Poster Number: P4: 016

Results of the Precipitable Water Vapor Derived from COSMIC-2 Radio Occultation

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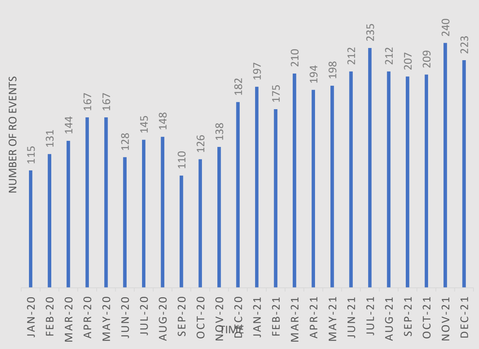
IGS Symposium & Workshop
July 1 to 5, 2024 in Bern, Switzerland
30 YEARS OF IGS

1. Summary

FORMOSAT-7/COSMIC-2 was launched in June 2019 and provides high spatial resolution radio occultation (RO) profile data. The data can be beneficial for weather and climate studies and increase the accuracy of weather forecasts. In this study, GNSS-PWV (precipitable water vapor) from PPP (precise point positioning) is compared with COSMIC-2 RO-PWV to verify the accuracy of RO-PWV. The mean GNSS-PWV is higher than the mean RO-PWV, which are 45.7 mm and 39.9 mm, respectively, from 2020 to 2021. RO-PWV derived from COSMIC-2 in 2020 and 2021 is underestimated when taking GNSS-PWV as a reference. The mean RO error is 6.8 mm, and the mean error on land is higher than that on the ocean, with magnitudes of 8.0 mm and 6.6 mm, respectively. In the monthly mean RO-PWV data from 2020 to 2021, the RO-PWV and its error show seasonal variations, with high values in summer (51.0 ± 9.2 mm) and low values in winter (31.9 ± 5.0 mm). The seasonal trend of RO-PWV is consistent with that of temperature. Here, we verify that the accuracy of COSMIC-2 RO-PWV is comparable to that of GNSS-PWV.

2. Data and methods



Time
- 2020-2021

GNSS-PWV
- CWA (Taiwan): 151 stations
- GEONET (Japan): 31 stations

RO-PWV
- **4213 RO events** are selected within 150 km of ground based GNSS station

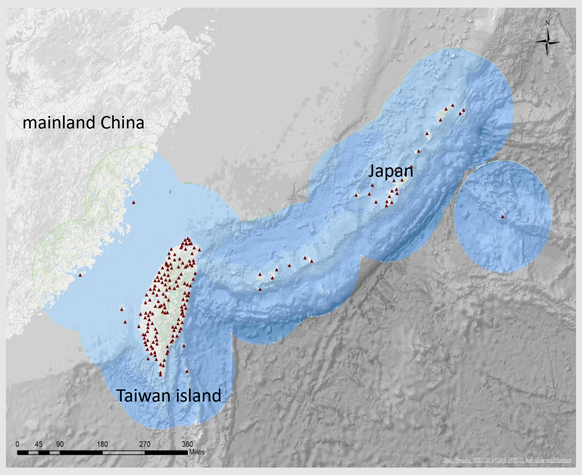


Fig. 1 The distribution of GNSS stations and the range of RO events.

Red triangle: GNSS stations
Blue area: RO events we search in this study

Altitude correction on PWV (Yeh *et al.*, 2016)

$$PWV_{alt} = PWV + 9.5 \times h$$

PWV_{alt} (in mm) is PWV after altitude correction
h (in km) is the elevation of GNSS station

GNSS-PWV
- GNSS-PWV obtained from the PPP technique can reach to **2~3 mm accuracy**
- Using **GNSS-PWV as a reference** to verify the accuracy of RO-PWV

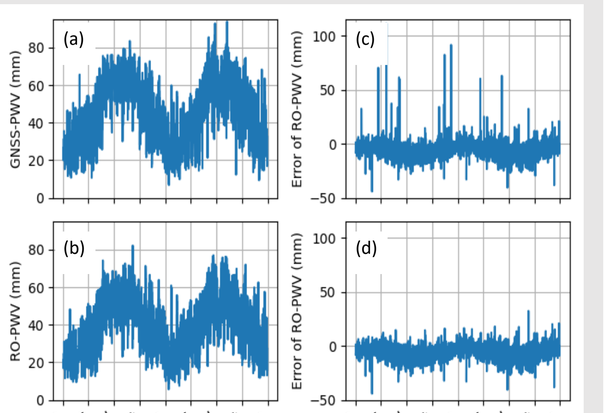
3. RO events matching

(a) to (d) are GNSS-PWV, RO-PWV, the error of RO-PWV (RO-error), and the RO error with outliers removed, respectively.

Location matching:
a pair is formed by combining one RO event with its nearest GNSS station

Time matching:
GNSS-PWV is paired with the time before and after 15 minutes of one RO event, since the temporal resolution of GNSS-PWV is 30 minutes

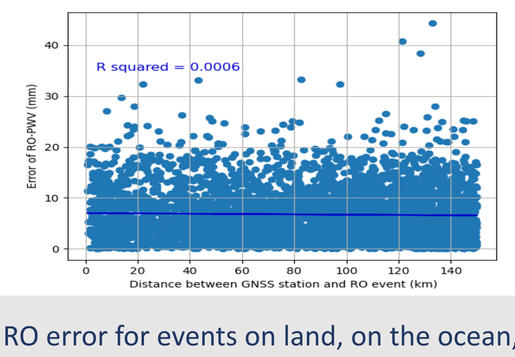
Result:
- **RO-PWV** is **lower** than **GNSS-PWV**
- Error of RO-PWV in **winter** is **less** than that in **summer**

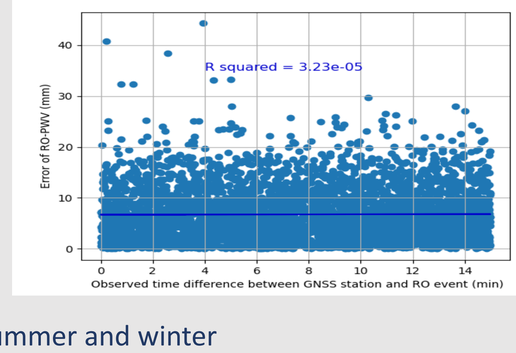


4. Error analysis of RO-PWV

Distance between RO events and their matched ground-based GNSS
- as close as 1 km; as far as 150 km away
- **NOT correlated** with an R-squared value of 0.0006

Asynchrony between RO events and ground-based GNSS
- RO events occur at irregular time interval
- Time difference up to 15 minutes
- **NOT correlated** with an R-squared value of 0.00003

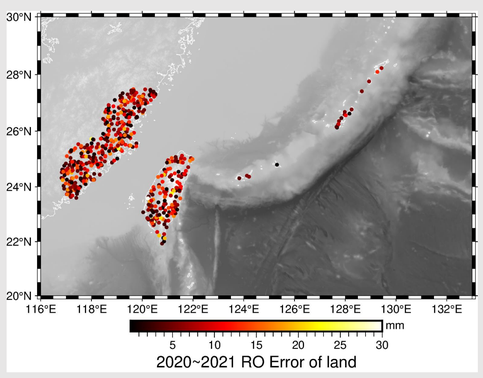


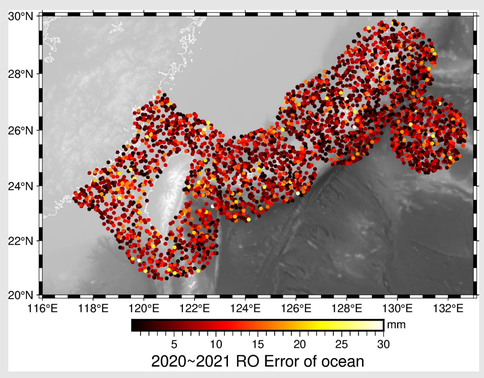


RO error for events on land, on the ocean, in summer and winter

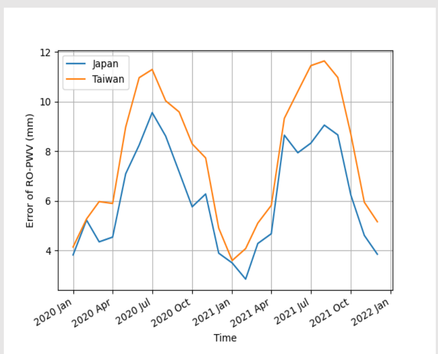
(in mm)	RO error	RO error on land	RO error on the ocean	RO error on summer	RO error in winter
Mean	6.8	**8.0**	**6.6**	**9.2**	**5.0**
Standard deviation	5.2	5.6	5.1	5.7	3.9
Median	5.7	7.2	5.6	8.8	4.1

RO-PWV error:
Land > Ocean
Summer > Winter



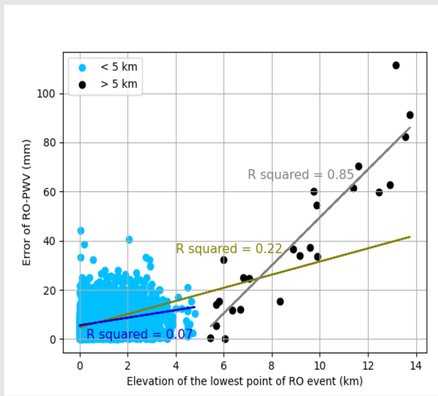


Elevation of the lowest point of RO events (ELP-RO)



Station	Country	Station number	RO event number			RO error (mm)	Elevation (m)
			all	land	ocean		
CWA	Taiwan	151	1653	533	1142	7.7	113
GEONET	Japan	31	2536	19	2495	6.1	68

- The magnitudes from **May to September** have greater differences.
- **Weather**: Taiwan start the **Mei-yu season** in May, with a rapid increase in temperature. After the rainy season, **typhoon** events from July to September make water vapor changes more complex.
- **RO event in the ocean**: Most of the RO events at the GEONET stations occurred in the **ocean (99.2%)**, while in the CWA stations, only **68.2%** of the RO events occurred in the ocean.



ELP-RO (km)	0	0~1	1~2	2~3	3~4	4~5	>5
RO-event number	259	2534	991	273	117	15	24
Percentage (%)	6.2	60.2	23.5	6.5	2.8	0.4	**0.6**

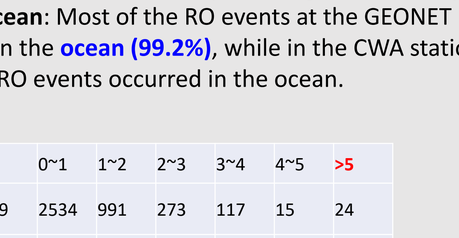
Removing RO events with an ELP-RO **above 5 km** to reduce the errors

- When removing ELP-RO above 5 km, their relationship becomes even less correlated, with an R-squared value of 0.07
- When considering only ELP-RO above 5 km, a **positive correlation** with RO error is observed, with an R-squared value of **0.85**

5. Temporal variations of GNSS-PWV and RO-PWV

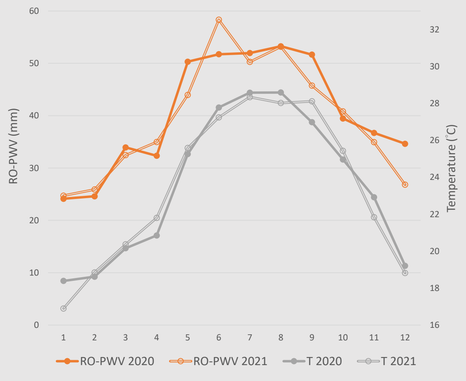
	Mean (mm)	Standard deviation (mm)	Median (mm)	Annual cycle	
				Amplitude (mm)	Phase (degree)
GNSS-PWV	**45.7**	16.4	45.9	**19.2**	191.8 (13 July)
RO-PWV	**39.9**	14.2	39.4	**16.1**	194.8 (16 July)

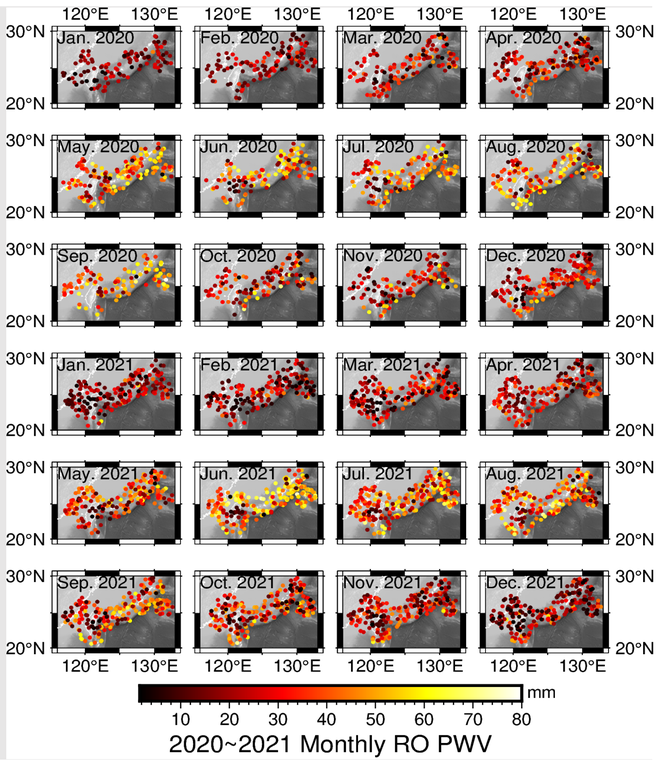
- **GNSS-PWV > RO-PWV**
- RO-PWV in summer > winter
- RO events in the ocean account for 86.8% of all events
- **RO-PWV on the ocean (40.0 mm) > land (38.7 mm)**



6. Temporal and spatial variations of RO-PWV

- The annual trends of RO-PWV in 2020 and 2021 are consistent
- The annual trend of temperature is consistent with RO-PWV
- Both RO-PWV and temperature **have higher values in 2020** than that in 2021





7. Conclusions

1) We found that **RO-PWV is smaller than GNSS-PWV** in the study area, and both have yearly variations, with high PWV in summer and low PWV in winter.
2) We analyzed possible error sources of RO-PWV and found that **the elevation of the lowest point of the RO event is the main factor** in RO-PWV accuracy.
3) The distribution of RO events varies with different altitudes of ELP-RO. Most RO events in Mount Wuyi and the Central Mountain Range occur at ELP-RO values of 1-2 km and 2-4 km, respectively, which correspond to their elevations.
4) The mean **RO error on land is 1.4 mm higher than that on the ocean**. This shows that the accuracy of RO-PWV from COSMIC-2 over the ocean is better than that over land in the study area.
5) The Mei-yu and typhoon seasons lead to unstable water vapor variations in this time period and may be the reasons for the higher RO error in Taiwan than in Japan.
6) We found that RO-PWV in summer is higher than that in winter, that in the ocean is higher than that on land, and that in **2020 is higher than that in 2021**.