Variations of Water Vapor Observed with a Hyper-Dense GNSS Network

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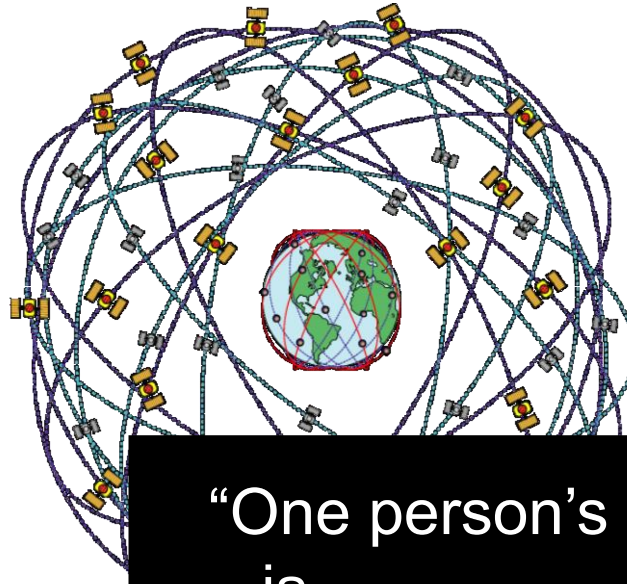
Brief overview of GNSS Meteorology

- Ground-based water vapor (PWV) measurements
- GNSS Radio Occultation (RO)

Hyper-dense GNSS network for PWV measurement

- Horizontal distribution of PWV
- A proposal of a real-time severe weather warning system

GNSS Meteorology



"One person's NOISE
is
another's SIGNAL"

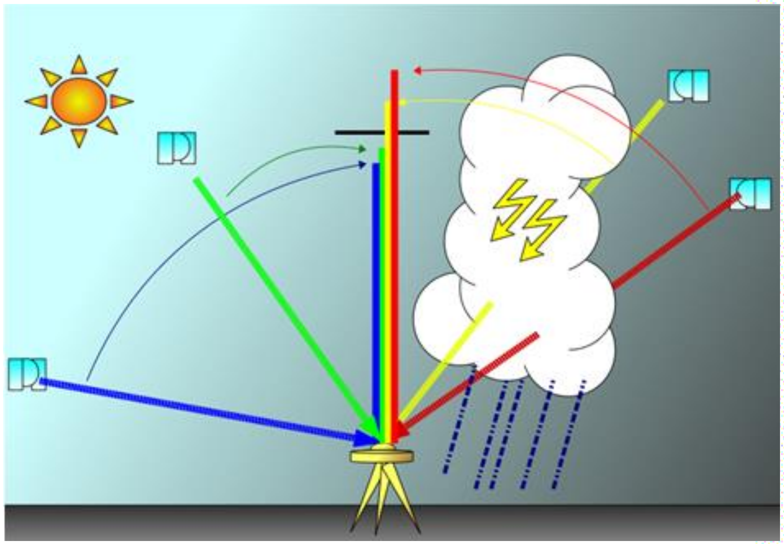
Accuracy of GNSS positioning
- code: a few m
- carrier phase: 1 mm

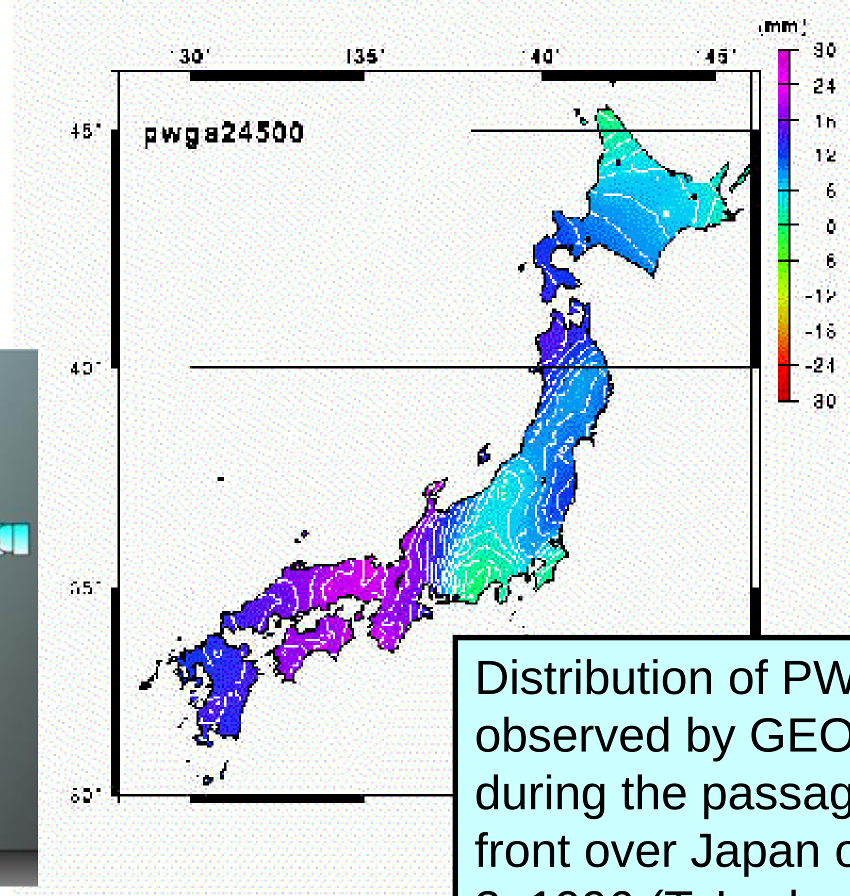
The ultimate accuracy of GNSS is determined by the propagation delay in the atmosphere.

GNSS Meteorology

The GNSS wet delays, estimated as by-products of accurate positioning, has been used for meteorological purposes through the assimilation into Numerical Weather Prediction (NWP) models.

Ground-base GNSS Meteorology





Distribution of PWV was observed by GEONET during the passage of a front over Japan on Sep.1–3, 1996 (T. Iwabuchi)

- ✓ The propagation delay of GNSS radio waves occurs due to the effects by the refractivity in the atmosphere and ionosphere.
- ✓ Integrated amount of water vapor (Precipitable Water Vapor; PWV) can be determined by mapping the atmospheric wet delay onto the zenith direction, assuming horizontal homogeneity of water vapor distribution.
- ✓ Total electron content (TEC) in the ionosphere can also be delineated.

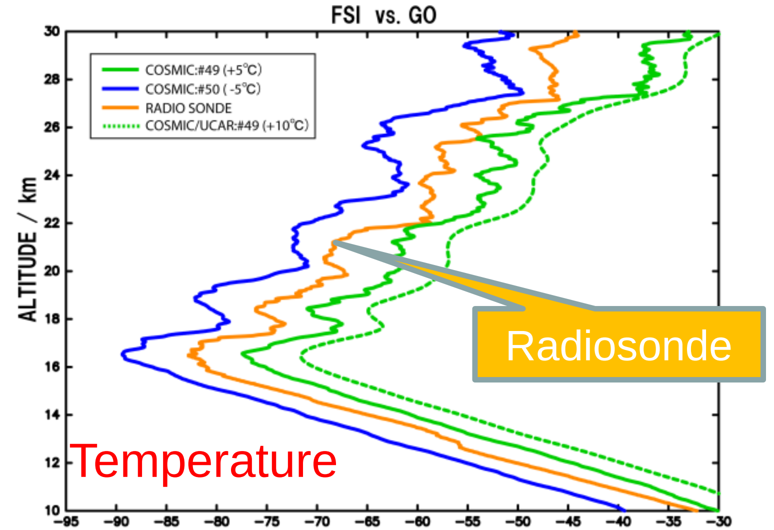
GNSS Radio Occultation (RO)

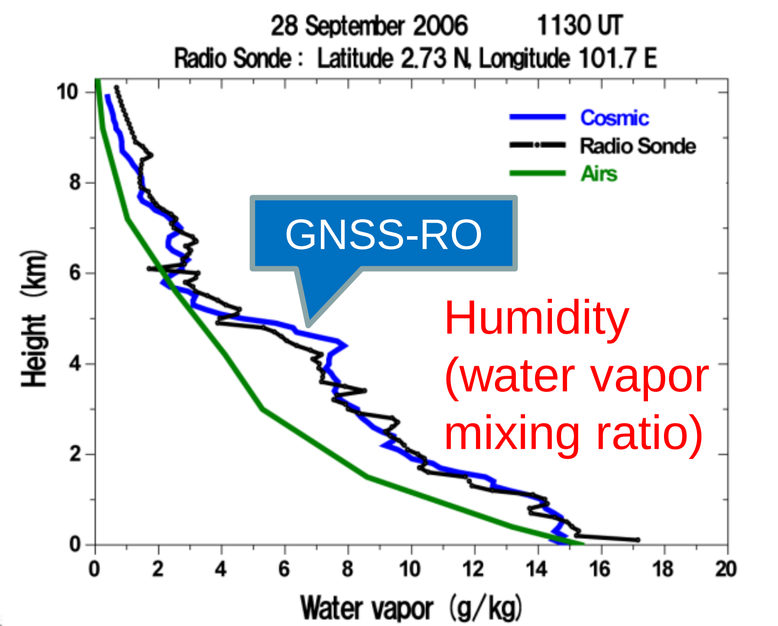
GNSS signals are received by a low-Earth orbiting (LEO) satellite.

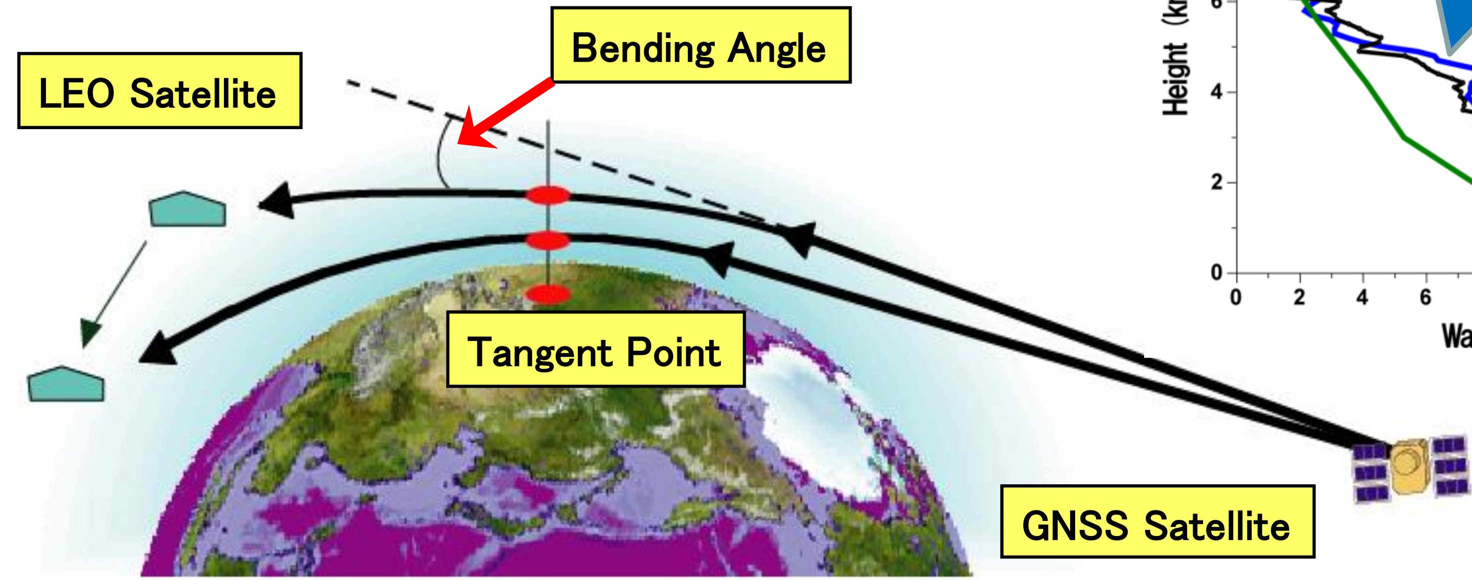
During setting/rising of a GNSS satellite, the radio rays successively scan the atmosphere (radio occultation).

From the ray bending angles, the refractive index profile can be retrieved.

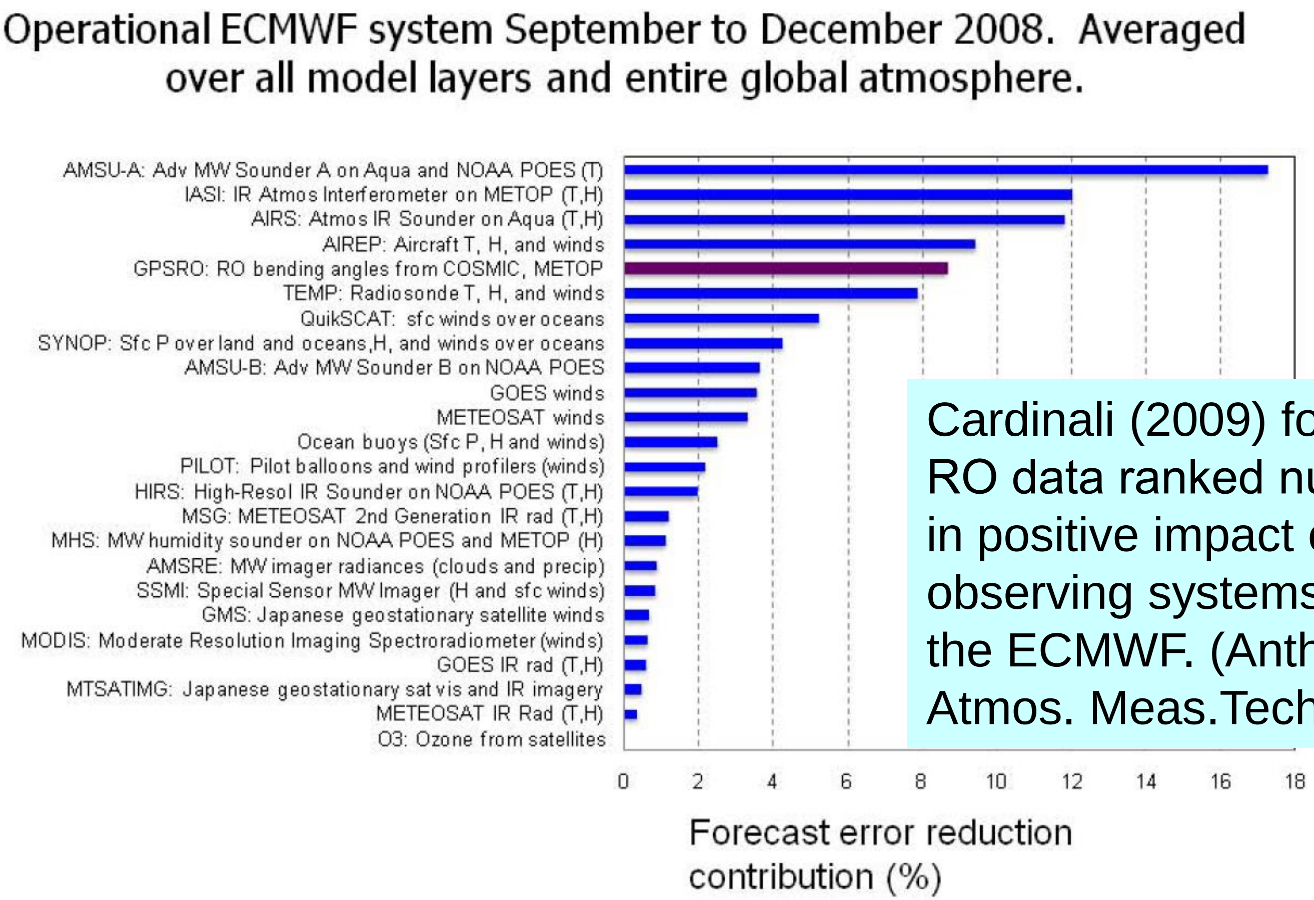
Profiles of temperature and humidity are further retrieved with the height resolution and accuracy comparable to a balloon sounding (radiosonde).







- ✓ The GNSS-PWV data is assimilated into numerical weather prediction (NWP) models at a meteorological agency.
- ✓ GNSS-RO is alos assimilated into global and meso-scale NWP models, showing great impacts on typhoon development and severe rainfalls.



Cardinali (2009) found that RO data ranked number five in positive impact of all the 24 observing systems used by the ECMWF. (Anthes, 2011, Atmos. Meas.Tech.)

Fig. 30. Contribution to the reduction in forecast error (in percent) by all the observing systems used by the ECMWF. RO is the fifth most important observing system in reducing forecast error (Cardinali, 2009a, b).

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Extreme weather and hazards

A severe rain event occurred about 30 minutes after formation of clouds with a horizontal scale of several kilometers.

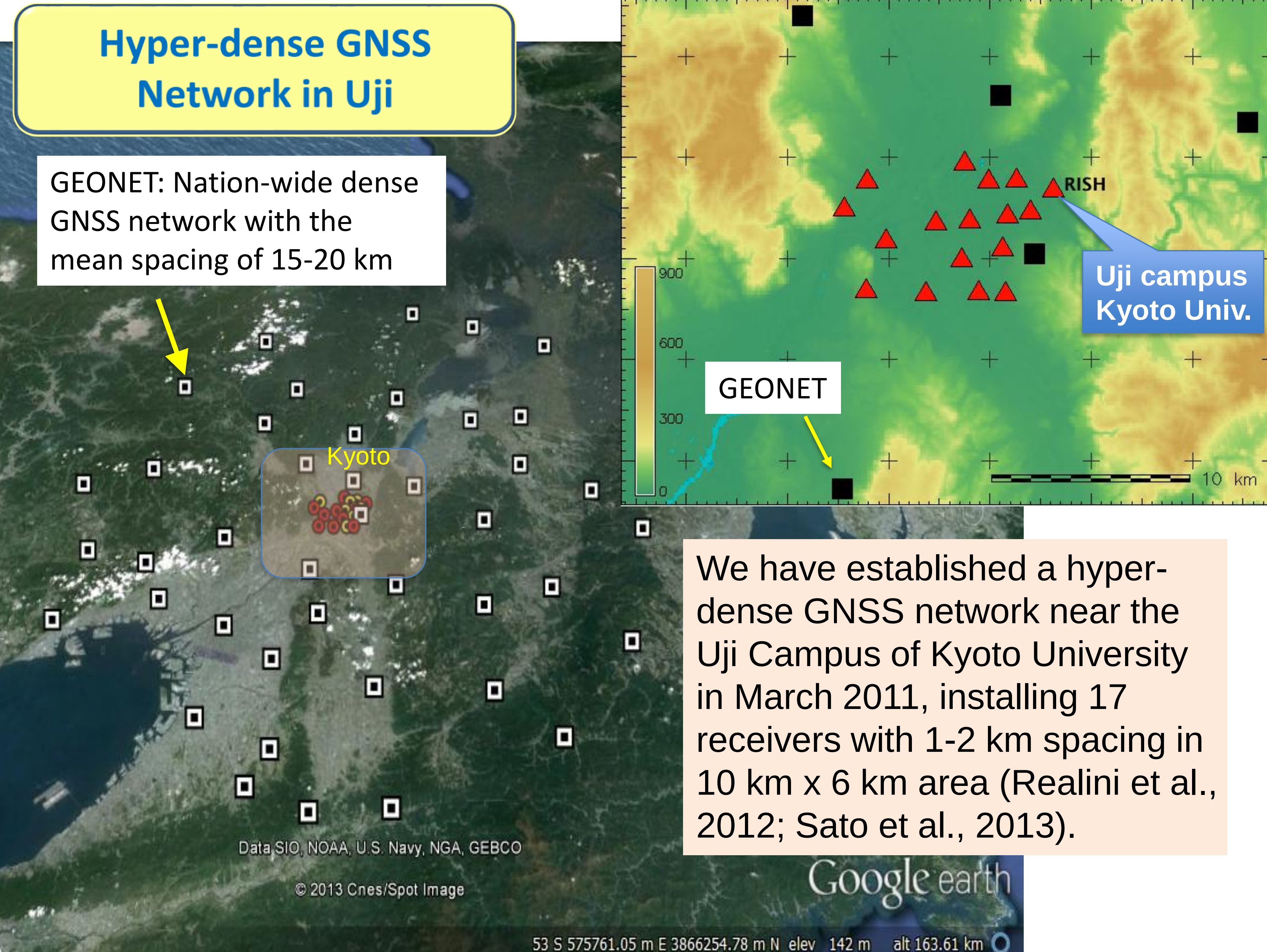
Copyright TV Asahi, Aug. 14, 2006

Torrential rain sometimes causes weather hazards, such as a sudden flood and landslides. (Heavy rainfall in Tokyo on September 4, 2006)

- ✓ A local heavy rainfall has a typical time scale shorter than one hour, which is currently difficult to predict by the operational weather forecast models. (A typical prediction cycle of the meso-scale and local scale NWP models is three and one hour, respectively.)
- ✓ We aim to develop a now-casting system of a severe rainfall by monitoring the water vapor variability at local scale with the GNSS-PWV method.

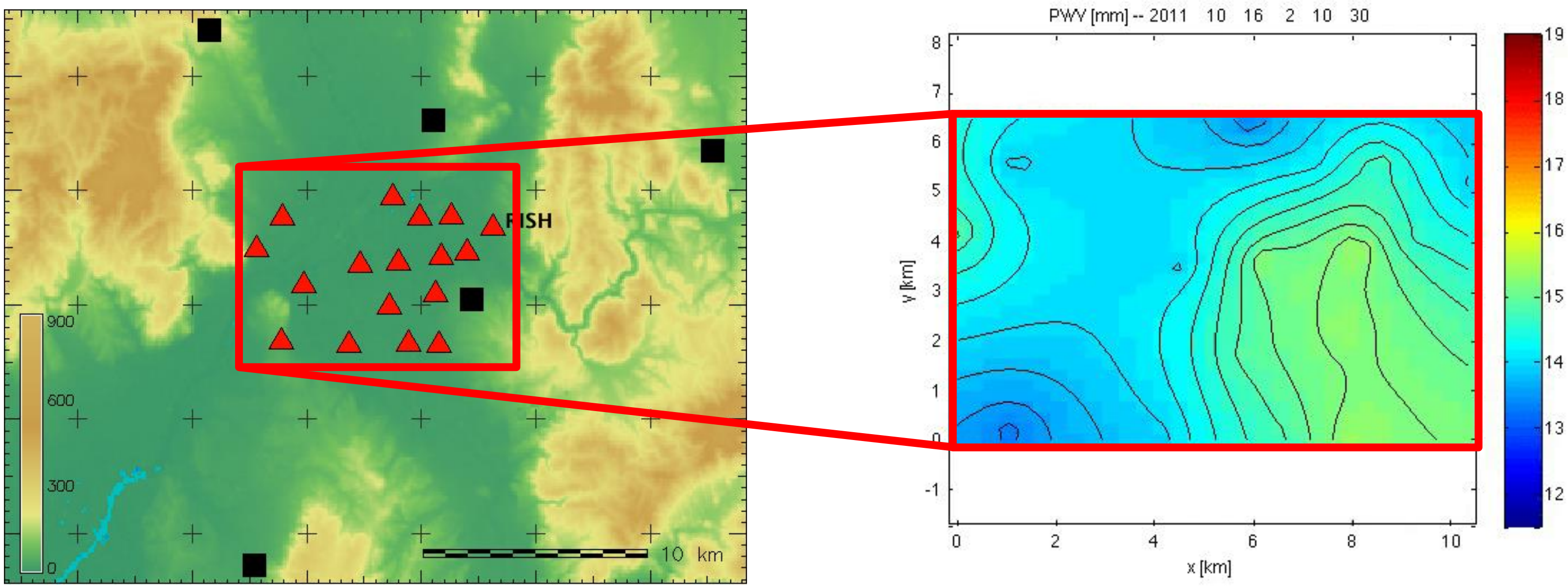
Hyper-dense GNSS Network in Uji

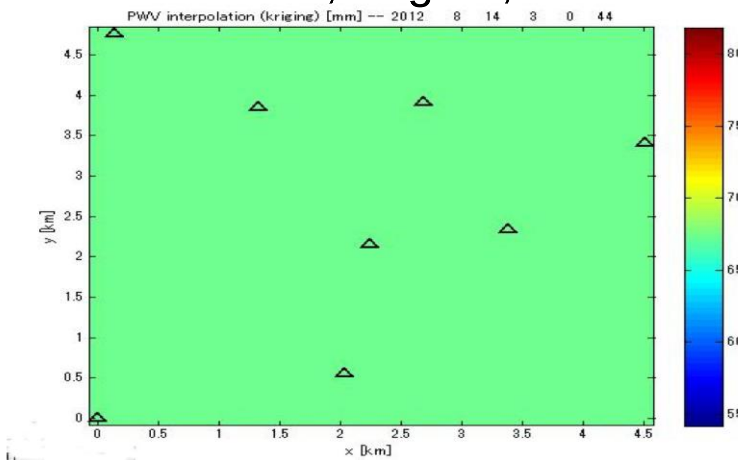
GEONET: Nation-wide dense GNSS network with the mean spacing of 15-20 km



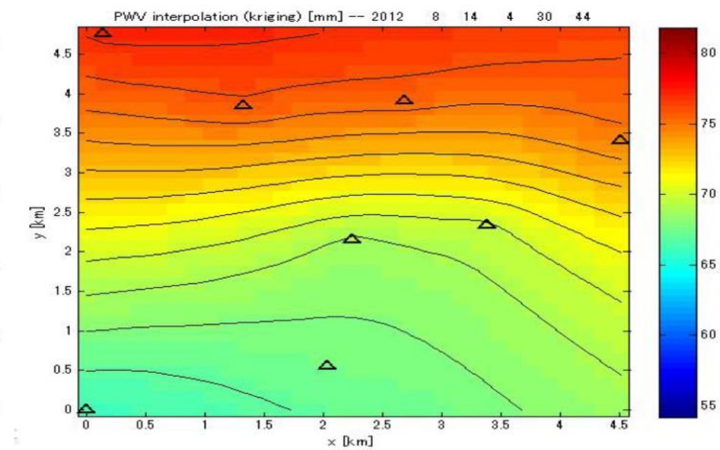
We have established a hyper-dense GNSS network near the Uji Campus of Kyoto University in March 2011, installing 17 receivers with 1-2 km spacing in 10 km x 6 km area (Realini et al., 2012; Sato et al., 2013).

Horizontal distribution of PWV observed by the Uji GNSS network





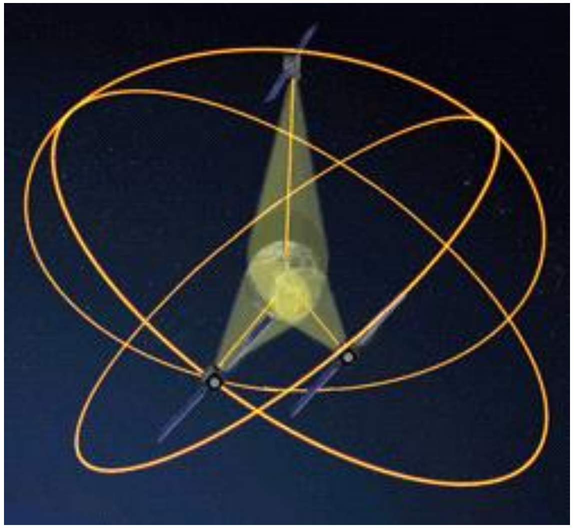
03:00 LT, Aug 14, 2012



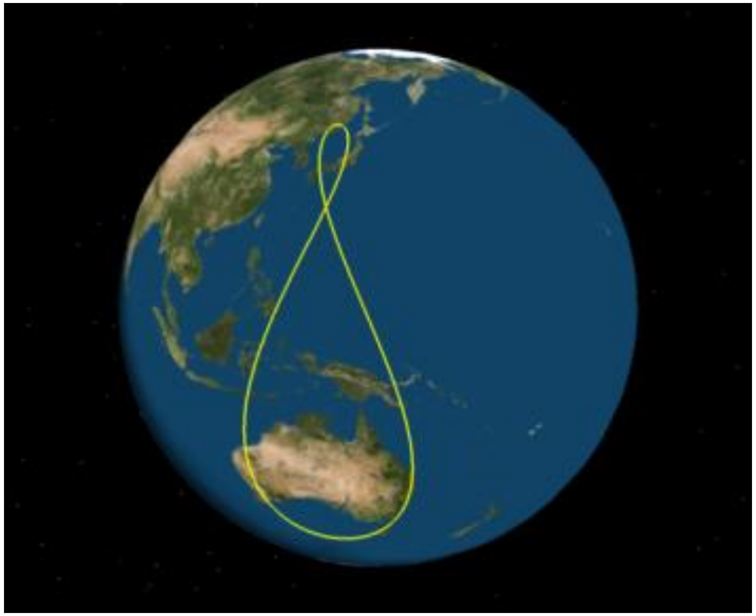
04:30 LT, Aug 14, 2012

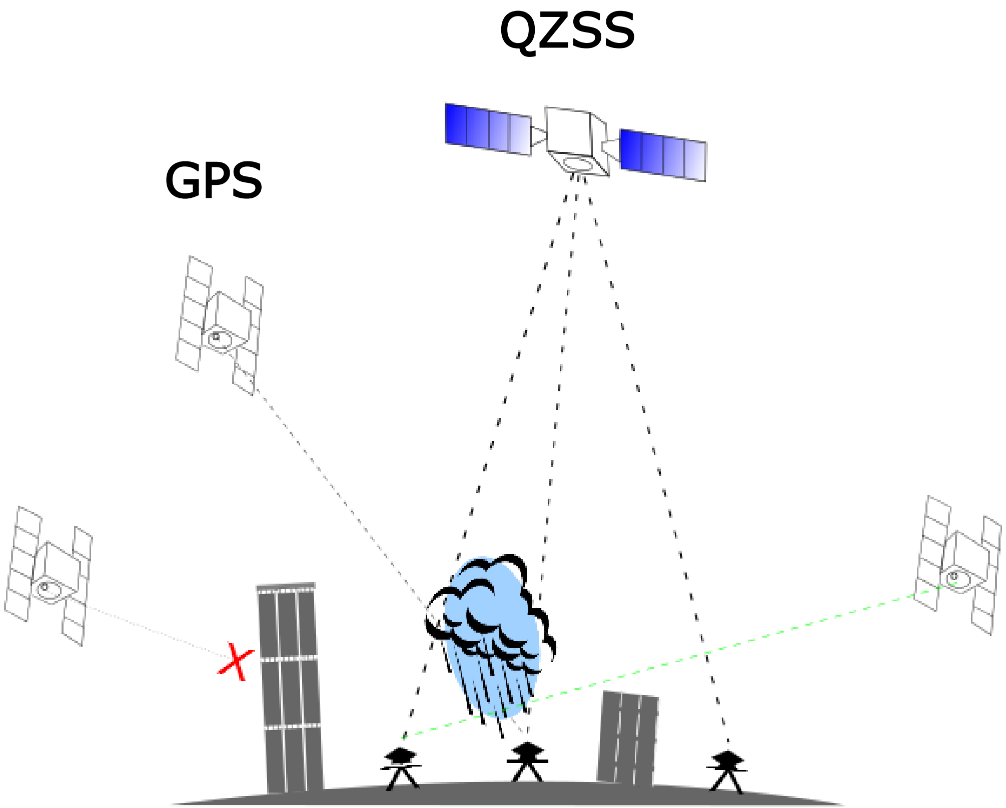
PWV uniformly distributed at 03:00 LT (Left) before a rain, but spatial inhomogeneity of PWV (larger than 5 mm) appeared at 04:30 LT (Right) during a heavy rainfall.

QZSS: Quasi-Zenith Satellite System



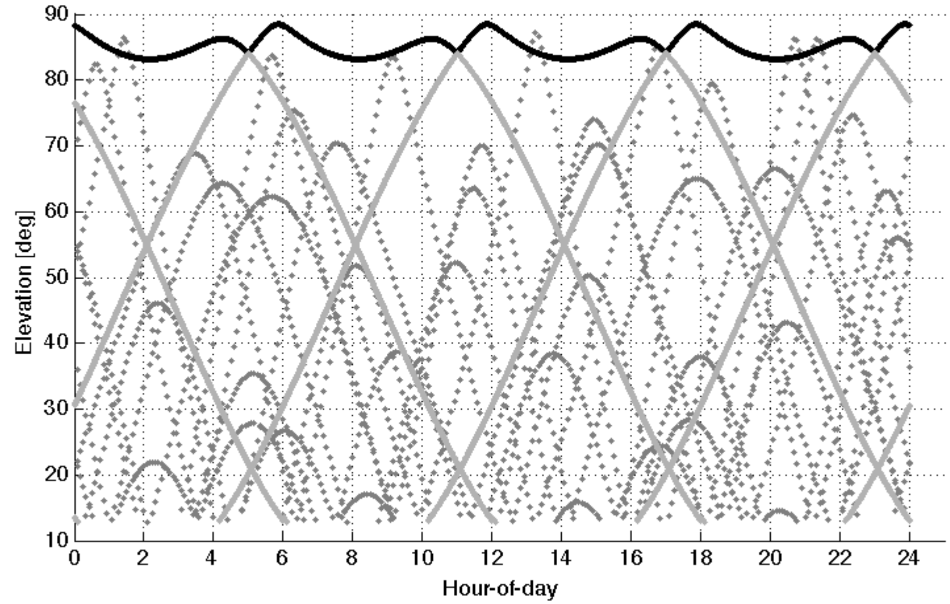
- QZSS (Michibiki) was first launched in September 2010 by JAXA.
- QZSS stays at high elevation angle over Japan continuously for about eight hours.

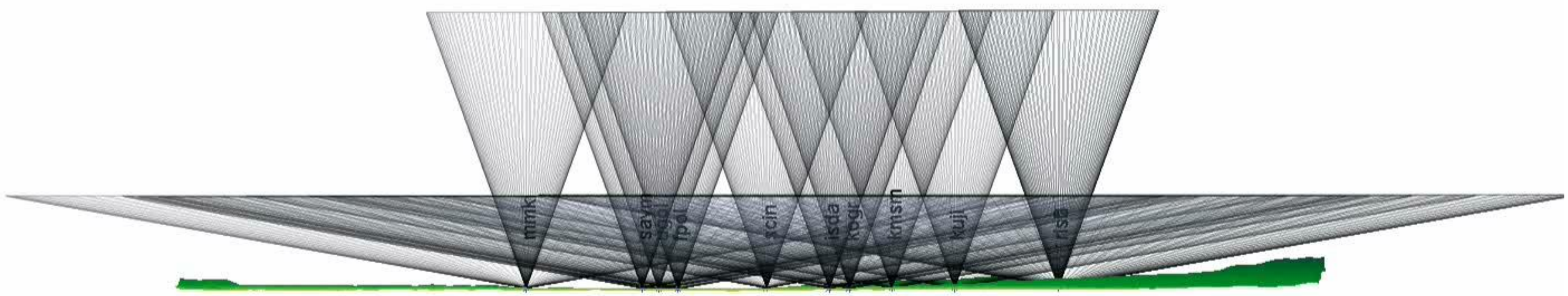




Horizontal Resolution of GNSS-PWV with the Uji Network

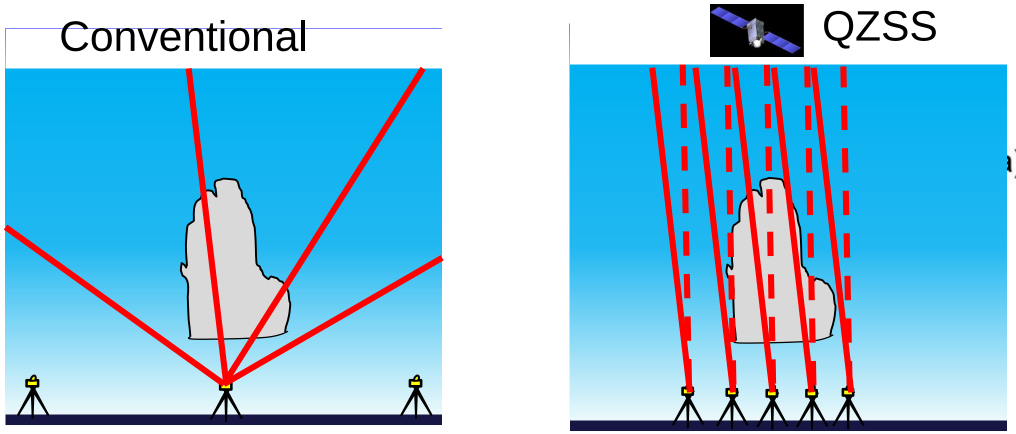
An example of time variations of the elevation angle of GPS satellites (dotted) and QZSS (thick solid)





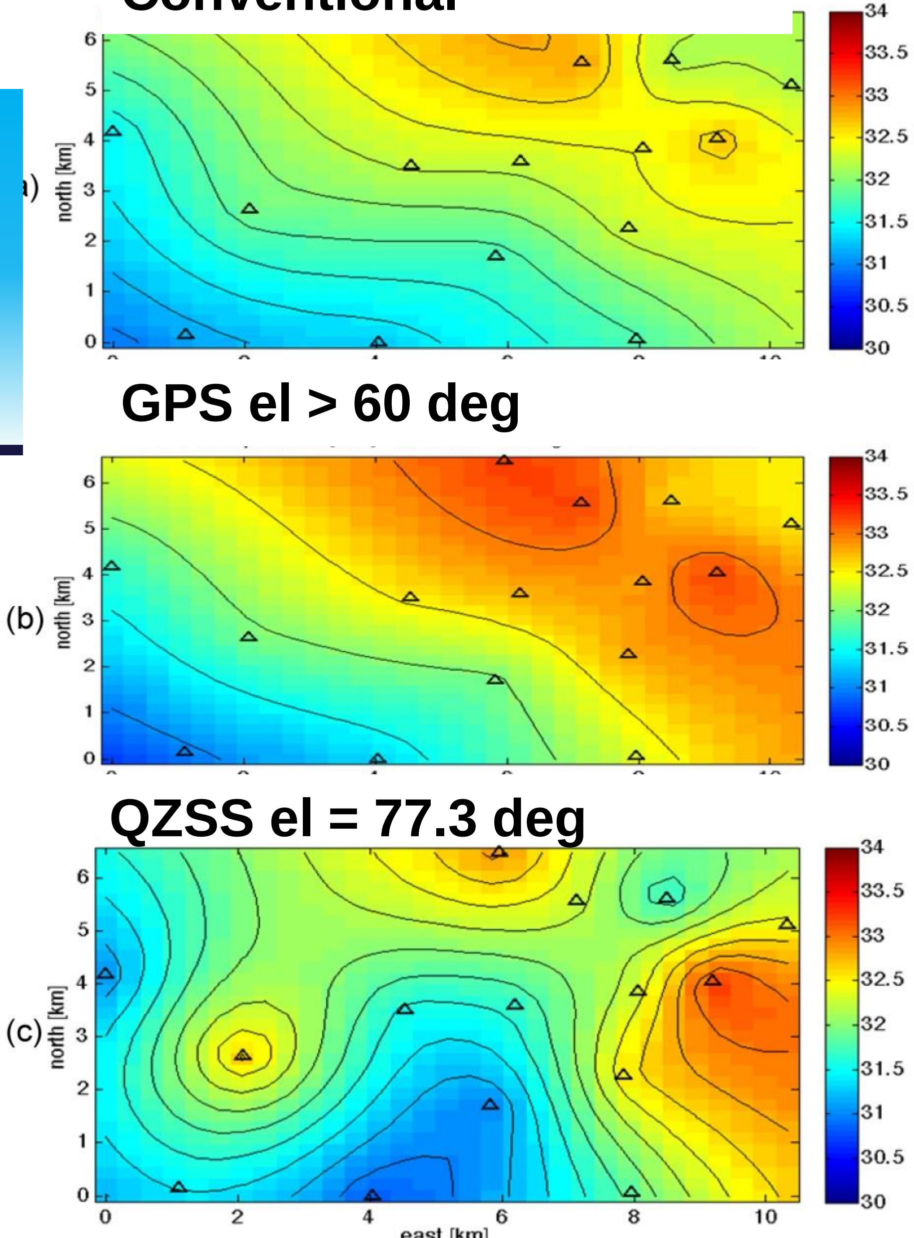
When the thickness of a water vapor layer is 3km, the effective radius of GNSS-PWV measurement becomes about 18 km by using all GNSS satellites with elevation angles above 10 degrees. By selecting satellites above 70 degrees, such as QZSS satellites, the radius can be reduced to about 1 km, which greatly improves horizontal resolution of PWV.

PWV distribution with different elevation angles of GNSS satellites



- Conventional GNSS-PWV estimation uses all available GNSS at elevation angles higher than 10º, so PWV is averaged in an inverse cone with a radius of bout 20 km.
- By selecting the high-elevation GNSS satellites only, the horizontal resolution of PWV can be improved.
- This method is especially effective by QZSS, which stays for about eight hours at high elevation angles (>70º).

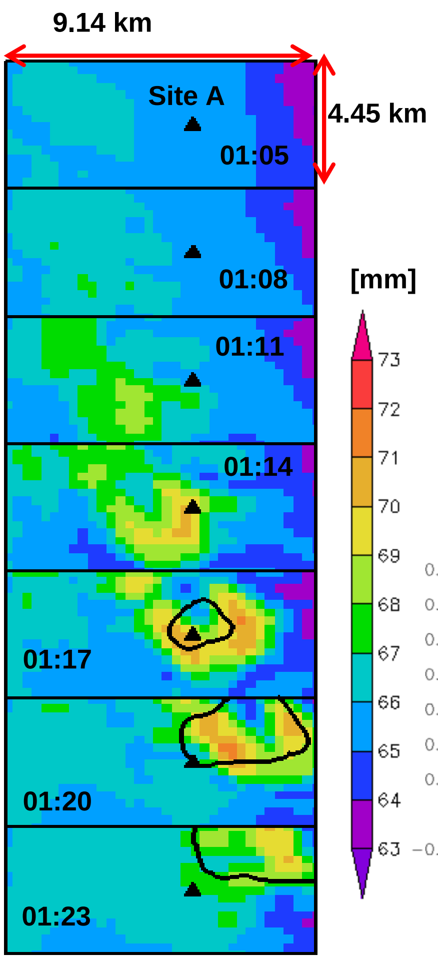
PWV with the Uji network



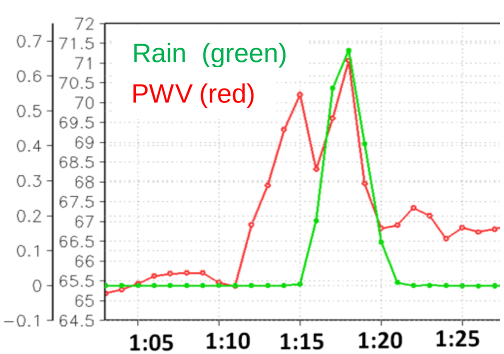
Time variations of PWV by the meso-scale NWP model and GNSS-PWV

Both the meso-scale NWP model (left) and GNSS-PWV observation (right) show increase of PWV by 5 mm when a rain cloud approached to the Uji GNSS network, which occurred about 10 minutes before precipitation was detected on the ground.

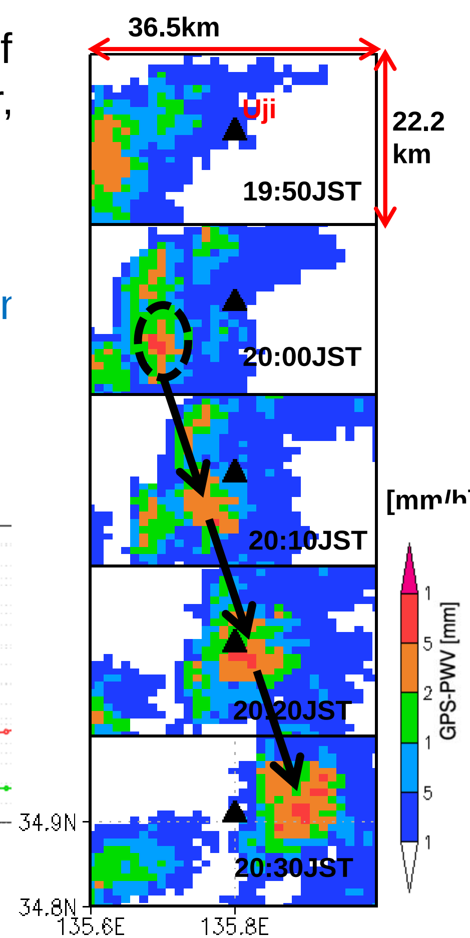
NWP model results



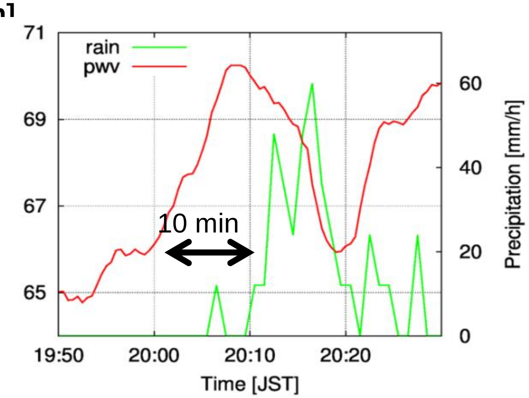
- MWP model results on August 4, 2012.
- Left: Time variation of PWV in color contour, and the precipitation area (black line)
- Bottom: PWV (red) increased about 9 mir before precipitation (green) at the site A (▲).



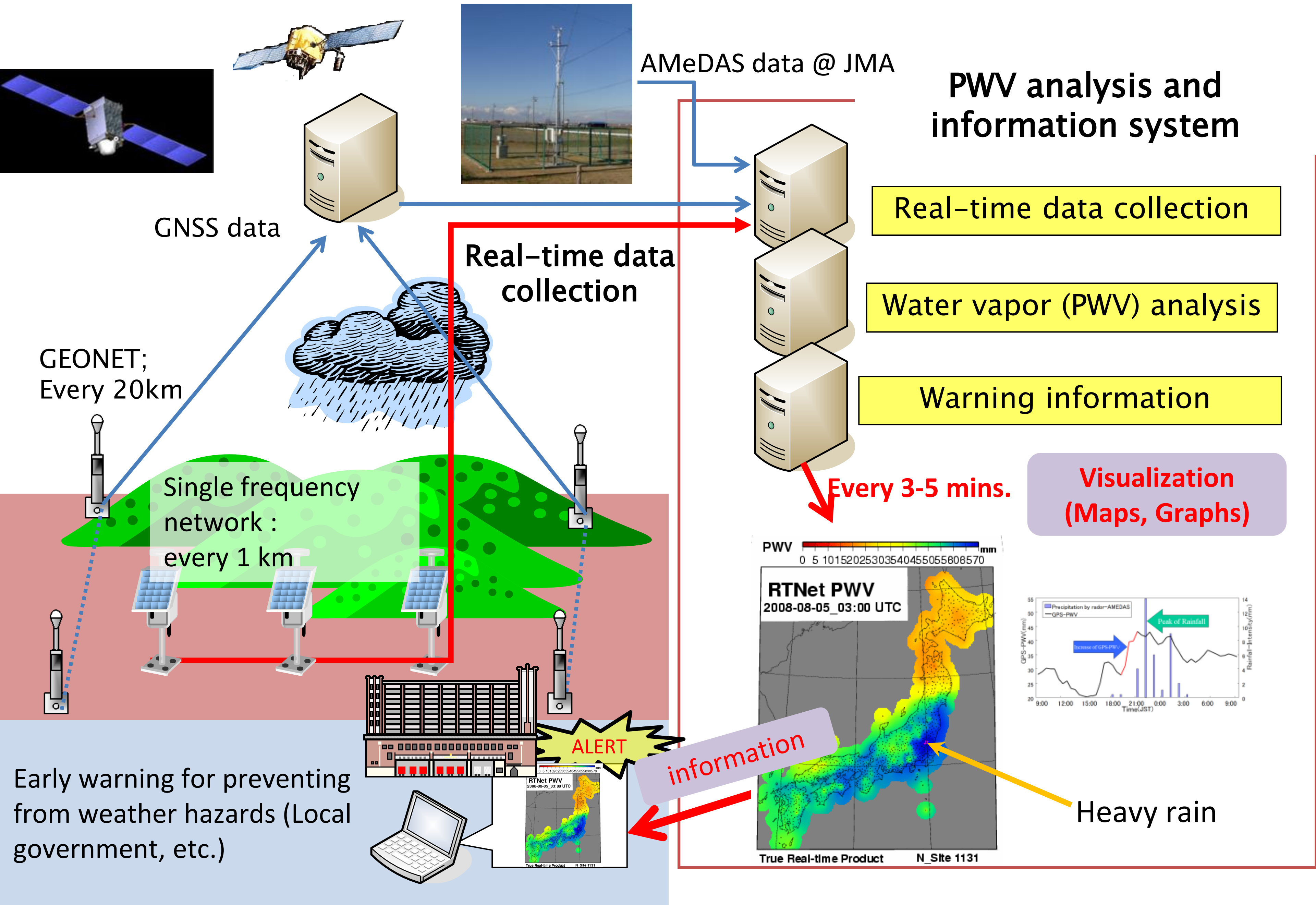
Observation



- Left: Radar images indicated a cumulous cloud passed over the Uji network.
- Bottom: GNSS-PWV and rain gauge showed that PWV rapidly increased about 10 min. before the start of rain on the ground.



Severe weather warning system by GNSS-PWV data



With the hyper-dense GNSS network in Uji with 1-2 km spacing, the horizontal variations of PWV in 10 km ranged 3-10 mm during a heavy rain. When we proceed to develop an operational severe weather warning system, we need to solve the following two major problems.

1. Real-time analysis: We need accurate orbit information comparable to the final precise ephemeris.
   - ✓ By using the real-time satellite orbit provided by Hitachi-Zosen Co., the error of PWV with the Uji network was estimated less than 1mm in RMS.

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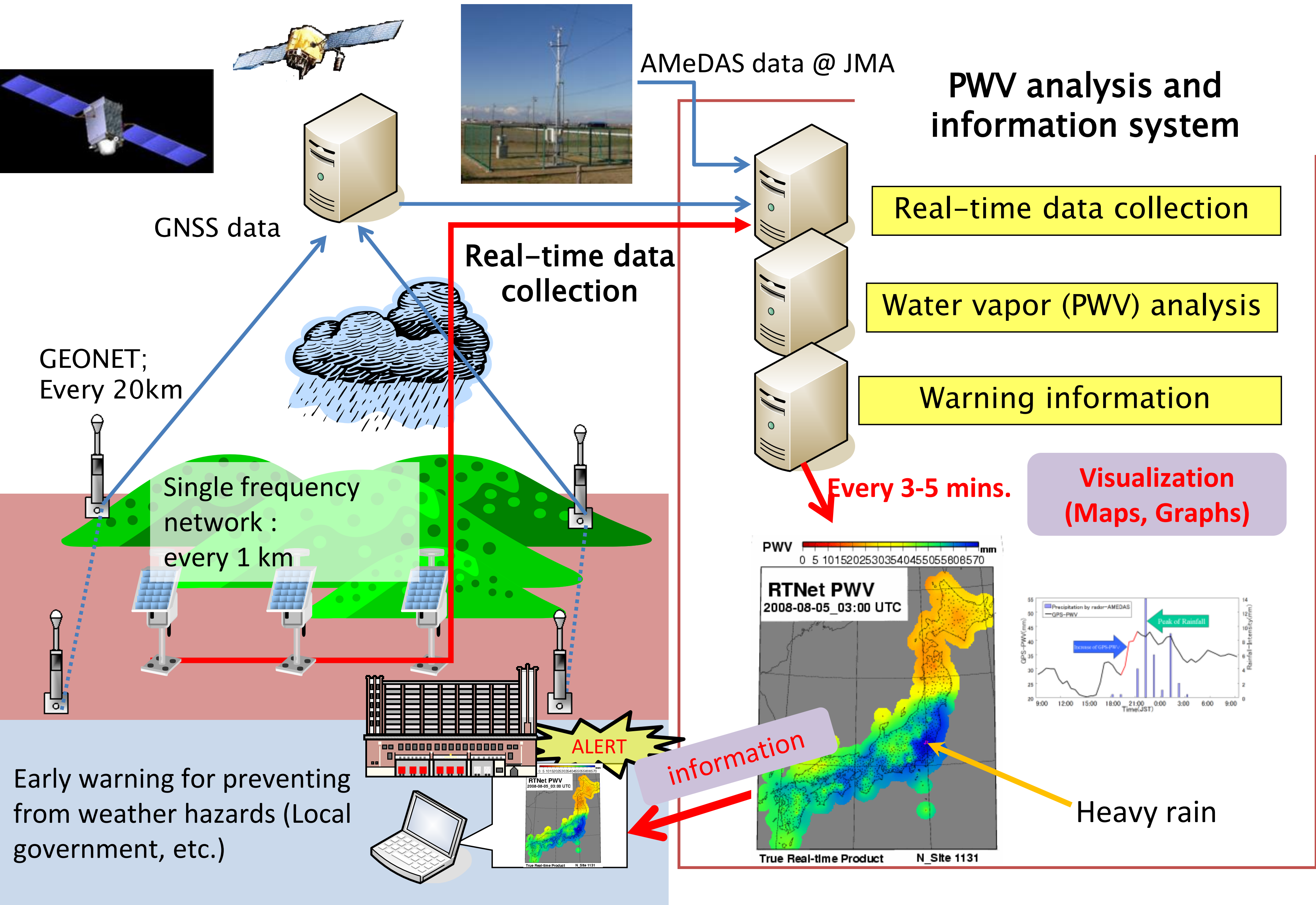

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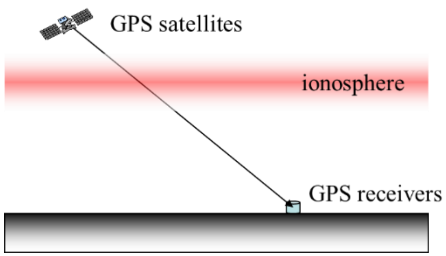
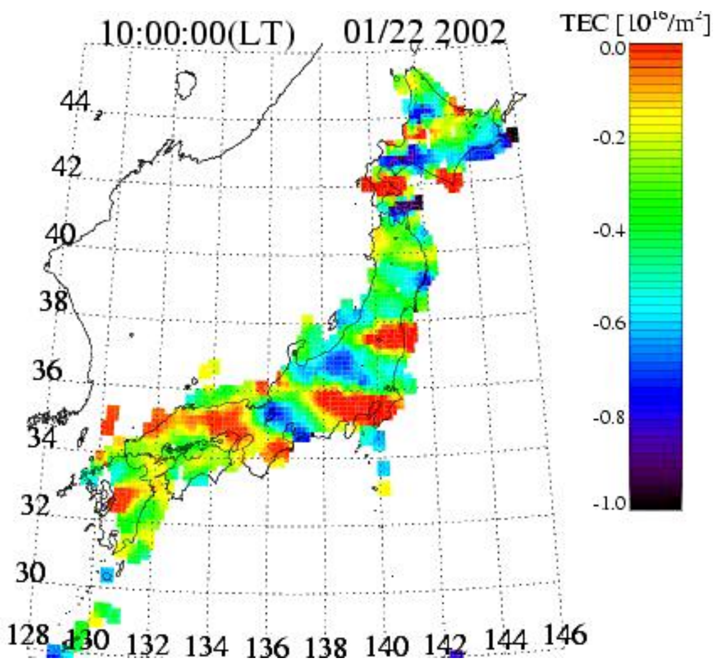
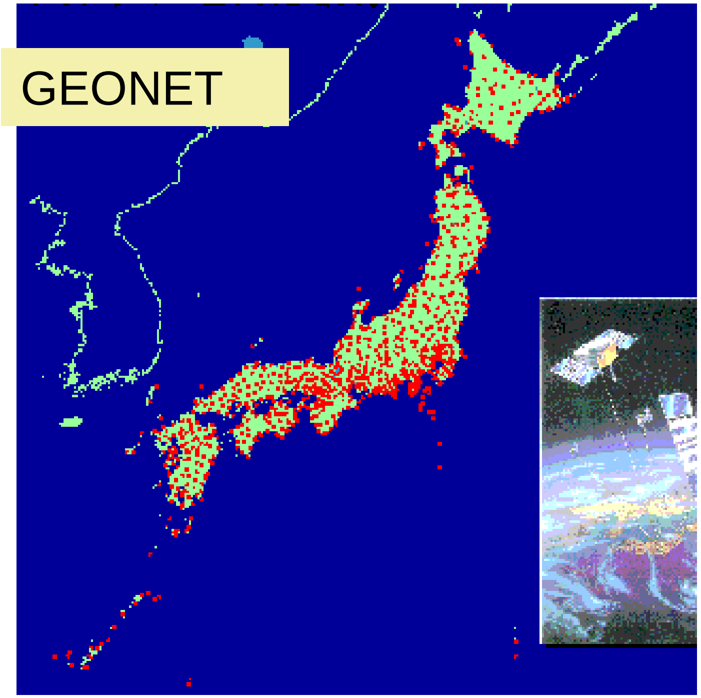
2. Very dense GNSS network:
   - ✓ When we install GNSS receivers with horizontal spacing of 2 km in an area of 40x40km, we need 400 receivers. In order to reduce the system cost, we better employ a single-frequency (SF) GNSS receiver.
   - ✓ Because the SF receiver cannot eliminate the ionospheric delay, we need to interpolate the delay referring to the results from nearby dual-frequency (DF) receivers, such as GEONET.

Ionospheric irregularities observed with GEONET



Integrated electron density (total electron content: TEC) can be estimated by the frequency dependence of the propagation delay of multiple GNSS signals.





GEONET results of the TEC variations due to the travelling ionospheric disturbances (TID) associated with atmospheric gravity waves. (Courtesy by Akinori Saito)

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   - ✓ Because the SF receiver cannot eliminate the ionospheric delay, we need to interpolate the delay referring to the results from nearby dual-frequency (DF) receivers, such as GEONET.
   - ✓ We employed the SEID model (Deng et al., 2009) to correct the ionospheric delay on SF observation with 30 sec sampling. Difference in PWV between SF and DF solutions was about 1.50 mm in RMS.

The overall error of a real-time estimate of PWV with SF receivers can be estimated as about 1.65 mm RMS, which is accurate enough to depict the horizontal variations of PWV during a severe rainfall event.

Thank you four your attention