THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

DEPARTMENT OF LAND SURVEYING AND GEO-INFORMATICS
土地測量及地理資訊學系

PolyU Micro-LARGE

GPS Water Vapor Data to Improve Water Vapor Retrieval from MERSI/FY-3B Remote Sensing Satellite

Zhizhao (George) LIU & Jia HE

Micro-Laboratory of Atmospheric Research and Geomatics Engineering
(Micro-LARGE)
Department of Land Surveying & Geo-Informatics
The Hong Kong Polytechnic University, Hong Kong, China
Email: lszzliu@polyu.edu.hk

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  - **China Meteorological Administration (CMA)** for providing MERSI/FY-3B Level 1b data (http://satellite.nsmc.org.cn)
  - **University Corporation for Atmospheric Research (UCAR) and SuomiNet project** for providing GPS water vapor data (http://www.suominet.ucar.edu/)

Zhizhao (George) LIU

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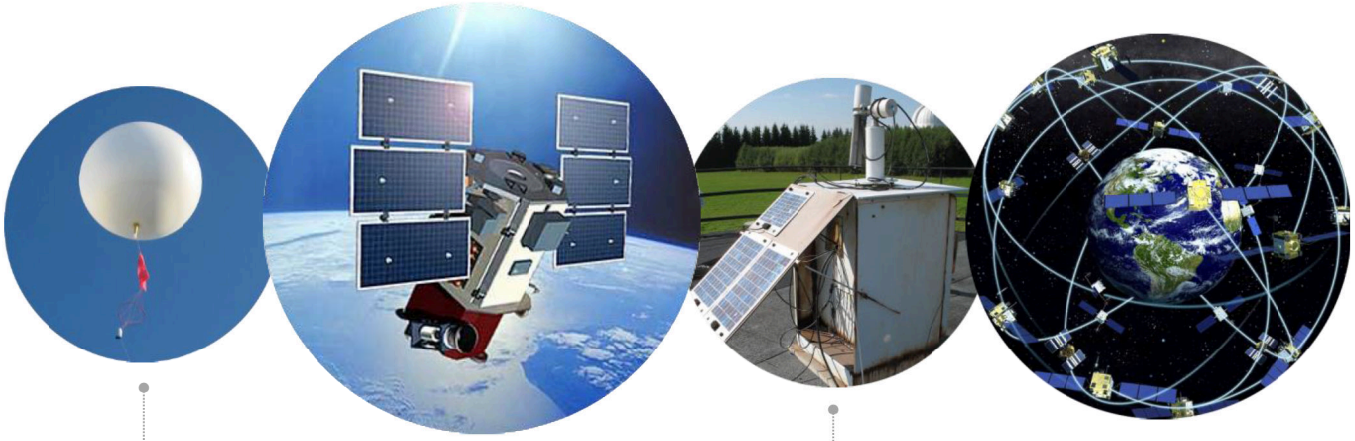
1. Introduction

Atmospheric Water Vapor Observation



Radiosonde
Earliest observation technique, high accuracy, daily observation

Remote Sensing
Global coverage, daily observation, low cost

Sun-photometer
Daily observation, high accuracy

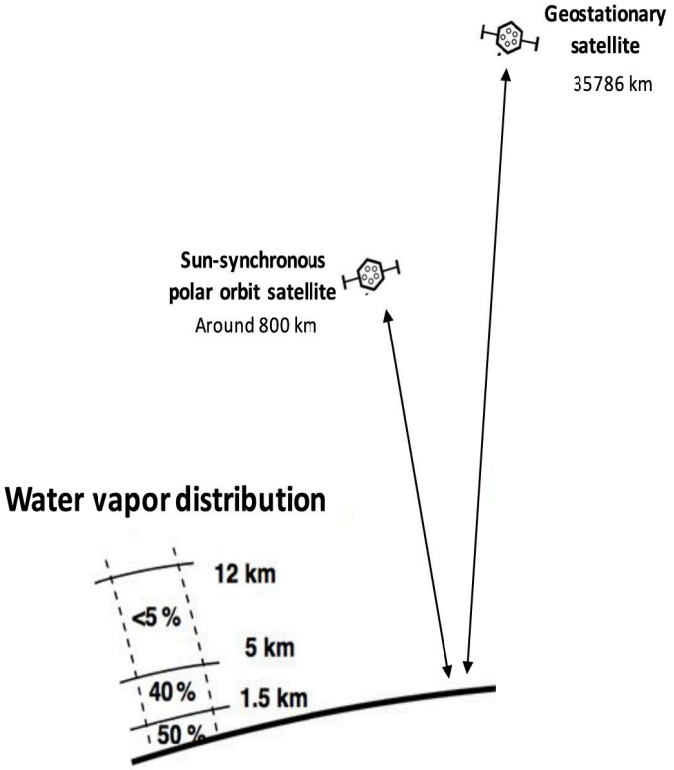
GNSS/GPS
Hourly observation, high accuracy, low cost

Remote sensing is the most **cost-effective** way to observe water vapor on the **global scale**. But it has **relatively low observation accuracy and poor temporal resolution**. **GNSS/GPS** measures water vapor with **high accuracy and high temporal resolution**.

1. Introduction

Chinese Fengyun Meteorological Satellites

- Chinese Fengyun (FY) Meteorological Satellite Mission is administrated by China Meteorological Administration (CMA)
- FY mission composed of
  - **sun-synchronous series** (1st and 3rd generations)
  - **geostationary Earth orbit series** (2nd and 4th generations)
- FY-3 series are **sun-synchronous polar-orbiting** meteorological satellites



1. Introduction

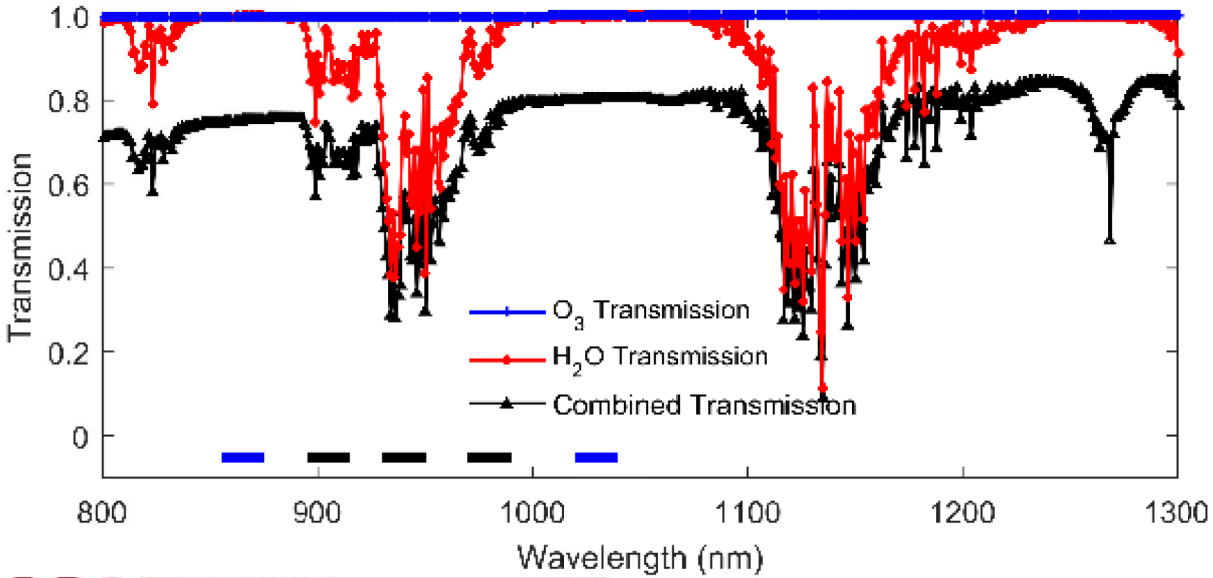
Chinese Fengyun Meteorological Satellites

- **FY-3B satellite:**
  - launched in Nov 2010
  - ECT: 14:45 asc.
  - 12 instruments onboard
  - **Medium Resolution Spectral Imager (MERSI)** is a MODIS-like sensor
- **MERSI:**
  - 20 bands
  - with both **visible** and **NIR channels**
  - 5 NIR water vapor related channels
  - resolution from 250 to 1000 m
- Level 1 Reflectance data from MERSI/FY3B are downloaded from CMA website

2. Methodology

Theoretical Background for NIR Remote Sensing Observation

- PWV from NIR channels is measured through its effect on **transmission absorption** when the radiance is transmitted down to the earth surface and back to the sensor.
- The ratio of NIR channels approximately equals to water vapor transmittance in the **Sun-Surface-Sensor** ray path.



Spectral transmission of atmosphere contents in the presence of water vapor at 0.6 g/cm^2, for the H_2O, O_3 and the combined transmission. MODTRAN 4 model was used in computation.

2. Methodology

Theoretical Background for NIR Remote Sensing Observation

- To optimize the retrieval algorithm from MERSI NIR channels, the **differential absorption technique** is applied to all the three absorption channels. The transmittance using **two-channel ratio method** is written as:

$$T_i = \rho^*{}_i / \rho^*{}_{16}$$

- Or using **three-channel ratio** method:

$$T_i = \rho^*{}_i / (C_1 \rho^*{}_{16} + C_2 \rho^*{}_{20})$$

- where the C_1 =0.8 and C_2 =0.2 (Gao and Kaufman, 2003)

- Transmittance T and Water Vapor W has a relationship expressed by an exponential formula:

$$\boldsymbol{T_w = \exp(\alpha - \beta\sqrt{W^*})}$$

- Weighted mean water vapor from the three channels is:

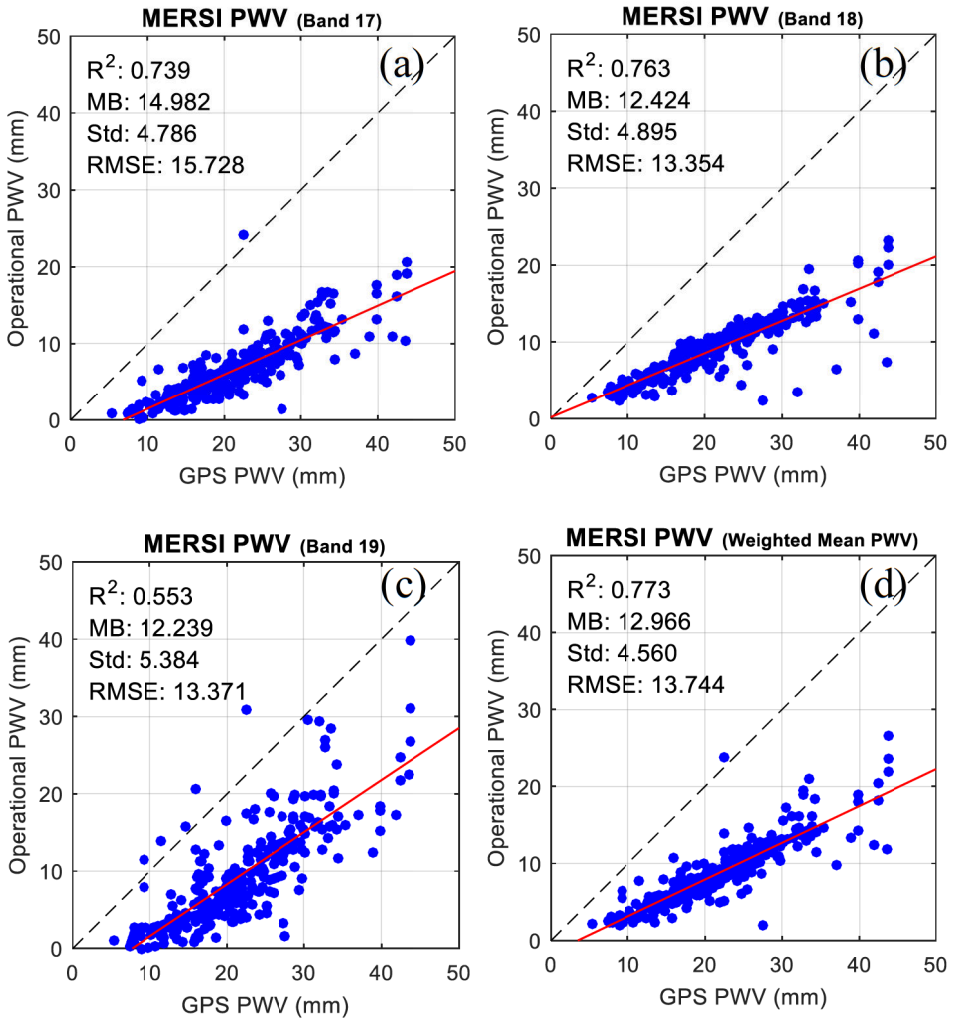
$$W = f_1 W_1 + f_2 W_2 + f_3 W_3$$

- f_1, f_2 and f_3 are calculated based on their sensitivity to water vapor variation

2. MERSI/FY-3B Operational Product

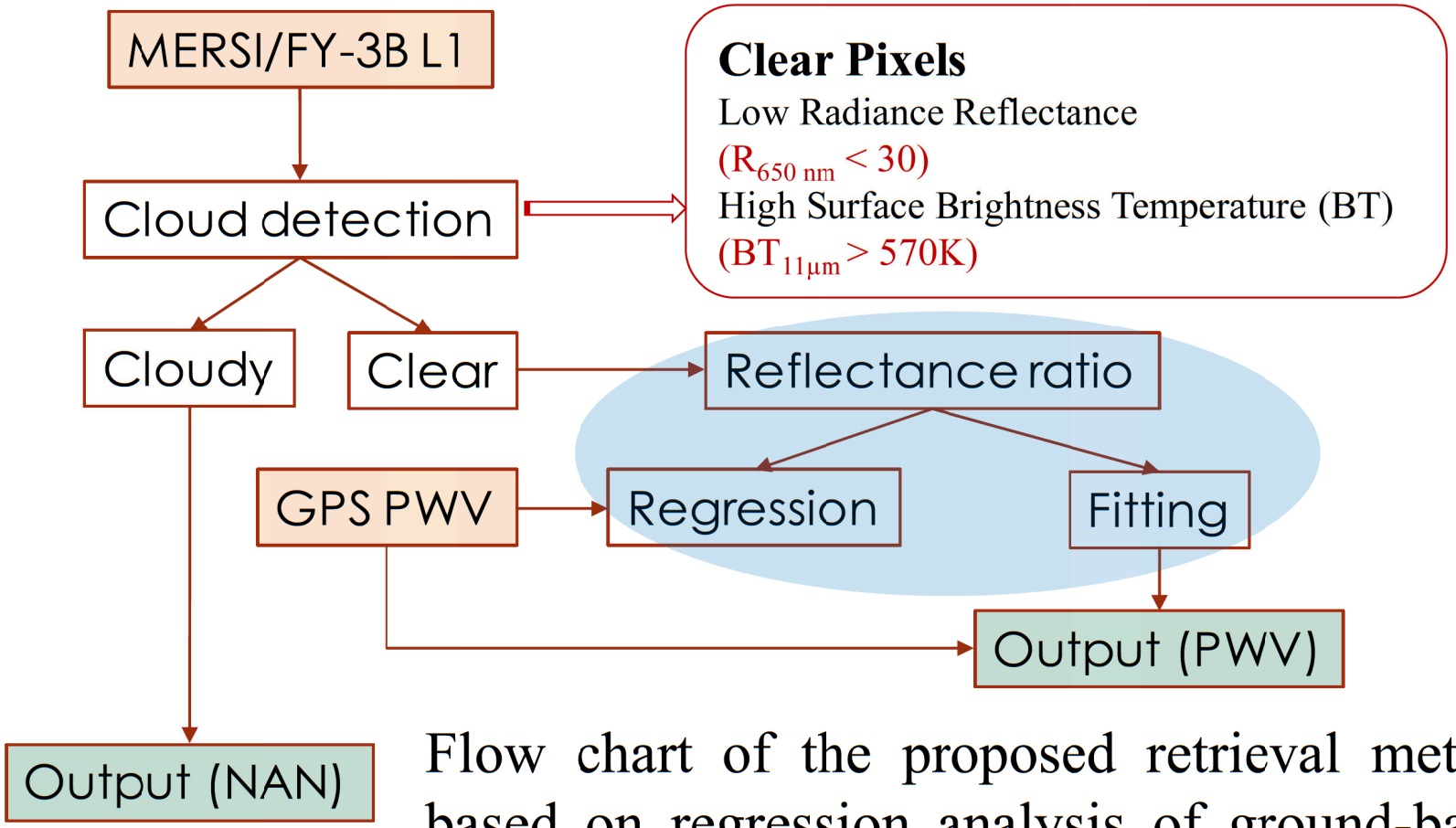
- **Dry bias** was observed from the operational PWV
- PWV observed from band 18 has the best retrieval accuracy in single channel observation, with RMSE of **13.354 mm**
- PWV obtained from band 19 has a weak correlation with collocated GPS data

Operational PWV products from MERSI/FY-3B against collocated GPS PWV data over western North America, from July 1st to July 10th, 2017.



2. Methodology

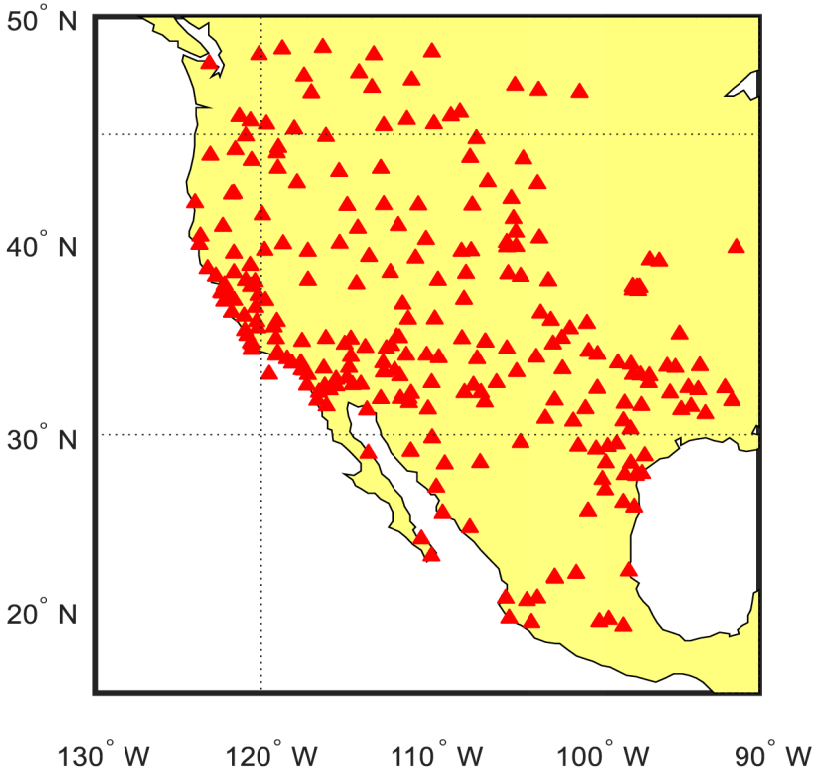
Calibrated Retrieval Method with GPS observation



Flow chart of the proposed retrieval method based on regression analysis of ground-based GPS observations

2. Methodology

Data Description – GPS PWV



256 GPS stations over western North America used for calibration and validation analysis

- **Hourly** GPS PWV data with **mm accuracy** are from the SuomiNet network, USA (Ware et al., 2000)
- SuomiNet network uses precise surveying quality dual-frequency Trimble™ receivers and antennas
- GPS data were processed with Bernese software developed at the University of Berne (Ware et al., 2000)

2. Methodology

Data Description – MERSI/FY-3B NIR

Descriptions of 5 NIR channels from MERSI/FY-3B

Band Number	Band Width (nm)	Center (nm)	FWHM (nm)	Spatial Resolution (m)	Description
16	855-875	865	20	1000	Window Channel
17	895-915	905	20	1000	Absorption Channel
18	930-950	940	20	1000	Absorption Channel
19	970-990	980	20	1000	Absorption Channel
20	1020-1040	1030	20	1000	Window Channel

Transmittance using **two-channel ratio method** is written as:

$$T_i = \rho^*_i / \rho^*_{16}$$

Or using **three-channel ratio method**:

$$T_i = \rho^*_i / (C_1 \rho^*_{16} + C_2 \rho^*_{20})$$

C_1=0.8 and C_2 =0.2 (Gao and Kaufman, 2003).

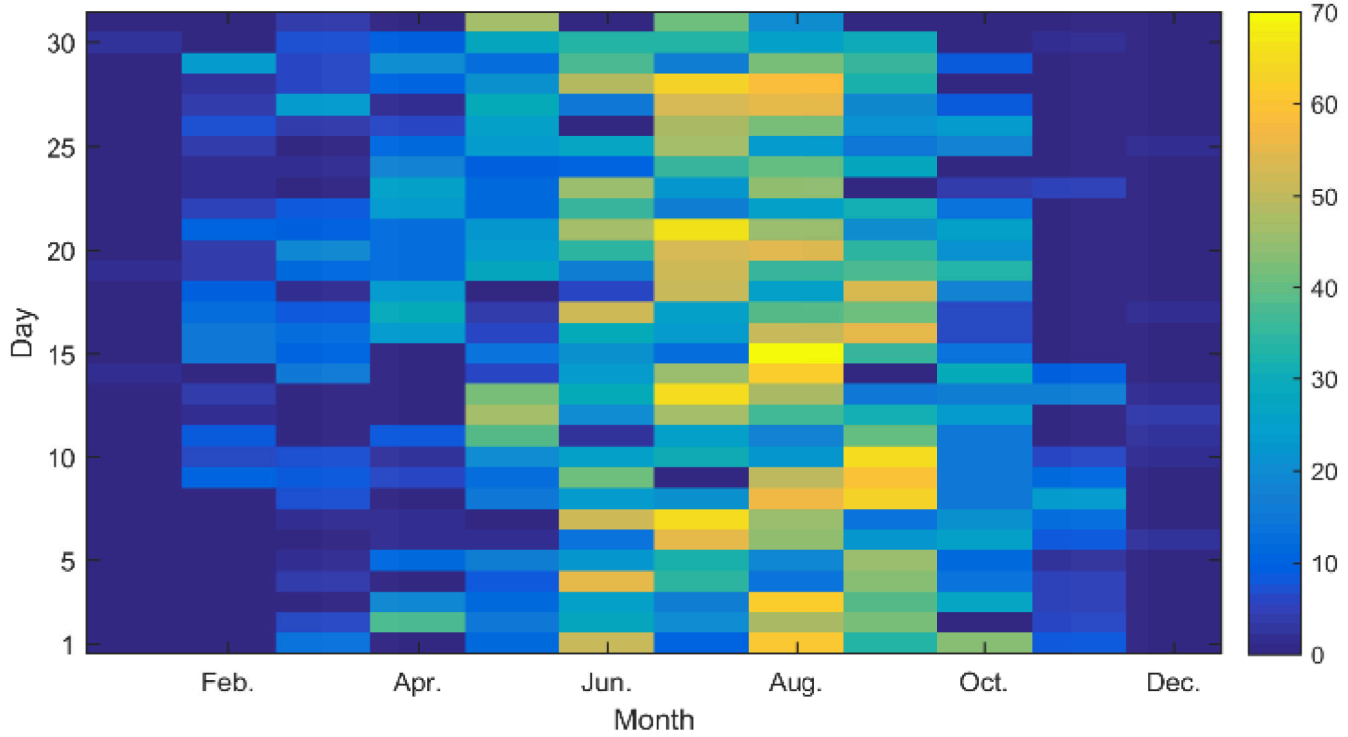
Weighted mean water vapor from the three channels is:

$$W = f_1 W_1 + f_2 W_2 + f_3 W_3$$

f_1, f_2 and f_3 are calculated based on their sensitivity to water vapor variation.

2. Methodology

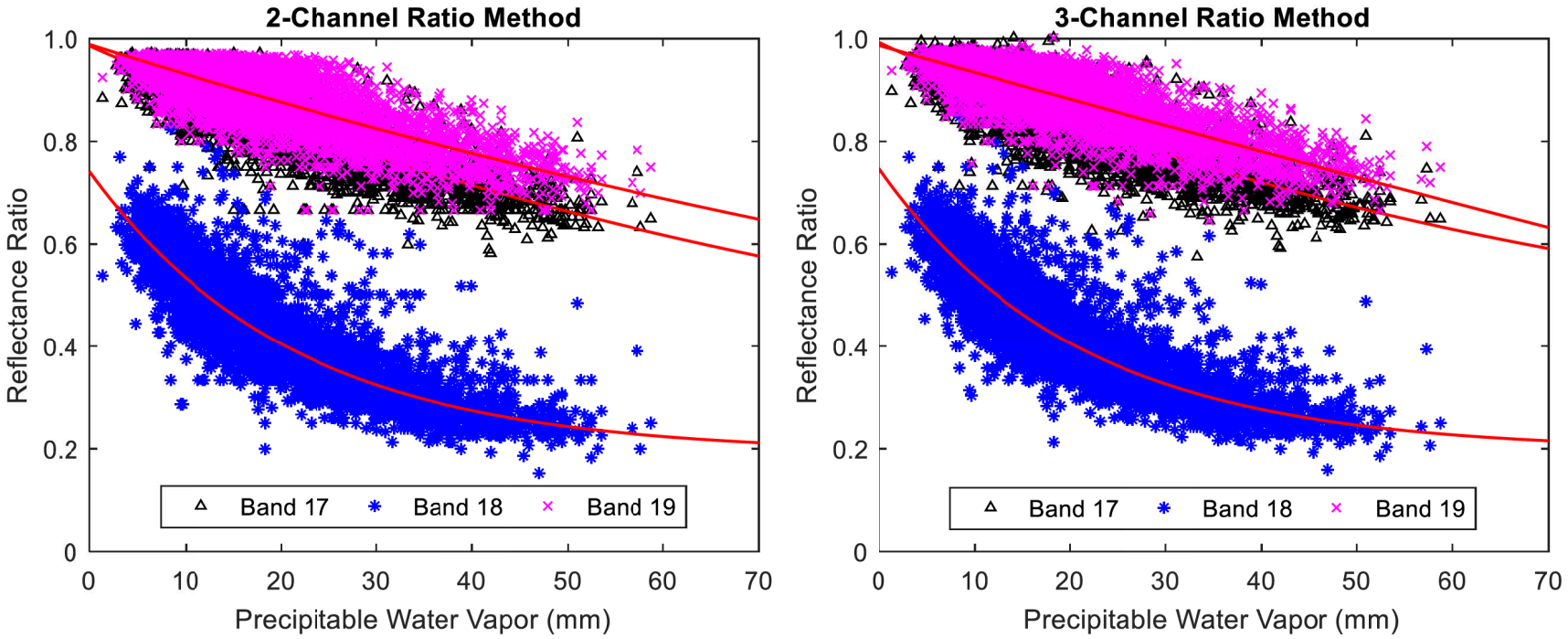
Data Description – Collocated Data Pairs for Calibration Analysis



Number of collocated pairs of PWV data of cloud-free MERSI/FY-3B and GPS with **time difference < 30 minutes** recorded in each day of 2016 over western North America.

2. Methodology

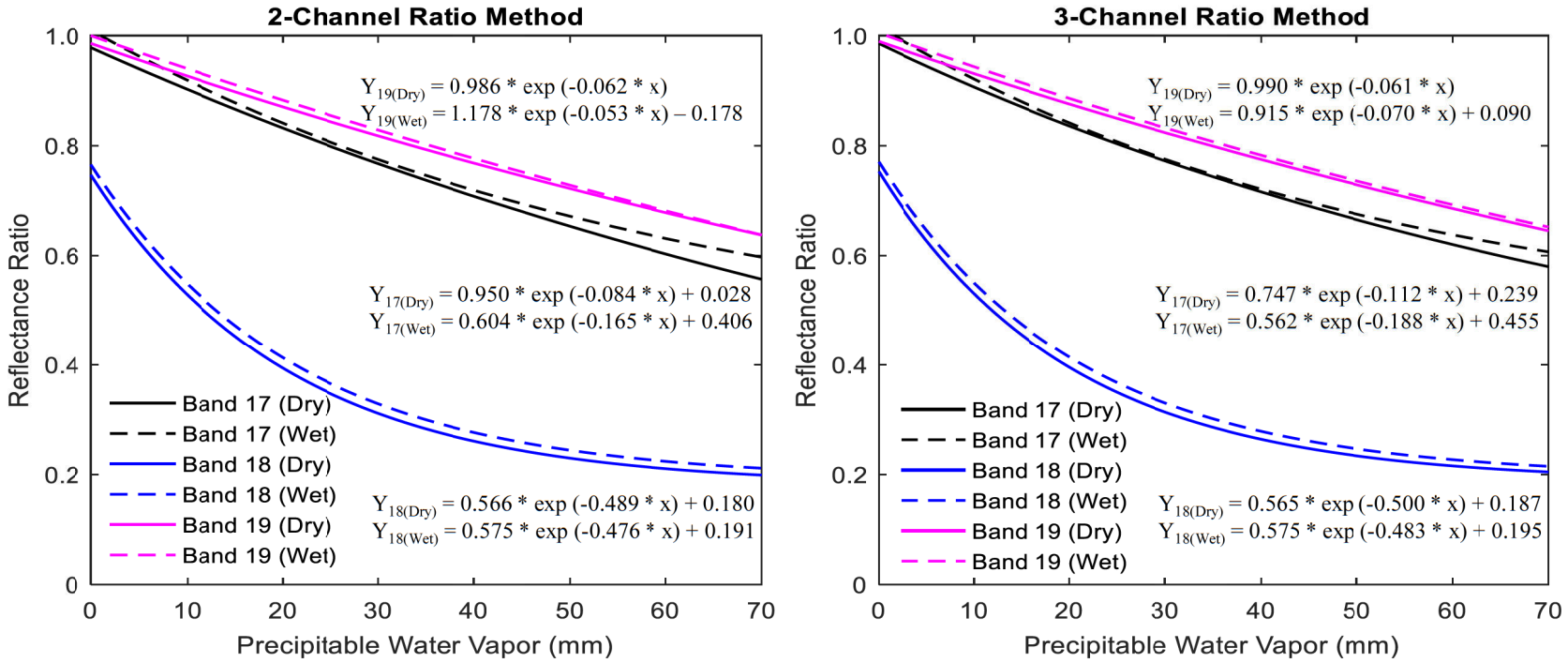
Calibration – Annual Regression



Annual Regression analysis to identify the relationship between reflectance ratio from PWV absorption channels of MERSI/FY-3B, and PWV measured by GPS, from Jan. 1st to Dec. 31st 2016, over western North America GPS stations. Data points with distance more than 3 std. are considered as outliers and they are excluded from the regression calculation.

2. Methodology

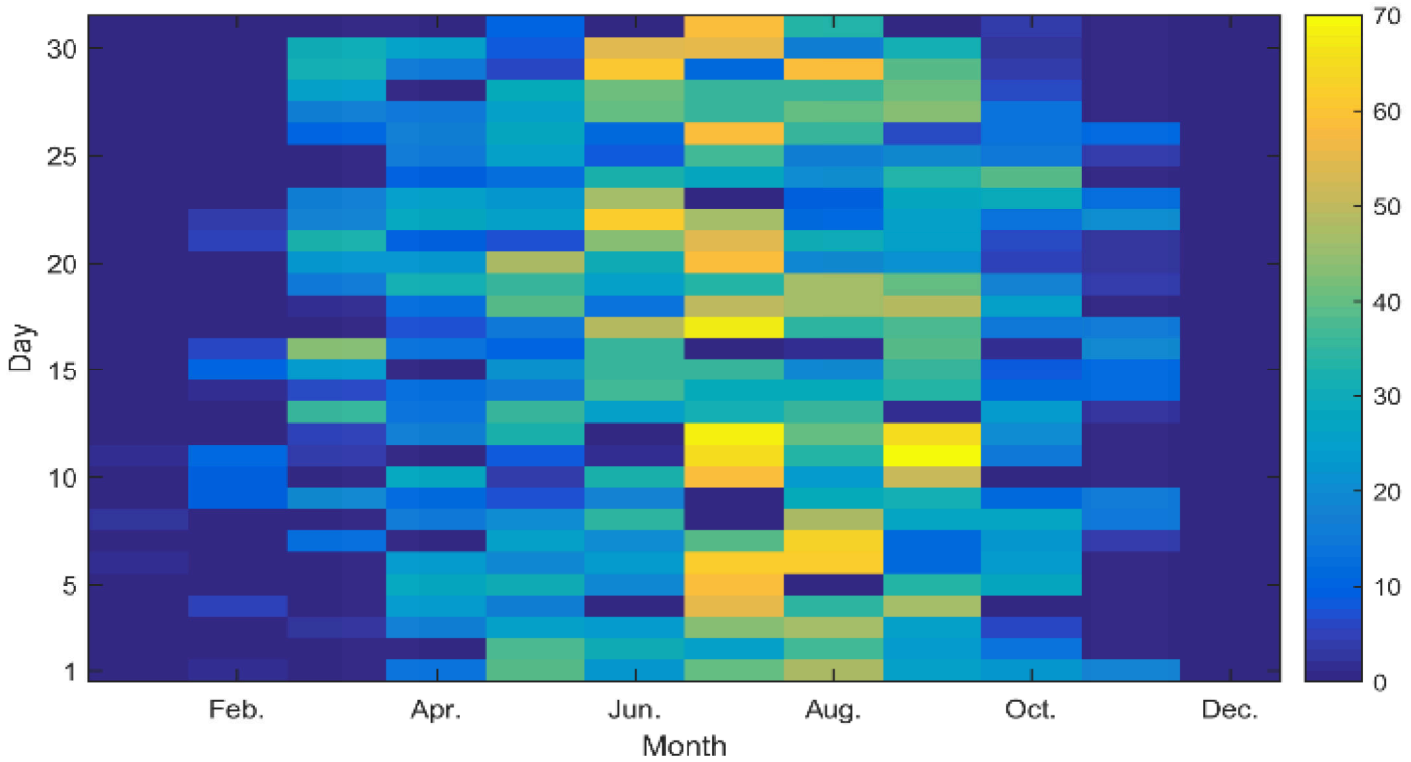
Calibration – Seasonal Regression



Seasonal Regression functions describing the relationship between reflectance ratio from PWV absorption channels of MERSI/FY-3B, and PWV measured by GPS over western North America. Solid lines represent functions obtained from data observed in **dry months** (Jan 01 to May 31 & Sep 01 to Dec 31 in 2016), and dashed lines are functions for **wet months** (June 01 to Aug 31 in 2016)

3. Validation

Number of Collocated Data Pairs for Validation Analysis

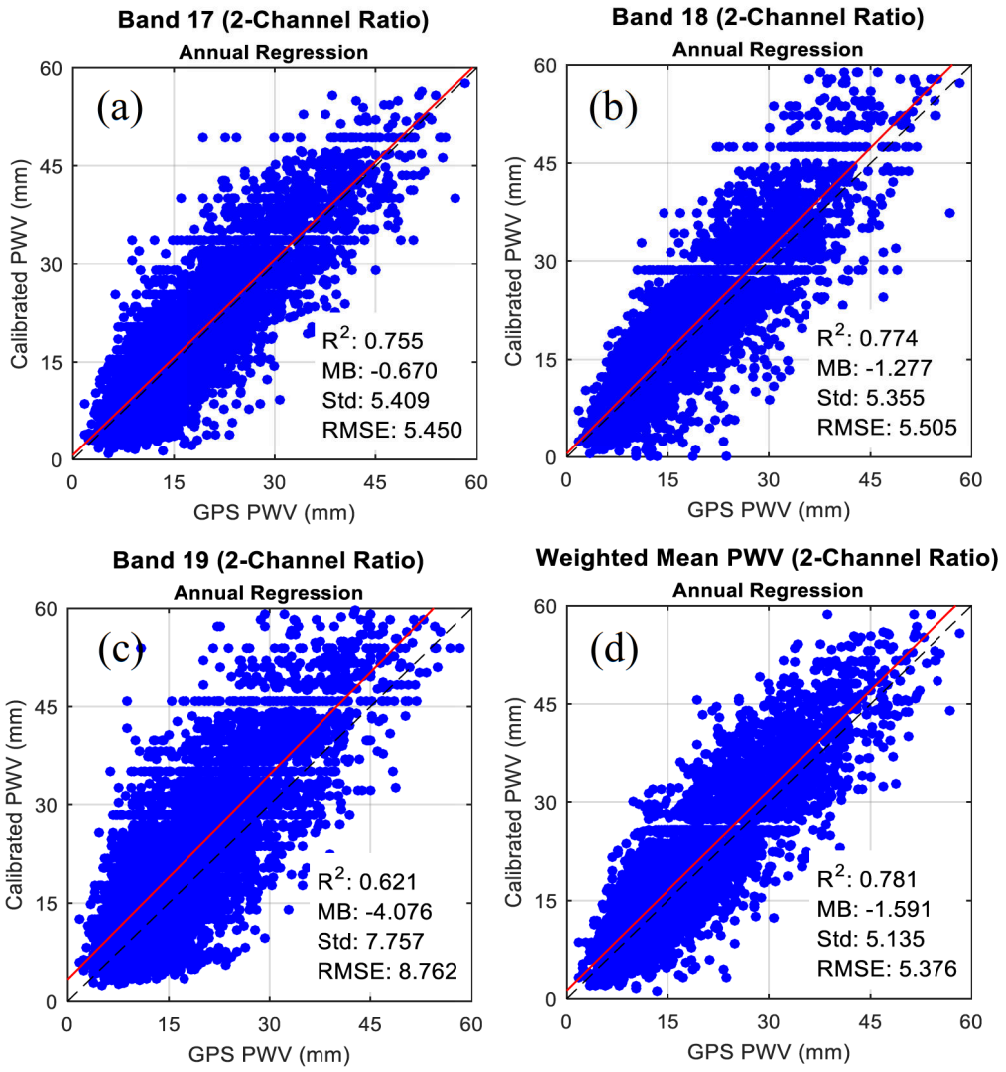


Number of collocated pairs of PWV data of cloud-free MERSI/FY-3B and GPS with **time difference < 30 minutes** recorded in each day of 2017 over western North America.

3. Validation—Annual Regression

- **Weighted mean value** from three absorption channels performs **better than single-channel observation**.
- Its RMSE is **5.376 mm**, **60.88%** smaller than operational product.

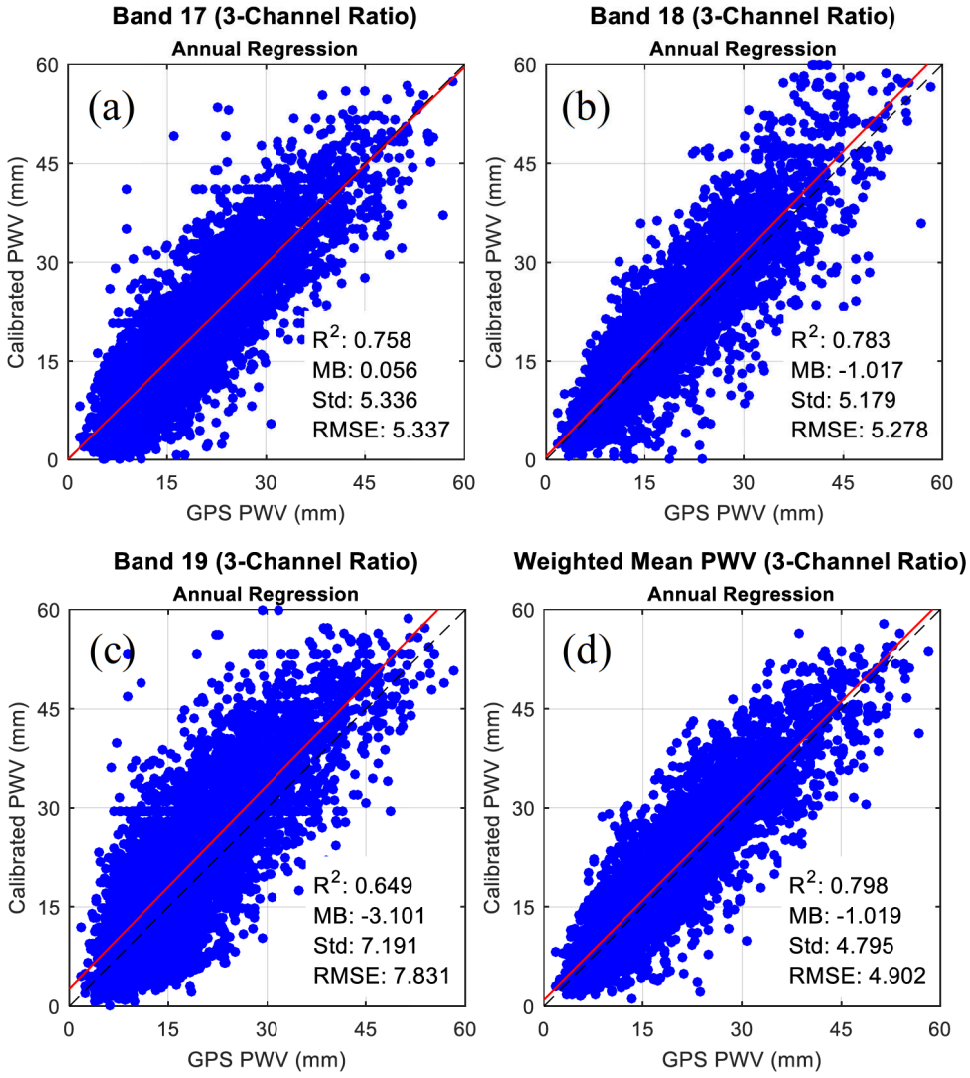
Validation analysis for the calibrated water vapor datasets from MERSI/FY-3B against collocated GPS PWV data over western North America, from Jan 1st to Dec 31st, 2017. Calibrated datasets are calculated with **annual regression functions** and **2-channel ratio method** from **(a) band 17** centered at 905 nm; **(b) band 18** centered at 940 nm; **(c) band 19** centered at 980 nm; **(d) weighted mean PWV** from three absorption channels.



3. Validation—Annual Regression

3-channel ratio method further improves the retrieval accuracy compared to **2-channel ratio method**

RMSE value for weighted mean value using 3-channel ratio method decreased to **4.902 mm**, with a reduction rate of **64.33%**

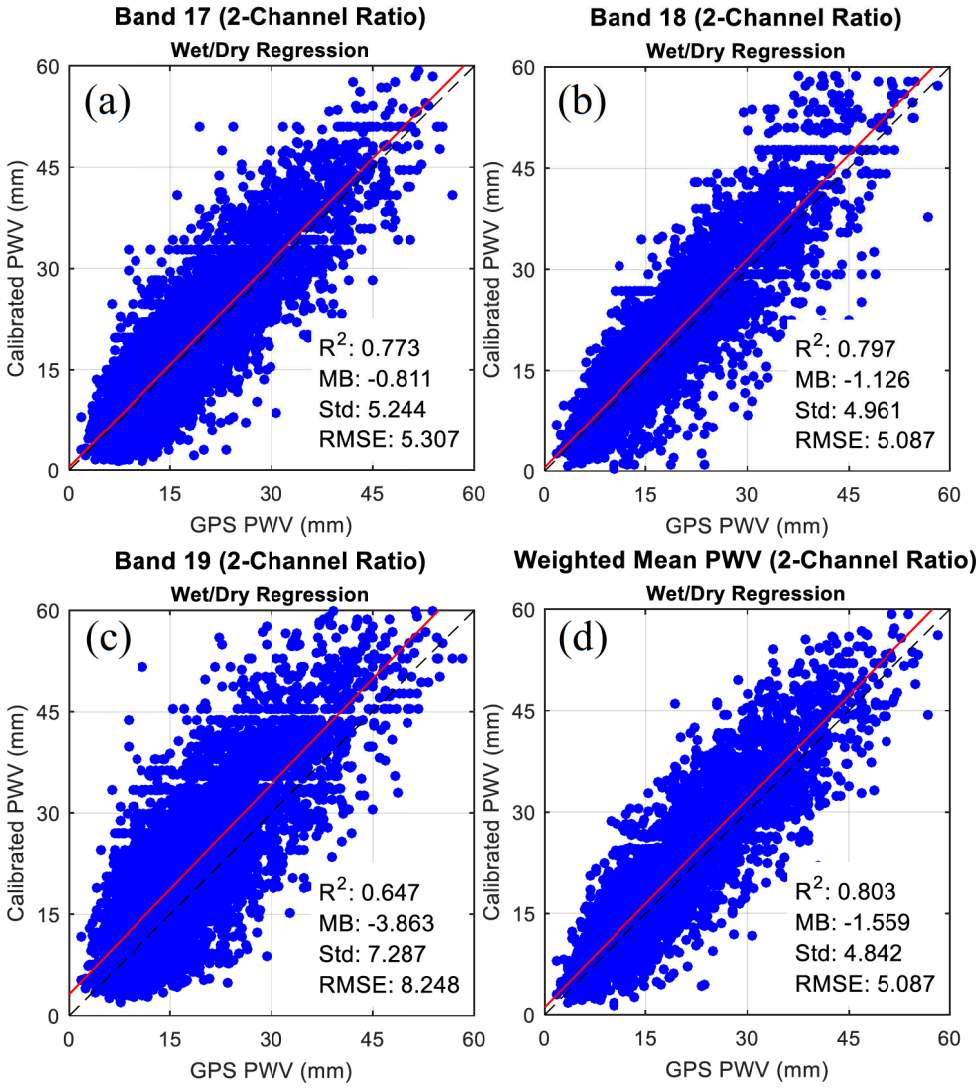


Validation analysis for the calibrated water vapor datasets from MERSI/FY-3B against collocated GPS PWV data over western North America, from Jan 1st to Dec 31st, 2017. Calibrated datasets are calculated with **annual regression functions** and **3-channel ratio method** from **(a) band 17**; **(b) band 18**; **(c) band 19**; **(d) weighted mean PWV** from three absorption channels

3. Validation—Wet / Dry Regression

June to August are defined as wet months, while other months are dry months;
Weighted mean PWV and PWV observed in band 18 have the same RMSE value, but the R^2 of weighted mean PWV is larger.

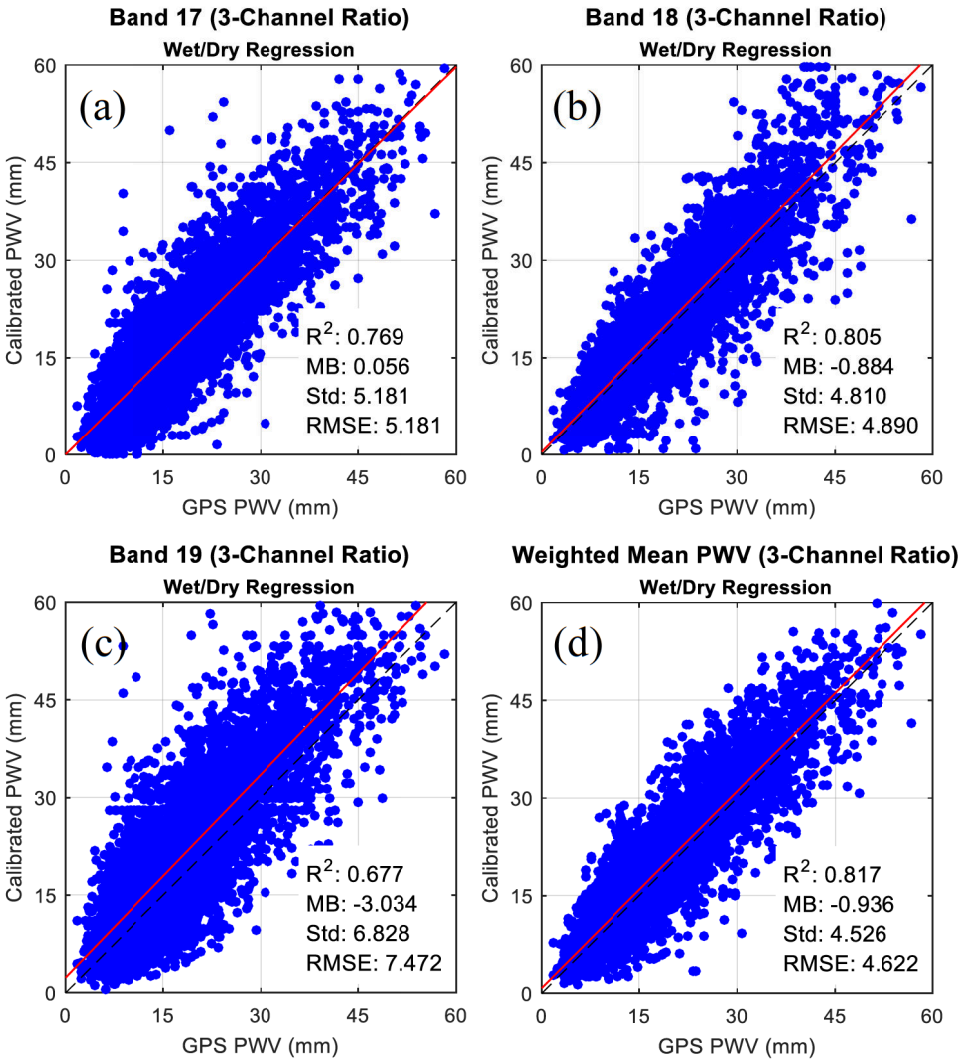
Validation analysis for the calibrated water vapor datasets from MERSI/FY-3B against collocated GPS PWV data over western North America, from Jan 1st to Dec 31st 2017. Calibrated datasets are calculated with wet/dry regression functions and **2-channel ratio method** from **(a) band 17**; **(b) band 18**; **(c) band 19**; **(d) weighted mean PWV** from three absorption channels.



3. Validation—Wet / Dry Regression

The weighted mean PWV calculated using wet/dry regression with **3-channel ratio method** has the best retrieval results, with the RMSE value of **4.622 mm**. The RMSE reduction rate for this dataset is **66.37%**.

Validation analysis for the calibrated water vapor datasets from MERSI/FY-3B against collocated GPS PWV data over western North America, from Jan 1st to Dec 31st 2017. Calibrated datasets are calculated with wet/dry regression functions and **3-channel ratio method** from **(a) band 17**; **(b) band 18**; **(c) band 19**; **(d) weighted mean PWV** from three absorption channels



4. Result Summary

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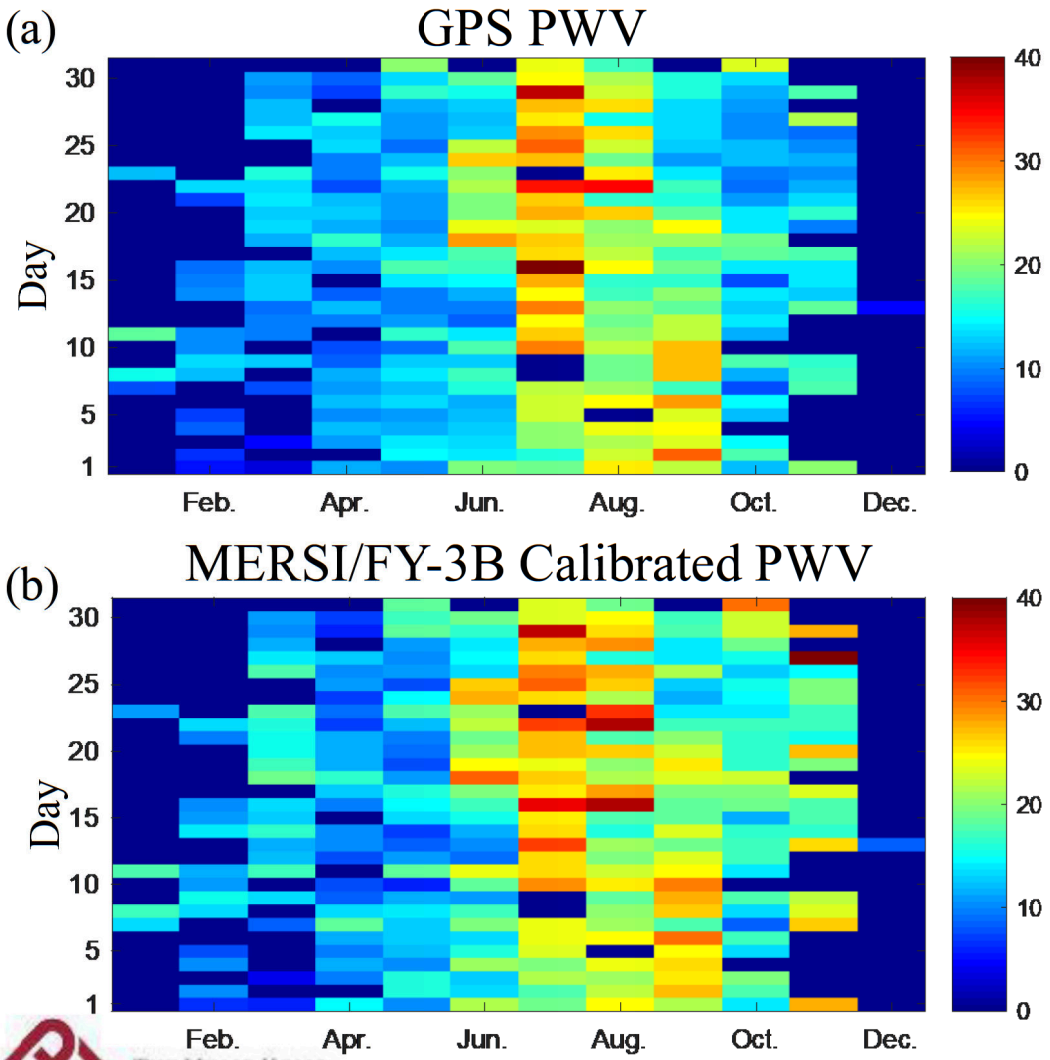
Calibration results for Jan 1st to Dec 31st 2017. The **operational** column is PWV product accuracy of MERSI/FY-3B for July 1st-10th, 2017 (obtained from CMA). RMSE reductions are compared against the **operational** PWV product accuracy

	Different Ratio Method	Band 17			Band 18			Band 19			Weighted Mean PWV		
		Operational	Annual	Wet/Dry	Operational	Annual	Wet/Dry	Operational	Annual	Wet/Dry	Operational	Annual	Wet/Dry
R^2	2-Channel	0.739	0.755	0.773	0.763	0.774	0.797	0.553	0.621	0.647	0.773	0.781	0.803
	3-Channel		0.758	0.769		0.783	0.805		0.649	0.667		0.798	**0.817**
MB	2-Channel	14.982	-0.670	-0.811	12.424	-1.277	-1.126	12.371	-4.076	-3.863	12.966	-1.591	-1.559
	3-Channel		0.056	0.056		-1.017	-0.884		-3.101	-3.034		-1.019	-0.936
Std	2-Channel	4.786	5.409	5.244	4.895	5.355	4.961	5.384	7.757	7.287	4.560	5.135	4.842
	3-Channel		5.336	5.181		5.179	4.810		7.191	6.828		4.795	**4.526**
RMSE	2-Channel	15.728	5.450	5.307	13.354	5.505	5.087	13.371	8.762	8.248	13.744	5.376	5.087
	3-Channel		5.337	5.181		5.278	4.890		7.831	7.472		4.902	**4.622**
RMSE Variation	2-Channel	-	-65.35%	-66.26%	-	-58.78%	-61.91%	-	-34.47%	-38.31%	-	-60.88%	-62.99%
	3-Channel		-66.07%	-67.06%		-60.48%	-63.38%		-41.43%	-44.12%		-64.33%	-66.37%

Weight mean PWV using 3-channel method and wet/dry function has the best performance (unit: mm)

4. Results —Daily Mean PWV

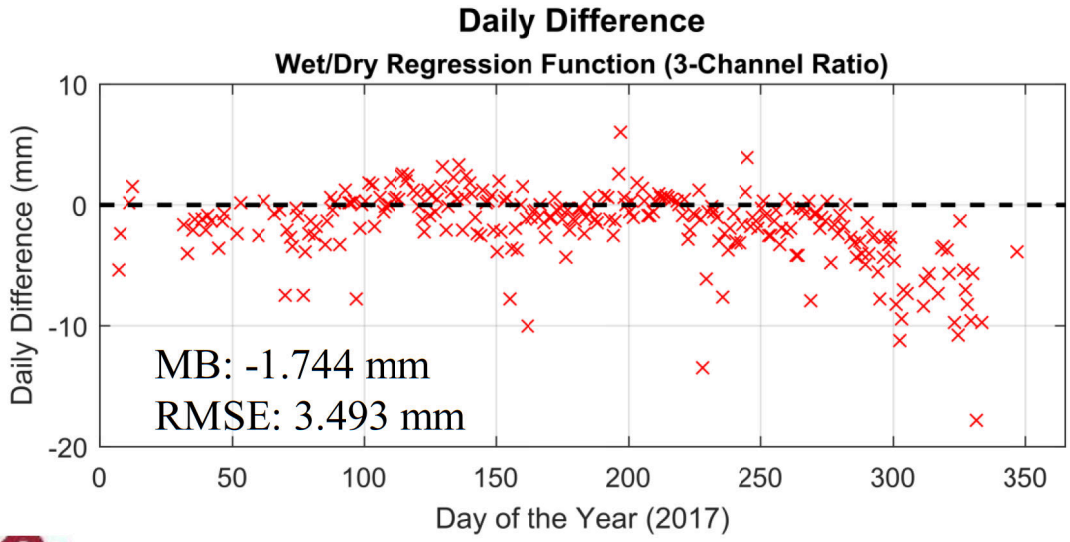


Daily mean PWV over western North America, from Jan 1st to Dec 31st 2017 (Unit: mm). (a) PWV observed from GPS stations; (b) **Weighted mean PWV** calculated from MERSI/FY-3B using **wet/dry regression functions (estimated from 2016 data)** and **3-channel ratio method**.

4. Results —Daily Mean PWV

Difference of Daily Mean PWV against GPS in 2017

- The daily mean PWV obtained from calibrated MERSI/FY-3B agrees well with GPS observed data;
- The mean bias for between GPS and calibrated MERSI PWV is **-1.744 mm,** and **RMSE** is **3.493 mm**;
- Wet bias for calibrated product was observed in November.



Daily difference of PWV observed from GPS and **weighted mean MERSI PWV** calculated from **wet/dry regression** functions with **3-channel ratio method** in 2017 over western North America.

4. Conclusions

- **Directly/independently** derive PWV data from FY-3B's MERSI sensor, based on GPS PWV
- The derived PWV has **much higher accuracy** than the MERSI PWV product itself
- **When compared to GPS PWV (SuomiNet):**
  - **uncalibrated** MERSI PWV (MERSI water vapor product) for the 10-day period (only 1-10 July 2017, other days' data not available from CMA) is **13.744 mm**
  - **calibrated** MERSI PWV for the whole year 2017 has an accuracy of **4.622 mm,** a reduction of **66.37% compared to 13.744 mm**
  - **calibrated** MERSI daily mean PWV for the whole year 2017 has an accuracy of **3.493 mm**

4. Conclusions

- The optimal calibration strategy is:
  - Weighted mean PWV using three channels
  - Using Wet/Dry Regression function
  - Using 3-channel ratio method
- For single channel, Band 18 (940 nm)
  - Has **strongest** absorption
  - Performs the **best**
  - Reduces PWV RMSE **from 13.354 mm to 4.890 mm,** a reduction of **63.38%**
- For single channel, Band 19 (980 nm)
  - Has **weakest** absorption
  - Performs the **worst**
  - Reduces PWV RMSE **from 13.371 mm to 8.762 mm**, a reduction of **34.47%**

5. Discussion

- GPS PWV data used in this research are obtained from SuomiNet Network
- GPS data are processed in 1-hour segments
- Compared with satellite remote sensing, it has **high temporal resolution** and **NOT affected by cloud**
- However, spatial resolution is coarser than remote sensing satellite

- Revisit period of FY-3B polar-orbiting satellite is **twice a day**, during day and night time
- NIR channels observe water vapor only during **daytime under cloud-free conditions**
- Spatial resolution is **1,000 m**

- **Significant accuracy improvement (34.47% to 66.37%)** in PWV retrieval has been shown compared to operational MERSI/FY-3B PWV products
- Moreover, GPS calibrated results significantly **reduces the dry bias** in MERSI NIR channels

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Zhizhao (George) LIU & Jia HE

Micro-Laboratory of Atmospheric Research and Geomatics Engineering
(Micro-LARGE)
Department of Land Surveying & Geo-Informatics
The Hong Kong Polytechnic University, Hong Kong, China
Email: lszzliu@polyu.edu.hk

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Appendix

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Summary of the validation results for the calibrated PWV retrieved from MERSI/FY-3B during **July 1st-10th 2017**. The calibrated PWV were calculated using annual and wet/dry regression functions with both 2-Channel ratio method and 3-Channel ratio method.

	Different Ratio Method	Band 17			Band 18			Band 19			Weighted Mean PWV		
		Operational	Annual	Wet/Dry	Operational	Annual	Wet/Dry	Operational	Annual	Wet/Dry	Operational	Annual	Wet/Dry
R^2	2-Channel	0.739	0.766	0.777	0.763	0.774	0.775	0.553	0.635	0.635	0.773	0.793	0.792
	3-Channel		0.768	0.769		0.782	0.783		0.649	0.652		0.803	0.802
MB	2-Channel	14.982	0.379	-0.539	12.424	-0.048	-0.719	12.371	-2.524	-3.276	12.966	-0.385	-1.169
	3-Channel		0.975	0.446		0.188	-0.460		-1.792	-2.57		0.089	-0.498
Std	2-Channel	4.786	5.066	4.923	4.895	5.380	5.274	5.384	7.731	7.252	4.560	5.073	4.943
	3-Channel		5.044	4.823		5.167	5.063		7.145	6.896		4.745	**4.627**
RMSE	2-Channel	15.728	5.080	4.952	13.354	5.380	5.322	13.371	8.132	7.957	13.744	5.088	5.079
	3-Channel		5.137	4.843		5.170	5.084		7.366	7.359		4.746	**4.653**
RMSE Variation	2-Channel	-	-67.70%	-68.51%	-	-59.71%	-60.15%	-	-39.18%	-40.49%	-	-62.98%	-63.05%
	3-Channel		-67.34%	-69.21%		-61.29%	-61.93%		-44.91%	-44.96%		-65.47%	-66.15%