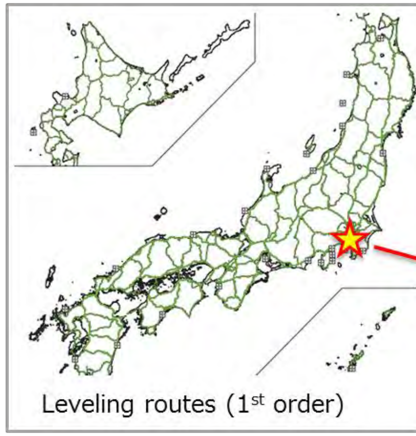
Leveling-based system

- Large cost, time consuming, labor intensive, disaster management, user unfriendly…

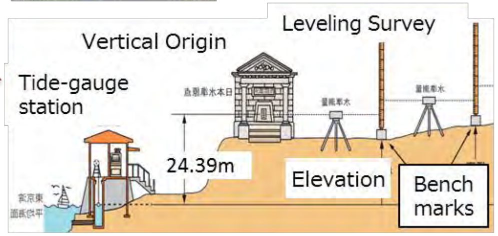
Future Japanese height system (planned from 2024)

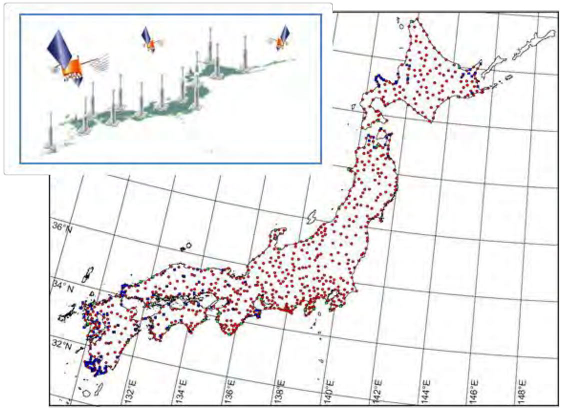
Geoid/GNSS-based system

- Cost effective, prompt, quick recovery, useful…
- Leveling for local surveys



Benchmark





Japanese GNSS CORS network (GEONET) consisting of ~1300 stations

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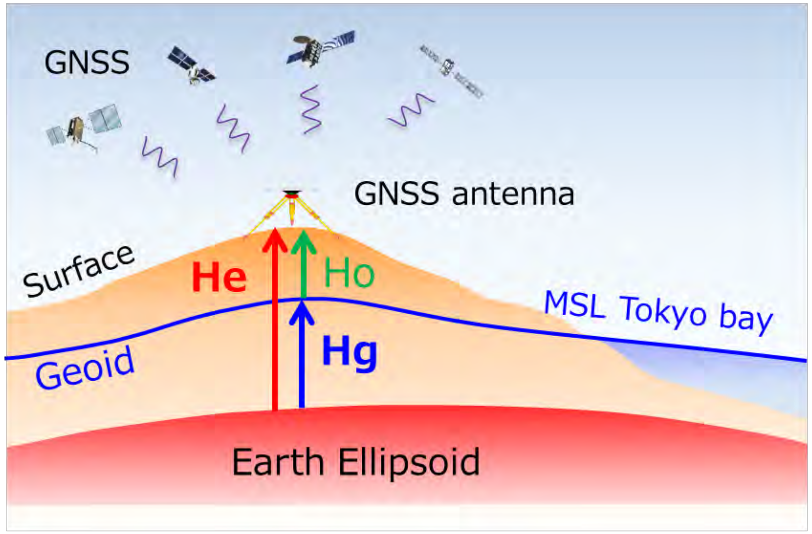
Airborne gravity measurement in Japan
- Current situation
- Schedule of measurements

Challenge for realizing a GNSS/Geoid-based system



Ho = He − Hg

Ho: Elevation (Orthometric Height)
He: Ellipsoidal Height
Hg: Geoid Height

GNSS provides **Ellipsoidal Height**
⇒ **about 1 cm accuracy**

Gravimetric geoid model provides **Geoid Height**
⇒ **about 8 cm accuracy so far in Japan**

Subtraction of **Geoid Height** from **Ellipsoidal Height** provides **Orthometric Height**
⇒ **about 8 cm accuracy**

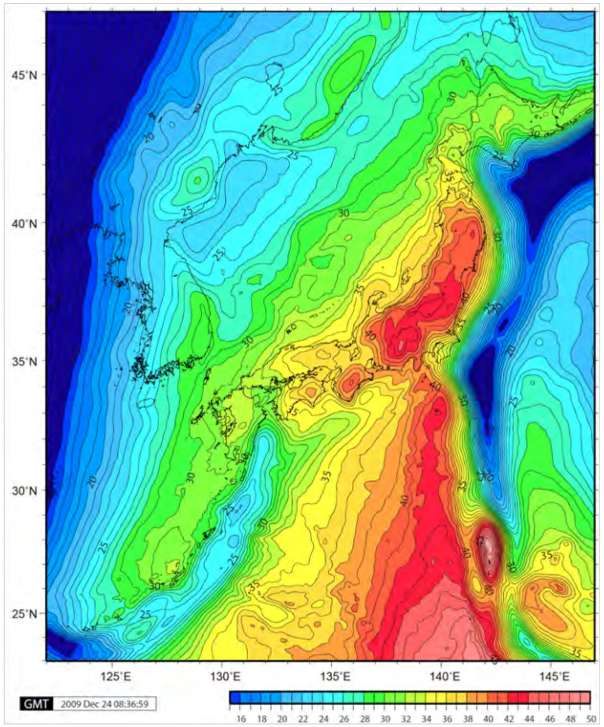
Target accuracy of **GNSS**/**Geoid**-based Orthometric Height is about 5cm
⇒ **about 3 cm accuracy** Geoid is necessary

More precise 'gravimetric' geoid model is necessary!!

Current gravimetric geoid model

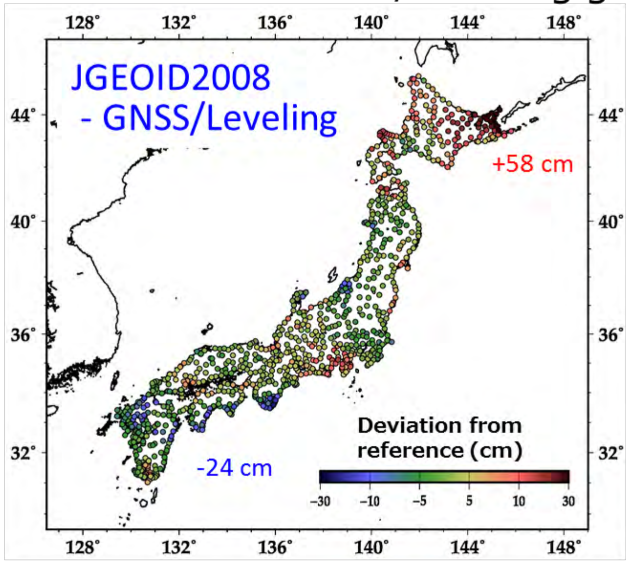
JGEOID2008 (Kuroishi, 2009)

- A current gravimetric geoid model released by GSI
- GRACE-based GGM (GGM02C) + EGM96 were used with land and marine gravity data



- 267,805 land and 579,186 marine gravity data
- GRACE satellite, GGM02C + EGM96 model (d/o 360)
- 250m grid DEM
- 2km resolution

The difference with GNSS/Leveling geoid



Average : **-22.53cm**
S.D. : **8.02cm**

Refinement of a gravimetric geoid model for Japan

Model	JGEOID2008	This study (Matsuo, under preparation)
Data		
Global Gravity Model	GGM02C/EGM96 (d/o 2~360)	XGM2016 (d/o 2~719) [Pail et al., 2017]
Land gravity data	268,805	315,876
Marine gravity data	KMS02 [Anderson & Knundsen, 1998] + 569,186 ship-borne data	SS v27.1 [Smith & Sandwell, 2019] + 2,825 ship-borne data
Digital Elevation Model	250 m grid	10 m grid
Computation method		
Gravity reduction	Stokes-Helmert method [Heiskanen & Moritz, 1967]	Stokes-Helmert method [Heiskanen & Moritz, 1967]
Terrain correction & Indirect Effect	Linear and planar approximation [Moritz, 1980]	Linear and planar approximation [Moritz, 1980]
Modification of Stokes' kernel	Meissl (1971)	Featherstone et al. (1998)
Residual terrain model	Not used	Indirectly used [Omang & Forsberg, 2000]
Numerical integration	1D spherical FFT	Direct integration (Newton-Cotes quadrature)

Computation of a gravimetric geoid model

Remove-Compute-Restore Stokes-Helmert Scheme

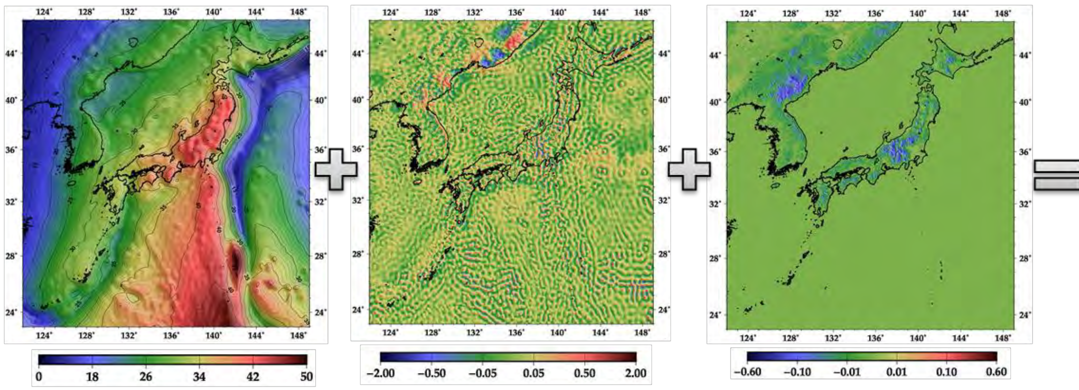
$$N = N_{GGM}^{Co} + N_{Res}^{Co} + N_{IDE}$$

N : geoid height

N_0^{Co} : cogeoid height

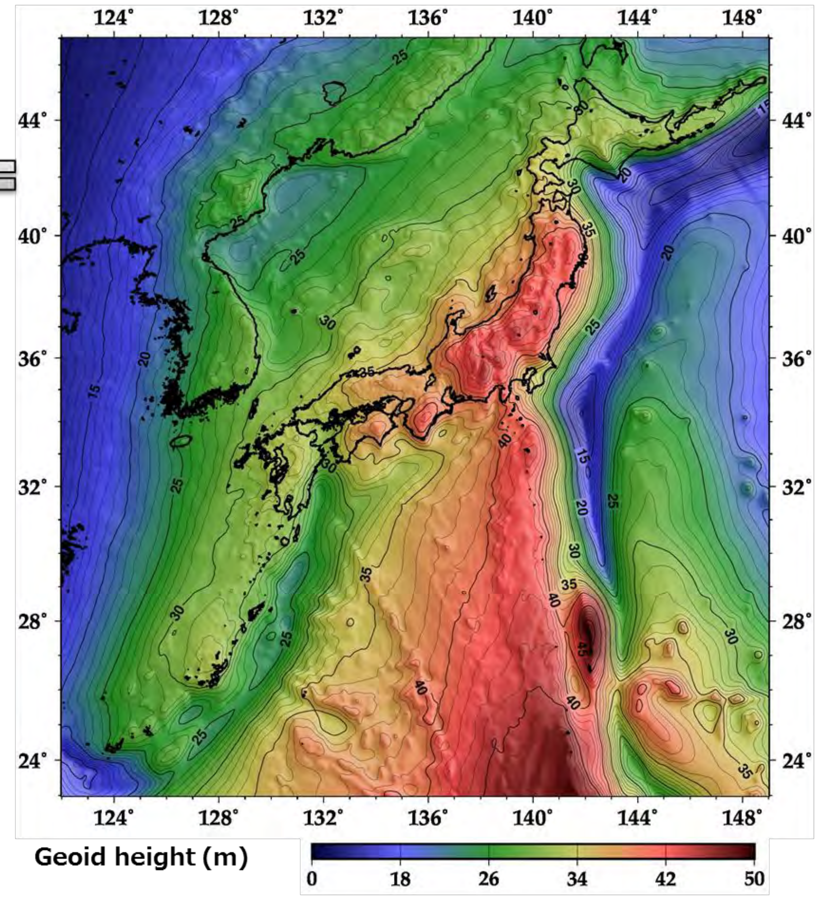
- N_{GGM}^{Co} : **GGM**-derived cogeoid height
  ⇒ Long to medium wavelength components of geoid undulation
- N_{Res}^{Co} : Residual cogeoid height derived from **terrestrial gravity, GGM, and DEM**
  ⇒ Medium to short wavelength components of geoid undulation
- N_{IDE} : Indirect effect derived from **DEM**
  ⇒ Conversion of cogeoid height to geoid height

A new experimental gravimetric geoid model for Japan



Cogeoid height (m) | Cogeoid height (m) | Geoid - Cogeoid (m)

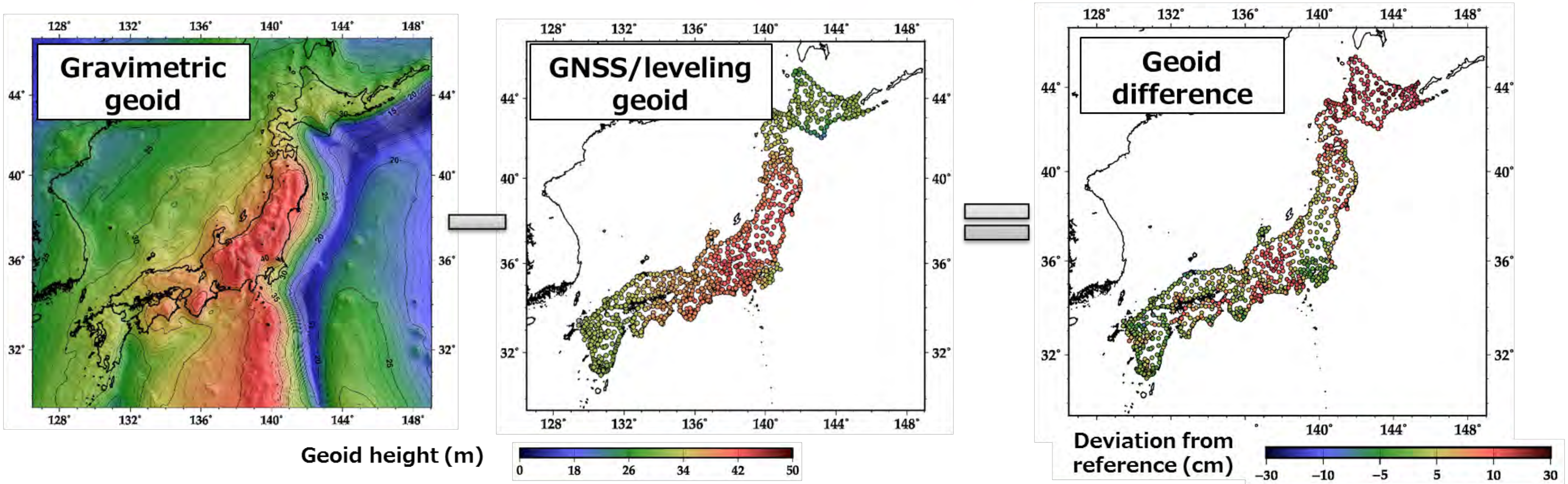
	Statistics of N over the Japanese islands
Max.	49.489 m
Min.	20.393 m
Mean	36.590 m
SD	4.606 m



Geoid height (m)

Developed without airborne gravity data

Evaluation of the gravimetric geoid model

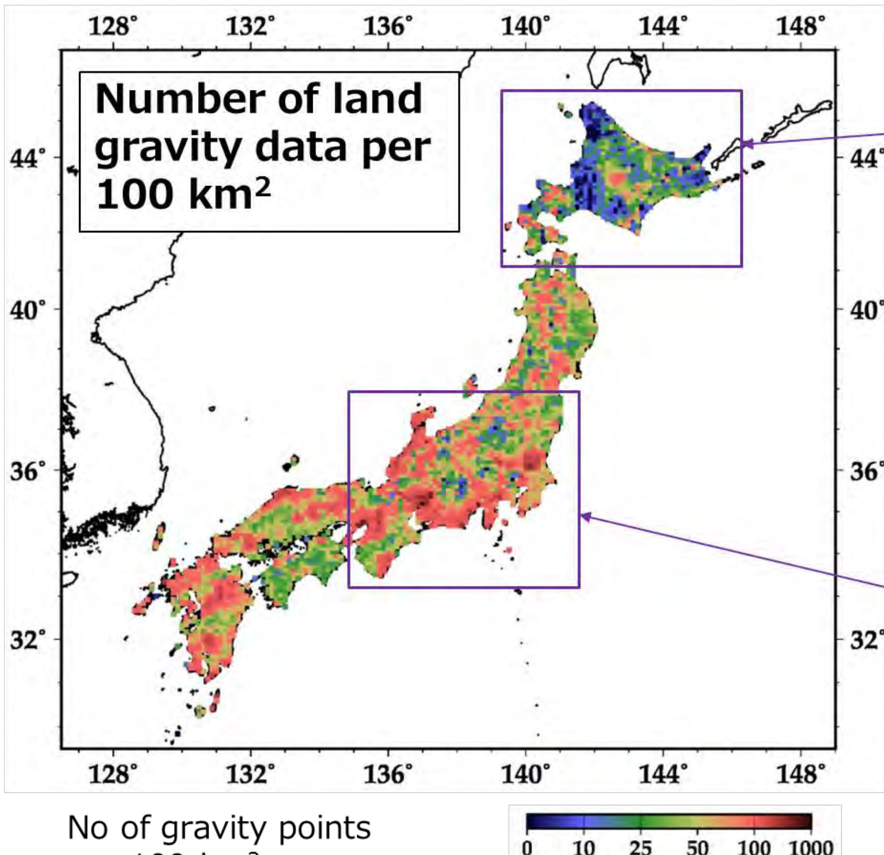


Gravimetric geoid model	Mean dif. (cm)	S.D. (cm)
JGEOID2008	- 22.53 (W0 = IERS2003)	8.02
This study (Matsuo)	5.01 (W0 = IAG2015)	5.75

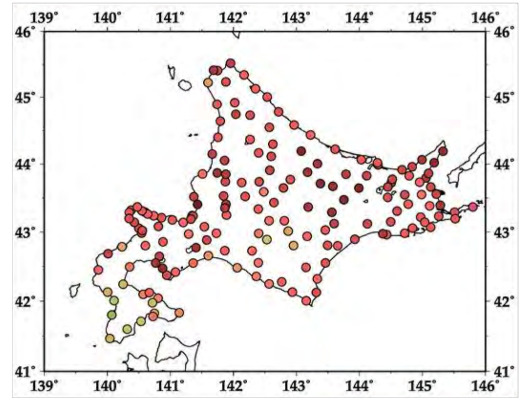
※ reference: Mean sea surface height at Tokyo bay

Improvement of 2.27 cm compared with JGEOID2008

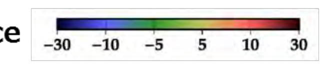
Brief discussion on geoid difference

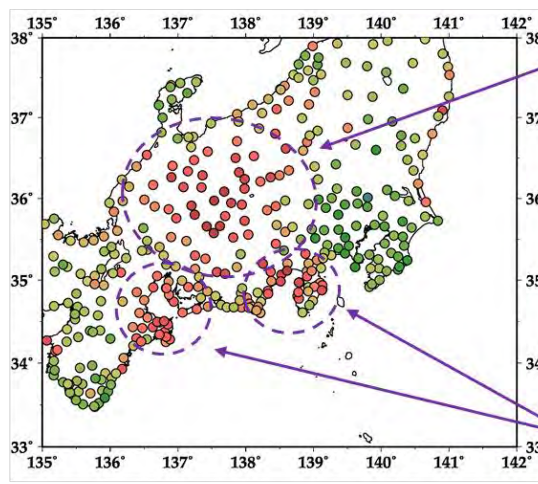


No of gravity points per 100 km²



Large differences in areas with sparse gravity data



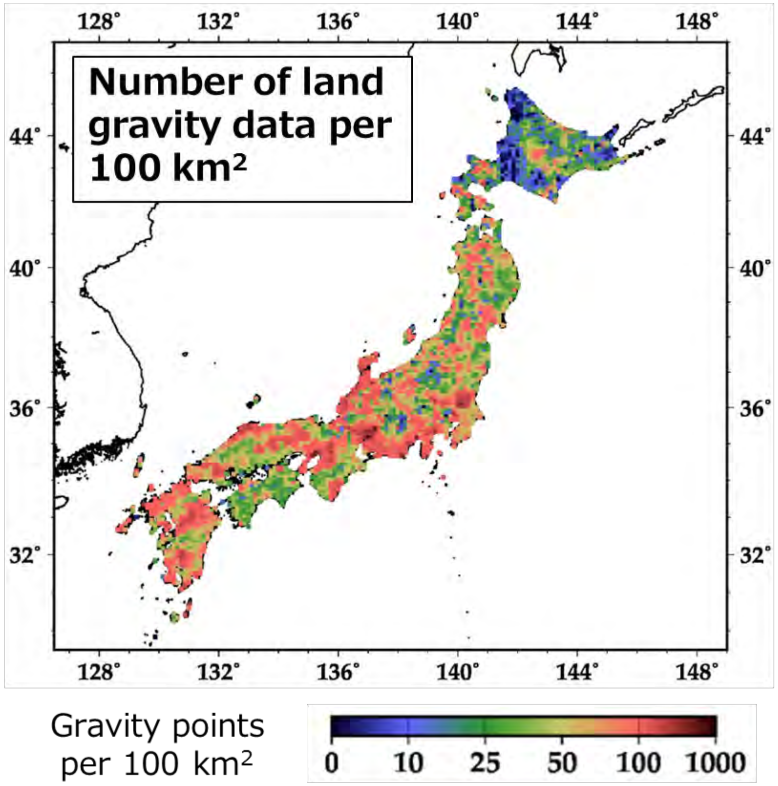


Large differences in mountainous areas

Large differences along shorelines of inland seas

Gravity data in Japan

- **Over 300,000 land gravity data are available**
  - Including other institutions, universities, etc.
- **But their quality is doubtful**
  - Most collected in 70~80's
  - No absolute gravimeter
  - No GNSS (poor coordinate accuracy)
  - Effect of several large earthquakes
  - Few data in mountainous & coastal areas



How to collect high quality gravity data in short time?

Resolution :

Airborne Gravity Survey

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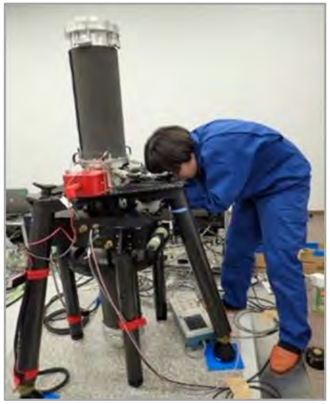
Schedule for airborne gravity surveys

2017 → 2018 → 2019 → 2020 → 2021 → 2022 → 2023 → 2024

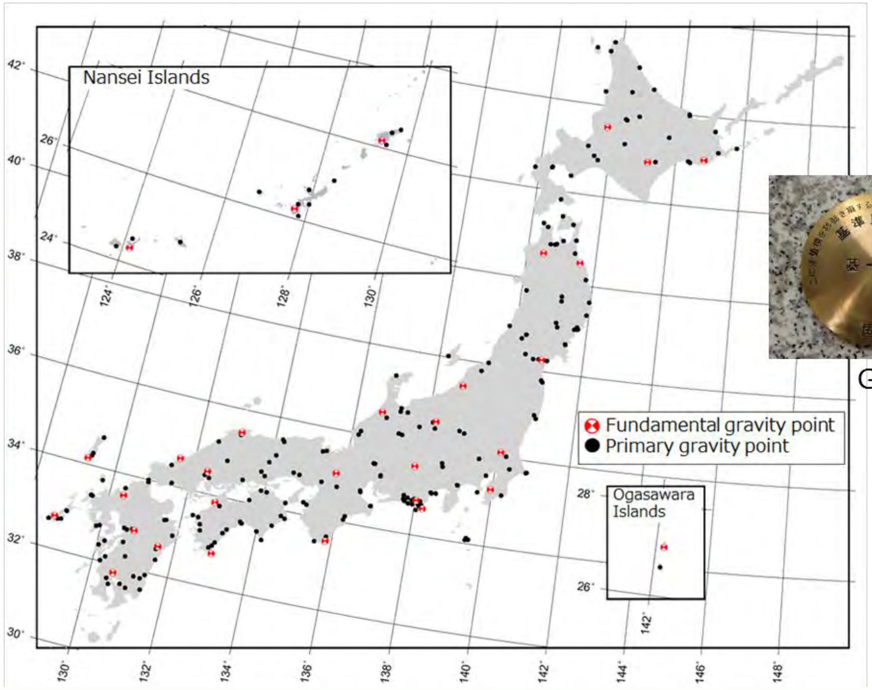
Release a new gravity standards net in Japan (JGSN2016)

- Based on absolute gravity values measured after the 2011 Tohoku EQ
- Utilized as reference values for the airborne gravity surveys



Absolute Gravity Measurement (FG5)

Relative Gravity Measurement (La-Coste)



Gravity Point

Schedule for airborne gravity surveys

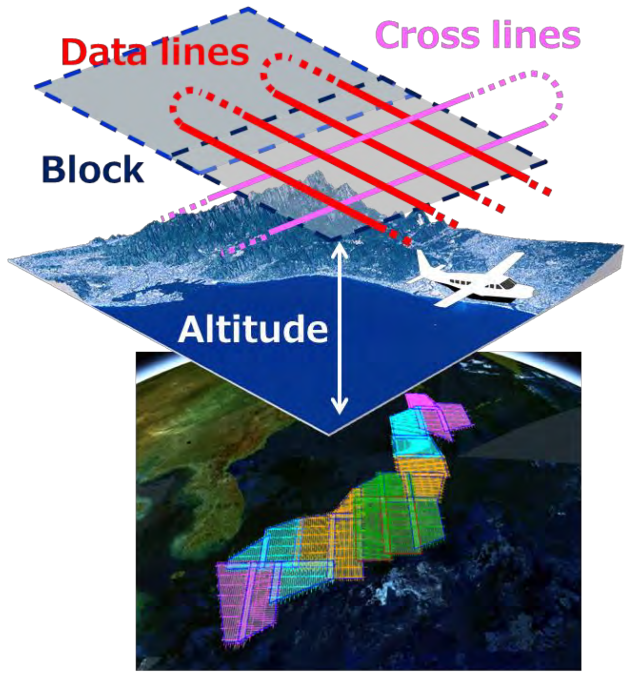
2018 → 2019 → 2020 → 2021 → 2022 → 2023 → 2024

Preparation for airborne gravity measurements

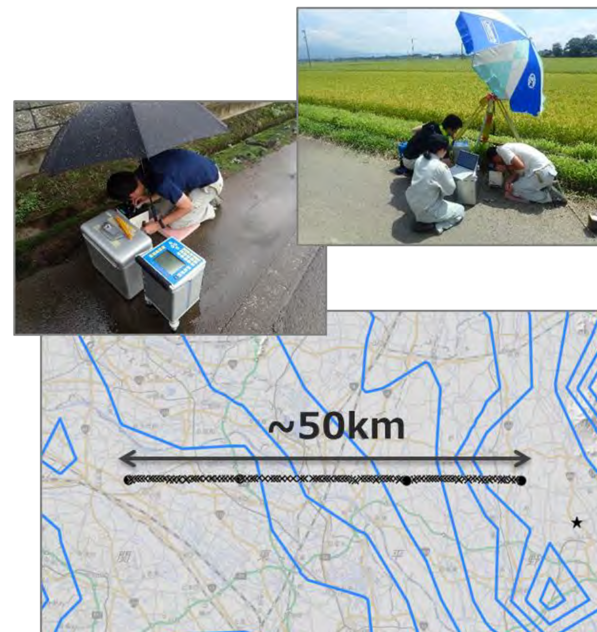
- Equipment, flight lines, a terrestrial calibration line, survey manuals, etc...

Airborne gravimeter:
TAGS-7 (Micro-g LaCoste Inc.)
*TAGS : Turnkey Airborne Gravity System

TAGS-7 meter reached on Dec. 10th



Flight lines



Terrestrial calibration line

Schedule for airborne gravity surveys

2018 → 2019 → 2020 → 2021 → 2022 → 2023 → 2024

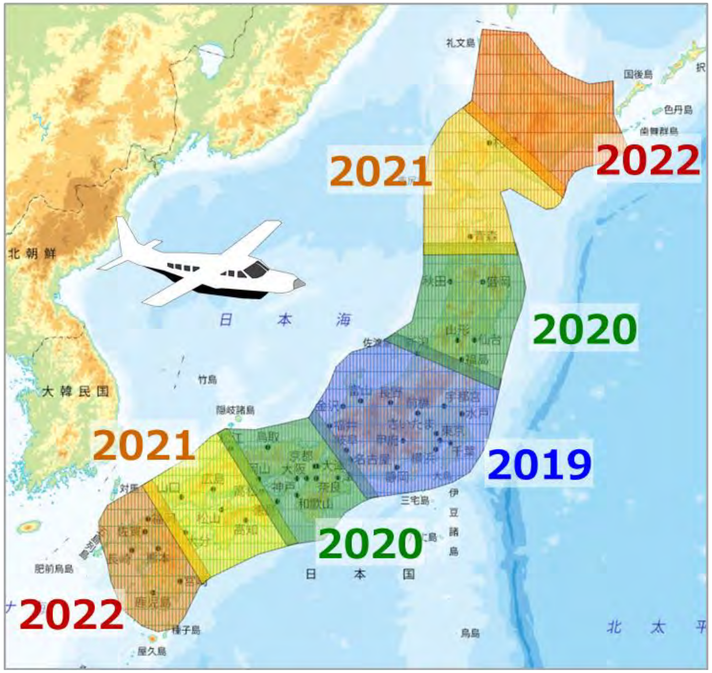
Conduct airborne gravity surveys over Japan

- Cover main land and coastal sea area in 4 years
- Publish collected gravity data and a beta version of geoid model every year

Survey design

Area : Main land and coastal area (~40km)
Data lines : Spaced 10km apart
Cross lines : Spaced 50km apart
Altitude : 3,000m over normal area
5,000m over Japan Alps
Aircraft : Cessna 208b Caravan
Speed : 250km/h
Line length : ~90,000km

Accuracy Target : 1mgal



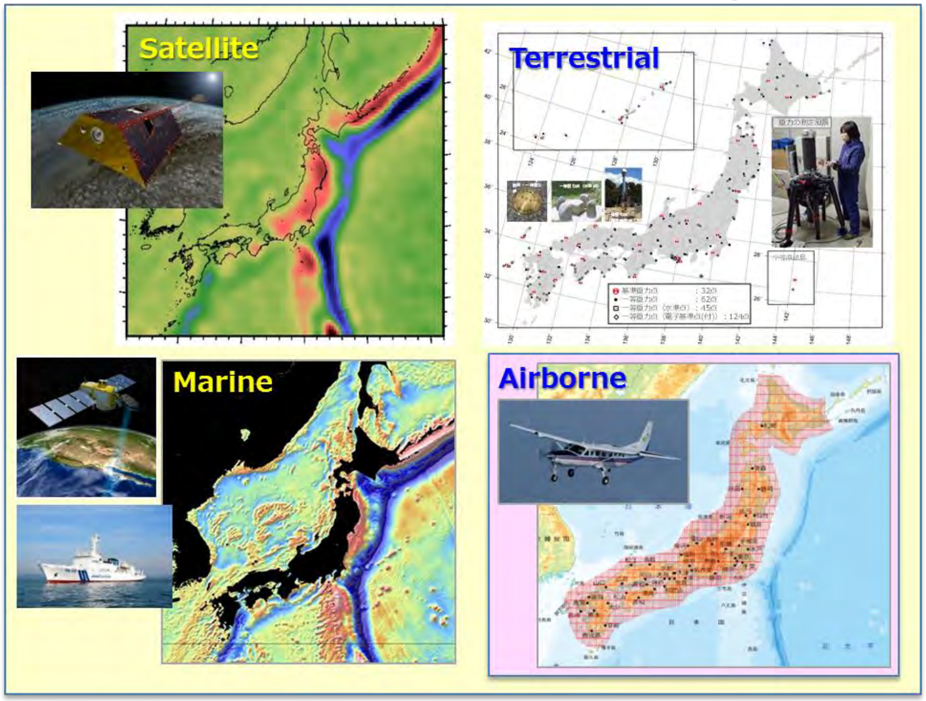
Schedule for airborne gravity surveys

2018 – 2019 – 2020 – 2021 – 2022 – **2023** → 2024

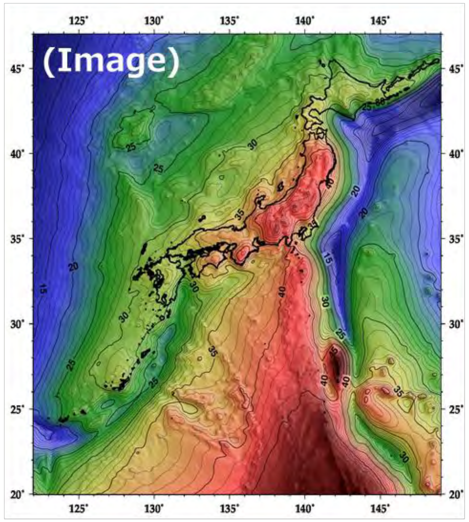
Prepare for starting the new height system

- Calculate the final geoid model
- Make rules how to utilize the new system

Input Gravity Data



Final Gravimetric geoid model



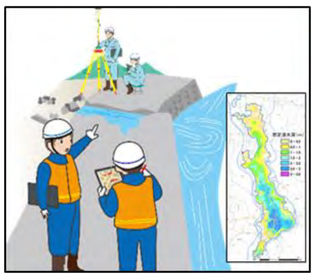
Accuracy Target: 3cm

Schedule for airborne gravity surveys

2018 → 2019 → 2020 → 2021 → 2022 → 2023 → **2024**

Start the new height system

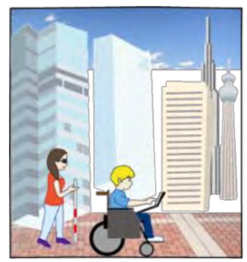
- Based on the precise geoid model and GNSS
- Expect to stimulate new services using real-time ‘3D’ positioning data



Disaster response

Navigation

UAV



Support

Transportation

Construction

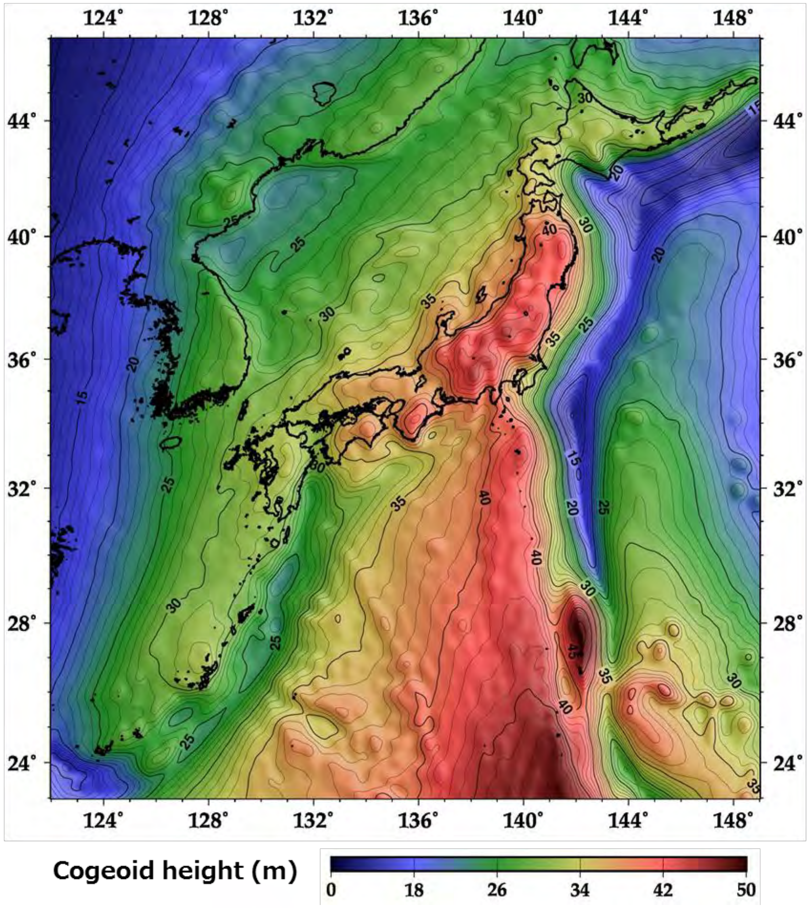
Agriculture

Summary

- GSI is considering to shift to Geoid/GNSS based height system which is more cost effective, prompt in disaster response, user-friendly than.
- For preparation to the shift, GSI has developed a new experimental gravimetric geoid model based on the Remove-Compute-Restore Stokes-Helmert Scheme.
- A new geoid model is consistent with GNSS/leveling with a standard deviation of 5.75 cm, which is 2.27 cm better than the current model (JGEOID2008)
- Large discrepancies between the geoid and GNSS/leveling were found in areas with sparse or poor-quality gravity data (Hokkaido, mountainous regions, and shoreline along inland sea areas).
- In order to further improve the gravimetric geoid model and realize accurate Geoid/GNSS-based vertical datum, we are planning to conduct airborne gravity surveys over the Japanese archipelago from 2019 to 2022.

Backup slides

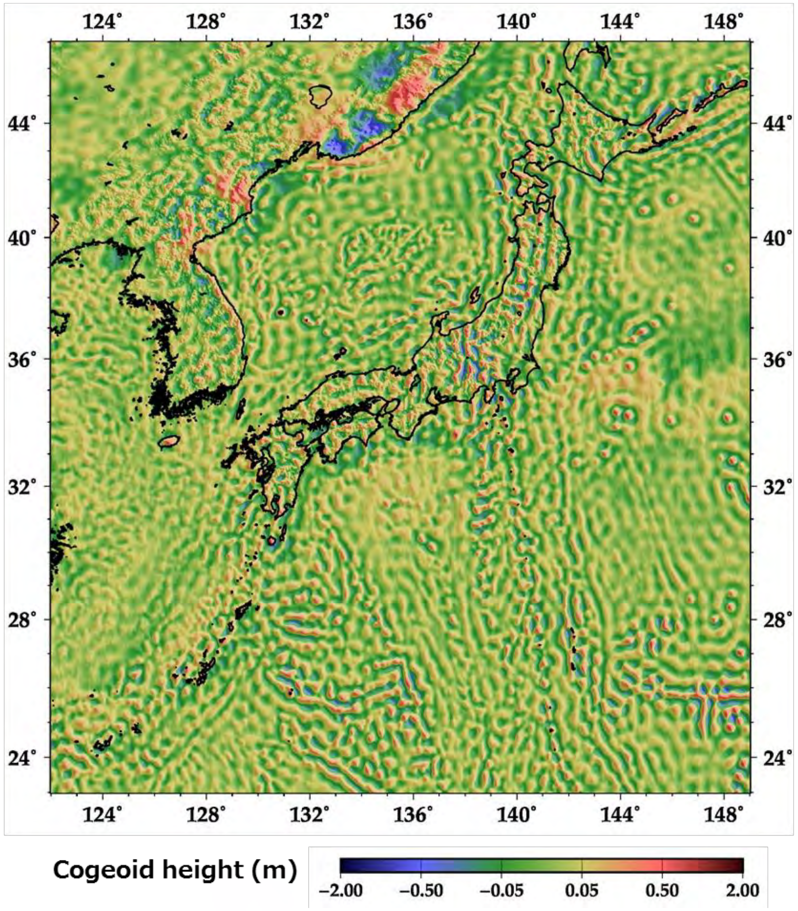
GGM-derived cogeoid height



- XGM2016 model (d/o 2~719)
- GRS80 system
- Tide-free system
- W0 value from IAG2015 (62,636,853.4 m^2/s^2)

	Statistics of N_{GGM}^{Co} over the Japanese islands
Max.	49.350 m
Min.	20.559 m
Mean	36.561 m
SD	4.622 m

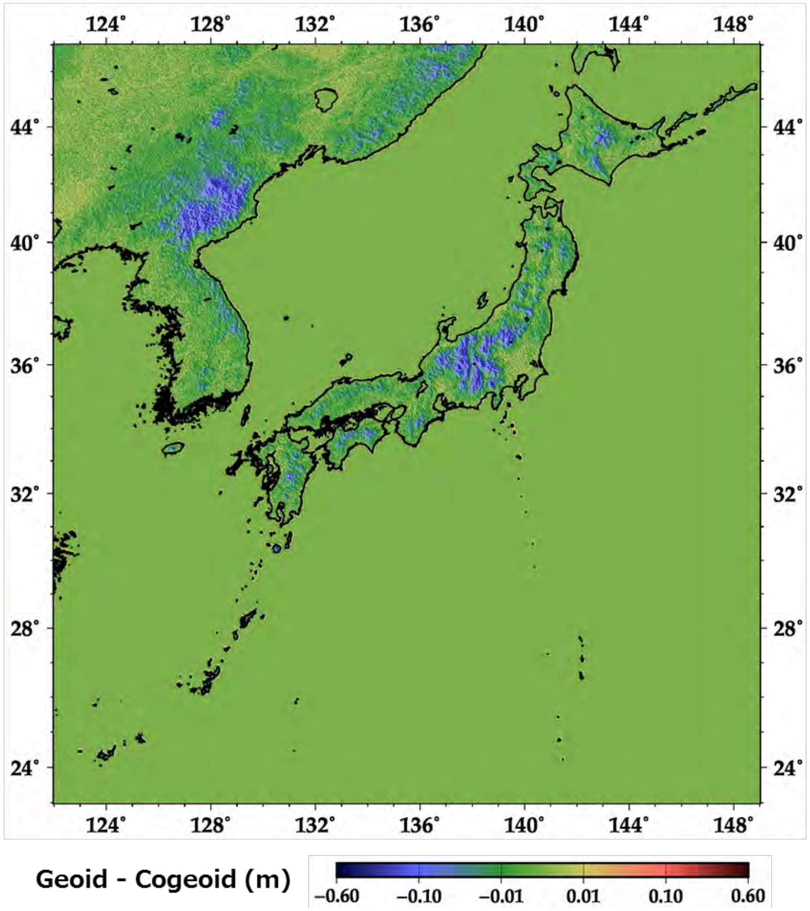
Residual cogeoid height



- 315,876 land + 2,825 shipborne gravity data
- SS v27 marine gravity model
- 10 m-mesh DEM over Japanese islands
  250 m-mesh DEM over other regions
- EGM2008 fill-in over other regions

	Statistics of N_{Res}^{Co} over the Japanese island
Max.	0.912 m
Min.	-0.515 m
Mean	0.046 m
SD	0.126 m

Indirect effect



- 2 km-mesh DEM
  (consistent with spatial resolution of the gravimetric geoid model)
- Linear and planer approximation
  (consistent with gravimetric terrain correction)

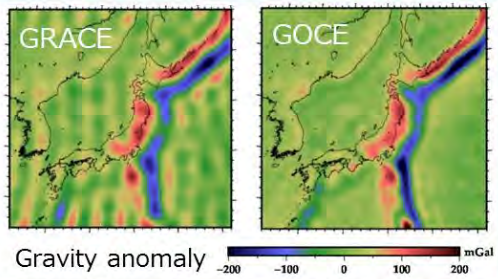
	Statistics of N_{IDE} over the Japanese islands
Max.	0.010 m
Min.	-0.546 m
Mean	-0.017 m
SD	0.034 m

Update of data

➢ Satellite gravity data

- Early GRACE-based GGM (GGM02C)
  ⇒ Latest GOCE-based GGM (GOCO05S)

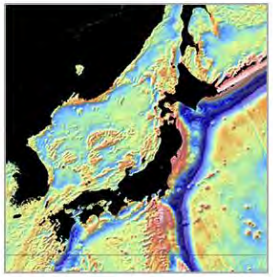
➡ **Improvement in long wavelength components**



➢ Marine gravity model

- Old altimetry-based model (KMS02)
  ⇒ Latest altimetry-based model (SS27.1)

Model	Accuracy
KMS02	5.20 mGal
SS21.1	3.01 mGal

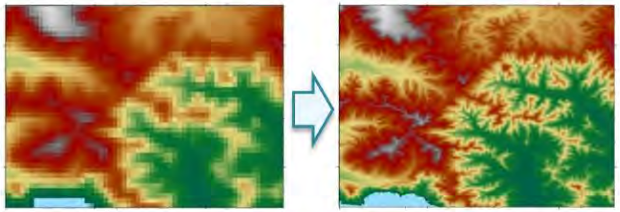


➡ **Improvement over ocean areas and along coastal areas**

➢ Digital Elevation Model (DEM)

- 250m mesh DEM ⇒ 10m mesh DEM
  → enabling accurate gravity reduction

➡ **Improvement in short wavelength components**



Improvement of computation method

➢ Modification of Stokes' integral kernel

- Meissl's modification [Meissl, 1971]
  ⇒ FEO modification [Featherstone et al., 1998]

➡ **Improvement mainly in long wavelength components**

➢ Numerical Integration

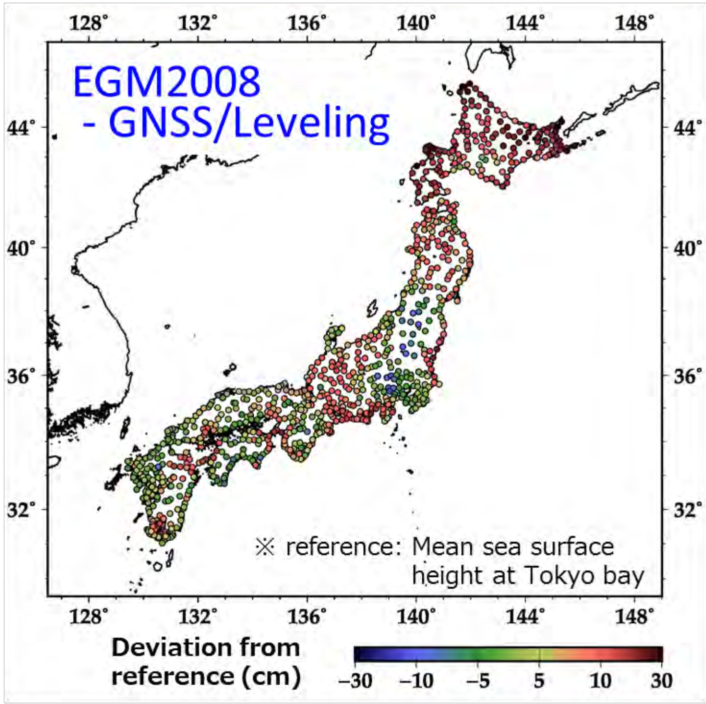
- 1D spherical FFT
  ⇒ Direct integration (Newton-Cotes quadrature)

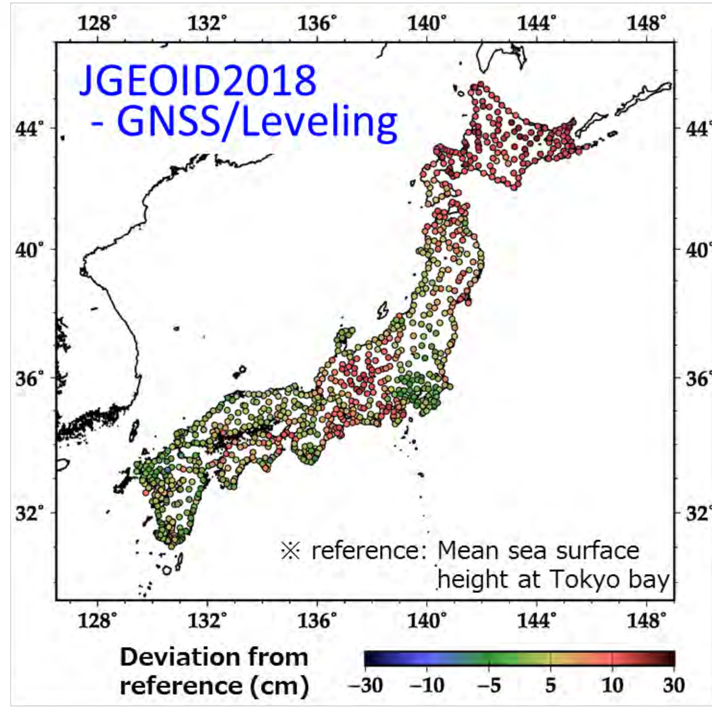
➡ **Improvement mainly in mid to short wavelength components**

➢ Introduction of Residual Terrain Model

➡ **Improvement in short wavelength components**

Geoid difference of EGM08 and JGEOID2018 with GNSS/leveling geoid





Gravimetric geoid model	Mean dif. (cm)	S.D. (cm)
EGM2008	2.25	7.99
JGEOID2018	5.01	5.75