



A Homogenized Global Comparison of DORIS and GNSS-Derived Zenith Tropospheric Delay (ZTD) Time Series (2016-2025) Using GINS

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OBJECTIVES

➤ **Build a Long-Term Global Zenith Total Delay Record (2016-2025)**

Develop a global ZTD data set using DORIS observations processed with CNES' GINS software.

➤ **Validate DORIS ZTD Against Co-Located GNSS (IGS)**

Use co-located IDS-IGS stations to compare ZTDs at matched epochs.

➤ **Quantify Technique Differences and Uncertainties**

Estimate bias, RMS, and drift between DORIS/GNSS ZTD solutions and ERA5 data. The European Center for Medium-Range Weather Forecasts (ECMWF) produces ERA5 (global atmospheric reanalysis dataset).

Unlike operational weather forecasts (which change models over time), ERA5 uses the *same model throughout the period*, making it suitable for climate studies.

MOTIVATION

- Very long-time span series with stable sites, which is not the case for GNSS (often antenna change); DORIS network is managed by CNES and IGN.
- ZTD measured by space geodetic techniques (DORIS) provides a stable, all-weather estimate of atmospheric water vapor, making it a key variable for climate monitoring and hydrological cycle studies. According to the Clausius-Clapeyron relation, for every 1°C increase in temperature, the atmosphere's saturation water vapor capacity increases by ~7%.

Stations for Analysis

A max. separation of 1 km between IGS and IDS stations is adopted to ensure both instruments observe the same atmospheric column, except for Toulouse which was retained as both stations are part of the same GRGS/CNES geodetic site and operate within a common local geodetic environment.

DORIS Station	DORIS ID	GPS ID	DORIS-GPS 3D Distance (m)
LIBREVILLE	LICB	NKLG	10.882
DJIBOUTI	DJIB	DJIG	55.717
TOULOUSE	TLSB	TLSE	1272.012
YELLOWKNIFE	YEMB	YELL	48.84
GREENBELT	GRFB	GODE	239.095
METSAHOVI	MEUB	METG	18.871
KOUROU	KRWB	KOUG	16.882
ASCENSION	ASEB	ASCG	9.999
LE-LAMENTIN	LAOB	LMMF	24.359
AREQUIPA	ARFB	AREG	40.288
PAPEETE	PAUB	THTG	5.57
HARTEBEESTHOEK	HBMB	HARB	24.889
YARRAGADEE	YASB	YAR2	48.088
MOUNT-STROMLO	MSPB	STR1	64.036
MOUNT-STROMLO	MSPB	STR2	17.185

Colocation < 1 km
Stations = 15, Sites = 14

Stations for Analysis

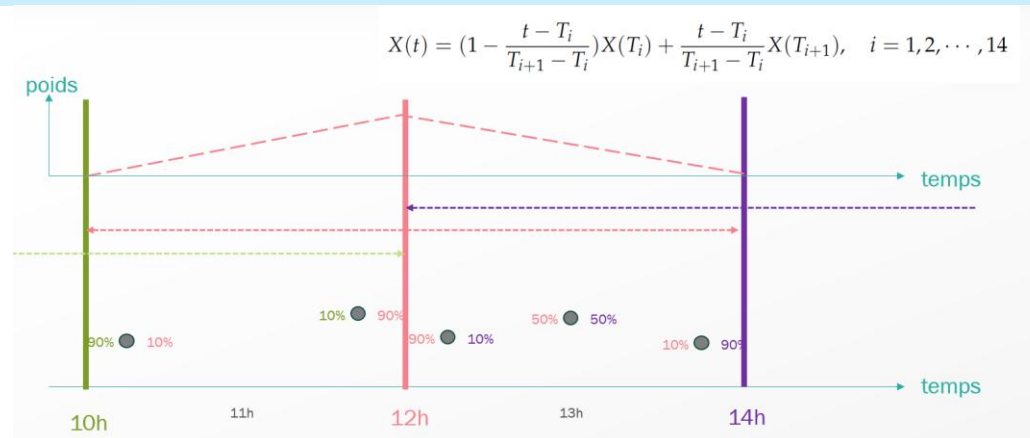
- ✓ Equatorial: Libreville, Djibouti
- ✓ Northern Hemisphere: Toulouse, Yellowknife, Greenbelt, Metsahovi
- ✓ SAA: Kourou, Ascension, Le-Lamentin, Arequipa
- ✓ Southern Hemisphere: Papeete, Hartebeesthoek, Yarragadee, Mont Stromlo



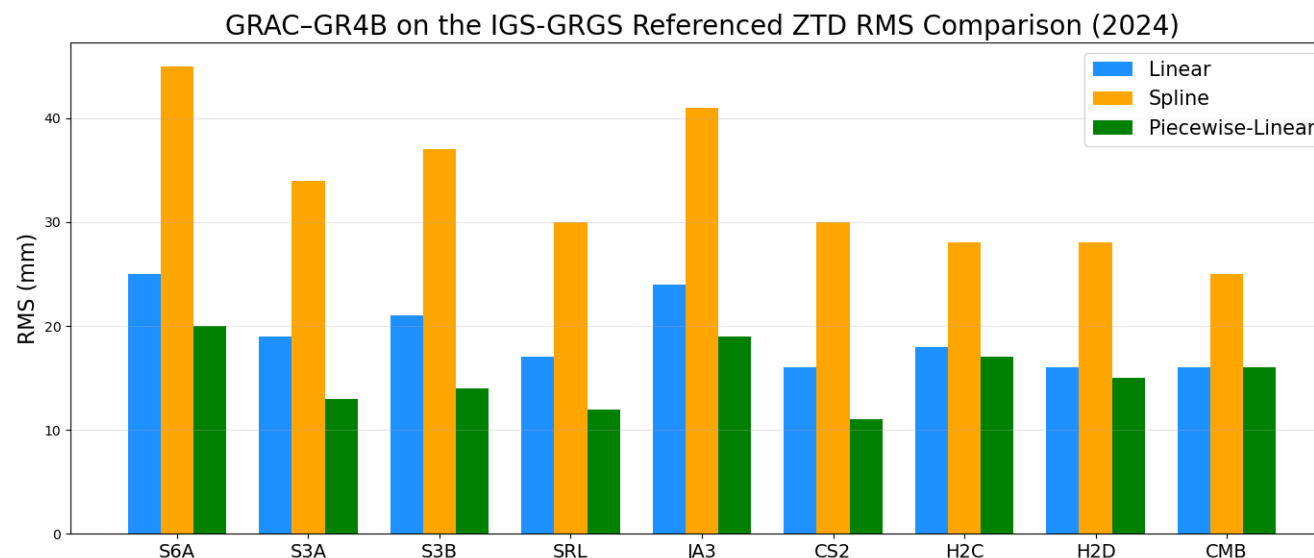
Different Solutions for analysis

- ❑ **GRG IDS:** From the CNES/CLS DORIS solutions processed with GINS Software with S.I. of 1 hour.
- ❑ **GRG IGS:** From the CNES/CLS IGS solutions processed with GINS Software with S.I. of 2 hours.
- ❑ **IGS Product:** From the CDDIS with the S.I. of 5 min.
- ❑ **ERA5:** From the ECMWF with S.I. of 6 hours.
- **Our interpolation strategy** proceeded from higher to lower data densities, and the methodology was applied consistently across all chosen co-located stations.
- **All solutions** are epoch-aligned to the IGS-GRGS 2-hour grid using piecewise-linear interpolation, with IGS Product as the reference and 6-hour grid with ERA5 as the reference.

Interpolation Methods for IDS (GRASSE)



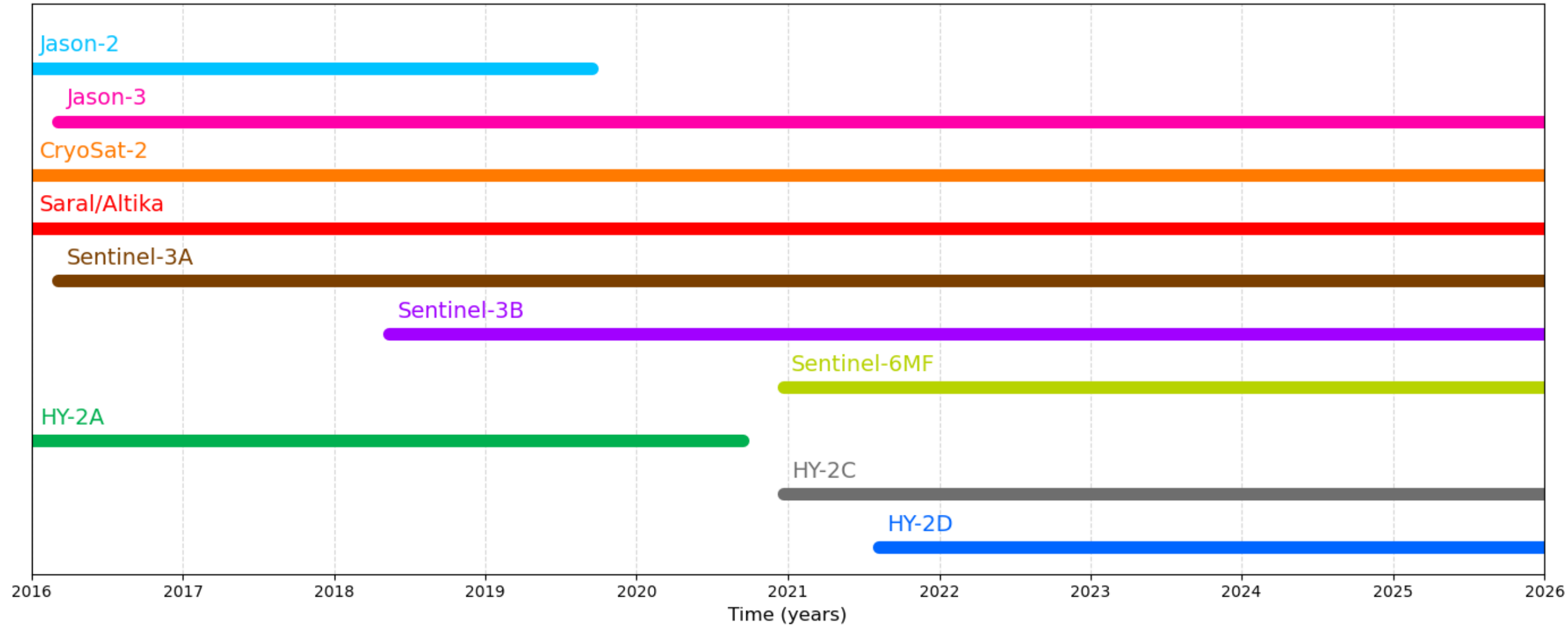
- Ex: Tropospheric at 12h is computed from data 10 am to 14 pm. So, a measure at 13 pm will contribute at 50% to the 12 pm tropospheric parameter and 50% to the 14 pm tropospheric parameter.
- All series were interpolated onto a common temporal grid using piecewise-linear. This method was selected after testing linear and cubic spline interpolation, as it provided the most stable residual behavior.



Different Satellites for analysis

IDS-GRGS solution is the combined solution of all available altimeter satellites.

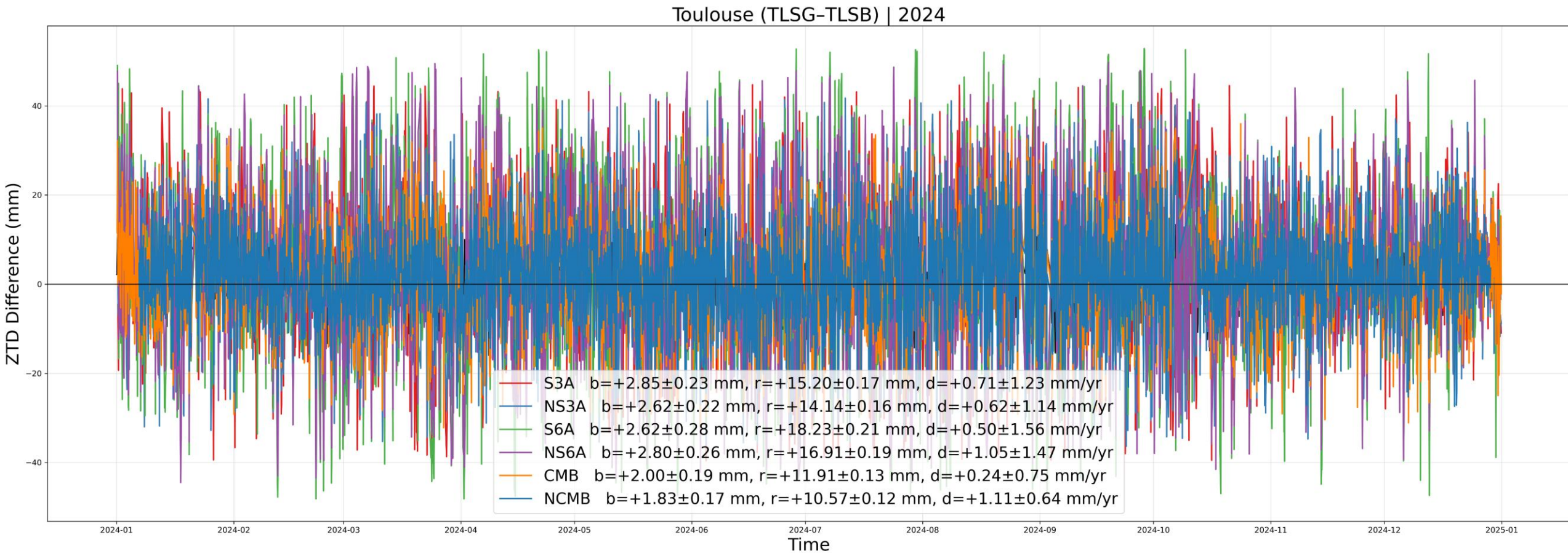
Satellite availability



DORIS Altimeter Satellites availability during the analysis period

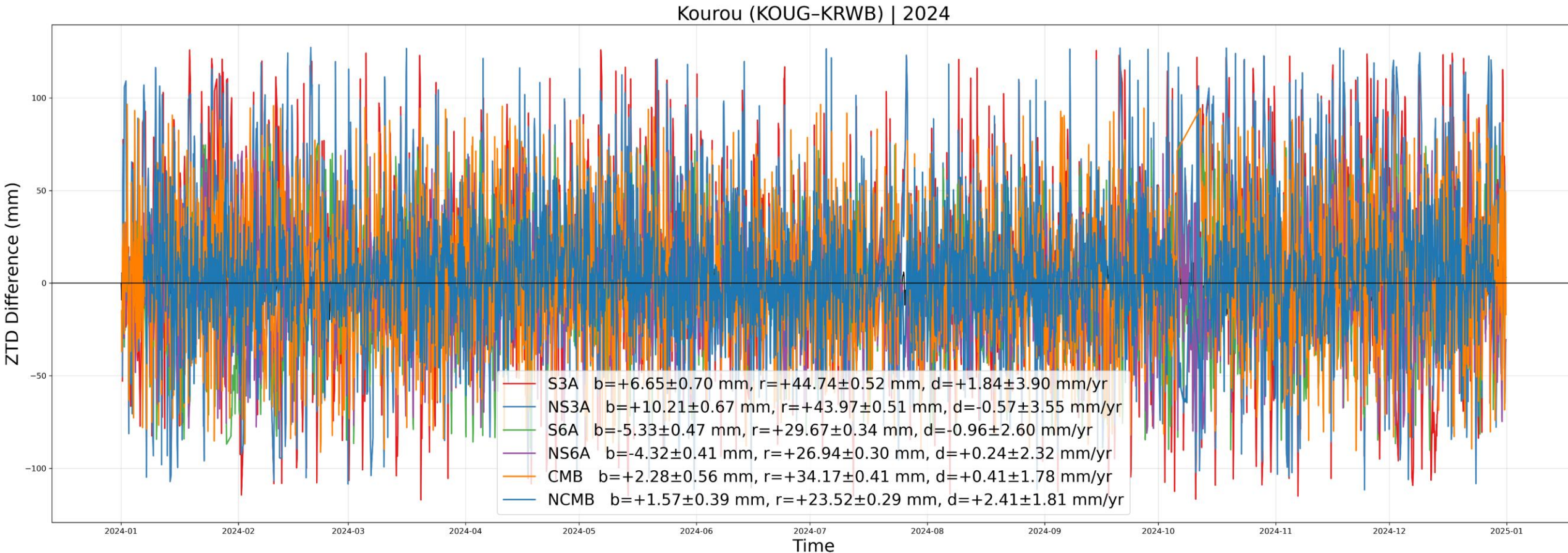
TOULOUSE

- ✓ S3A, S6A, CMB – 10° Cutoff
- ✓ NS3A, NS6A, NCMB – 7° Cutoff

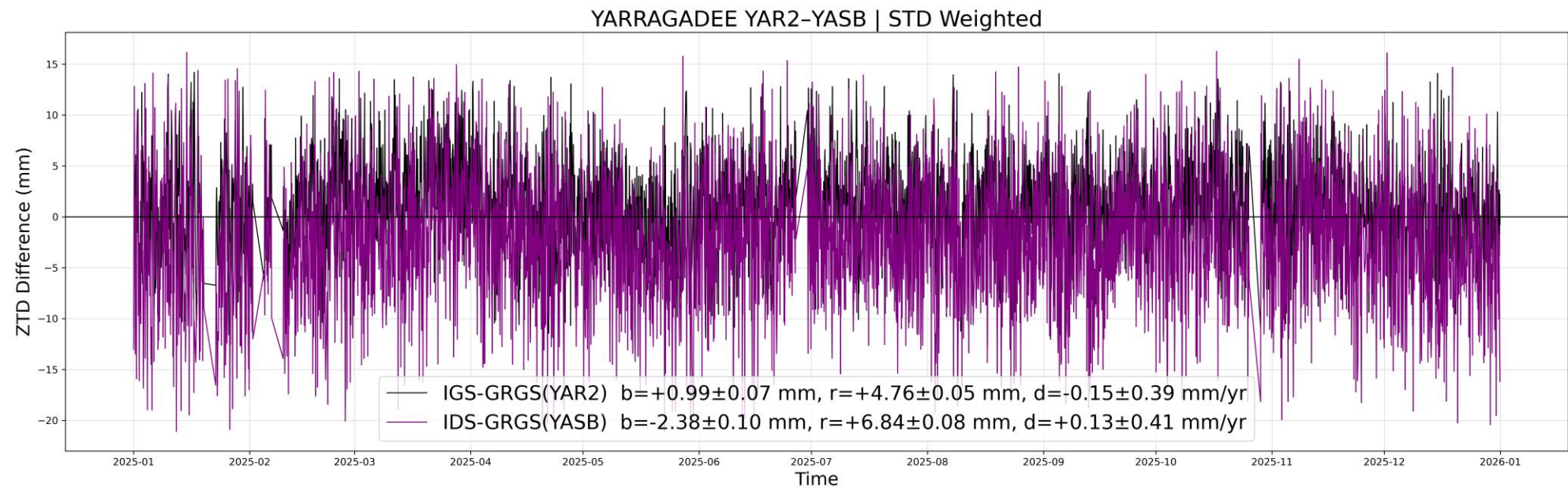
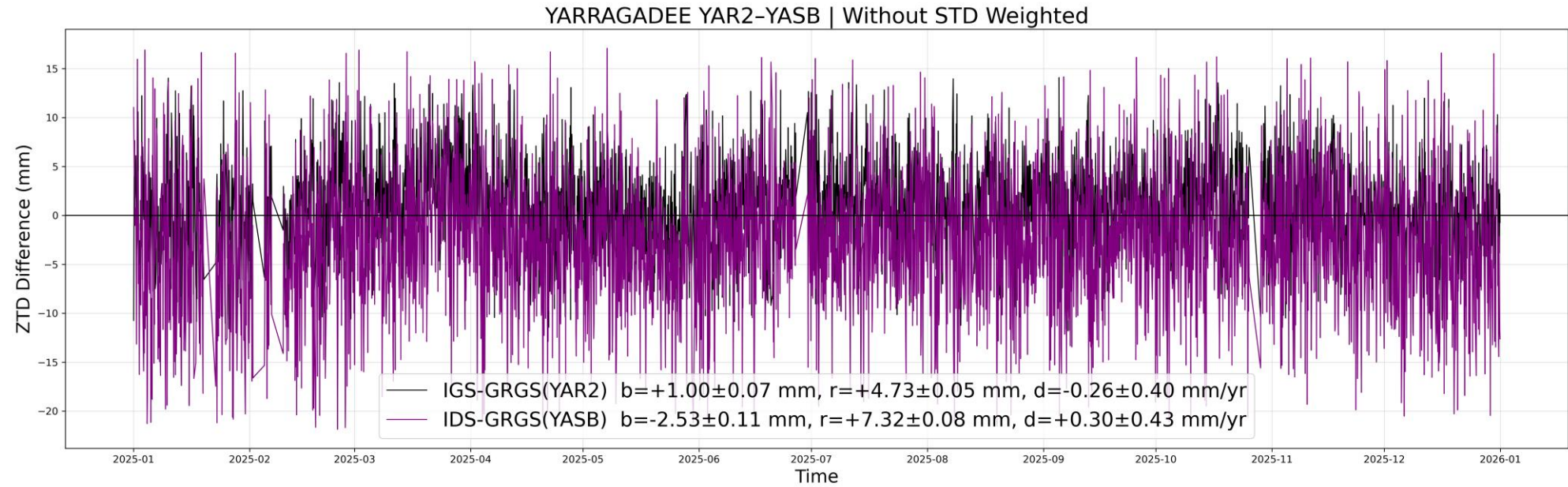


KOUROU

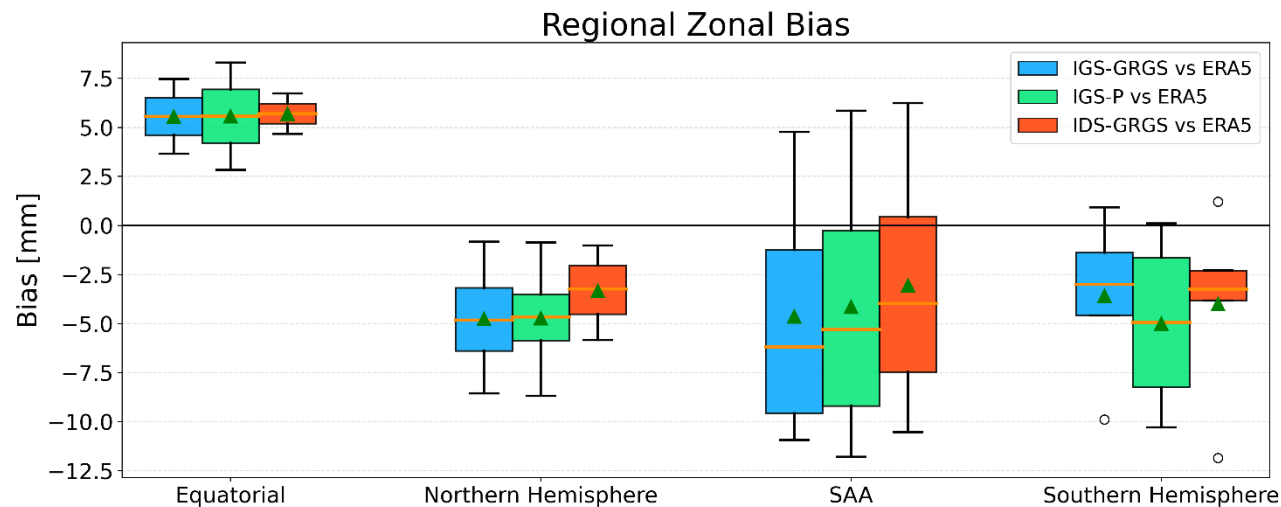
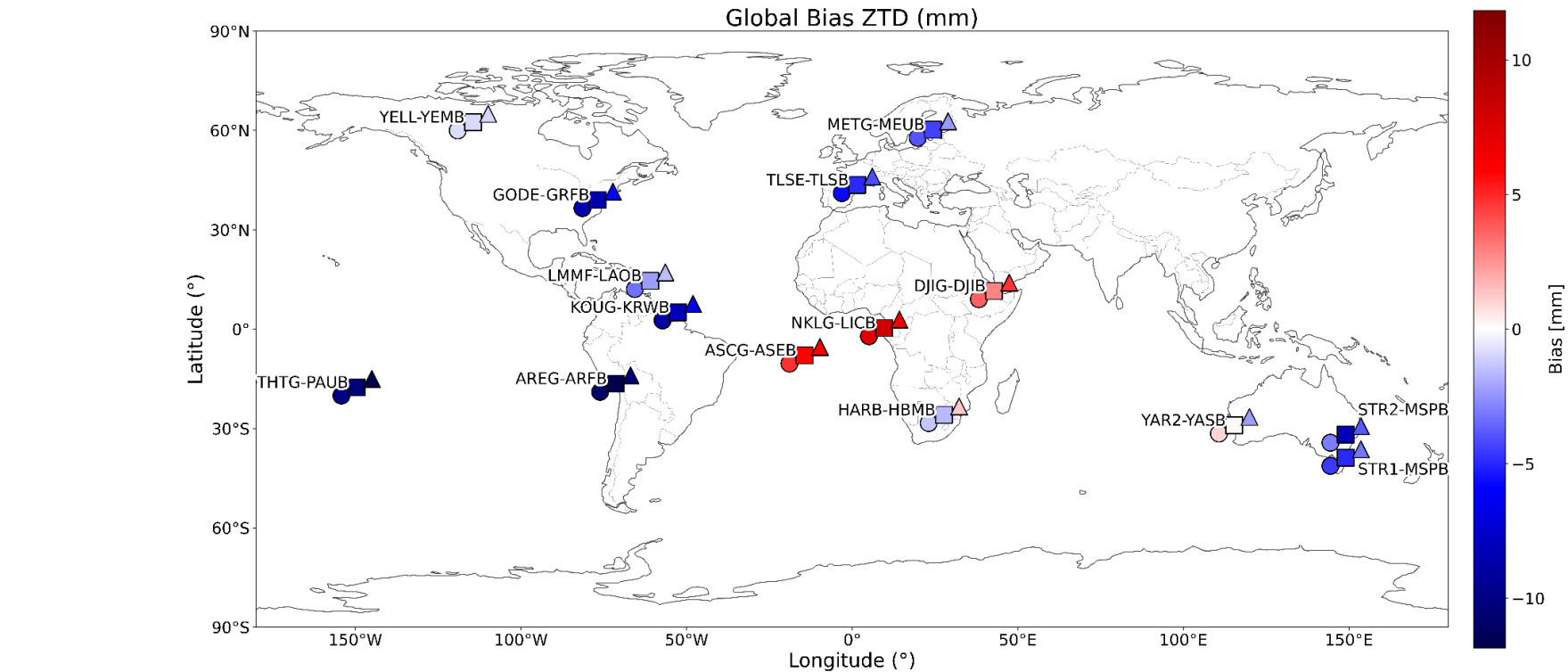
- ✓ S3A, S6A, CMB – 10° Cutoff, satellites impacted by the SAA effect at SAA stations
- ✓ NS3A, NS6A, NCMB – 7° Cutoff, Excluding satellites impacted by the SAA effect at SAA stations



Weighted STD Comparison (Yarragadee)

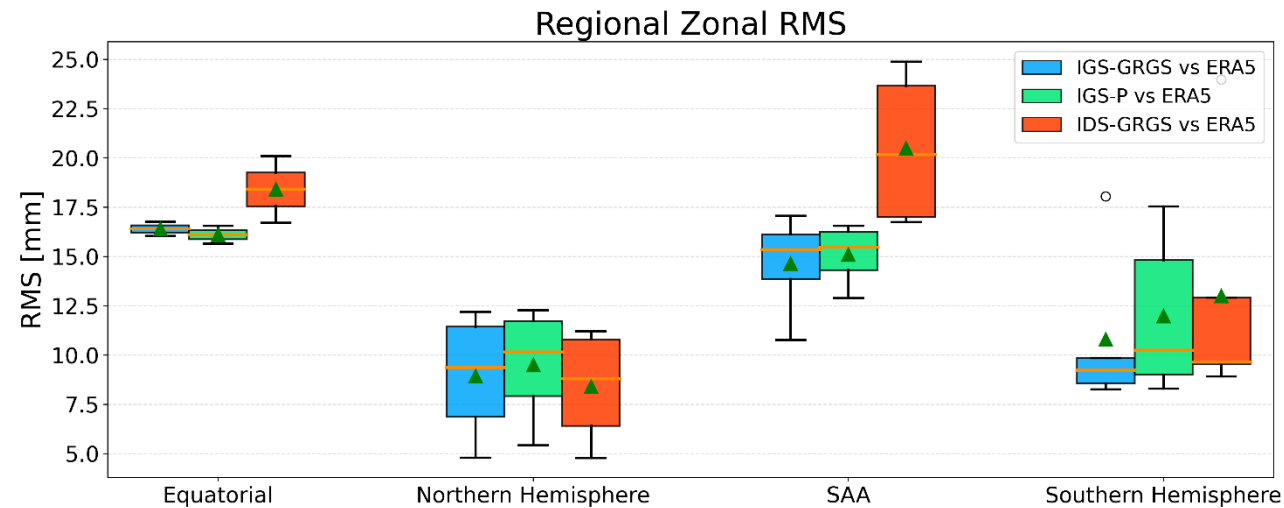
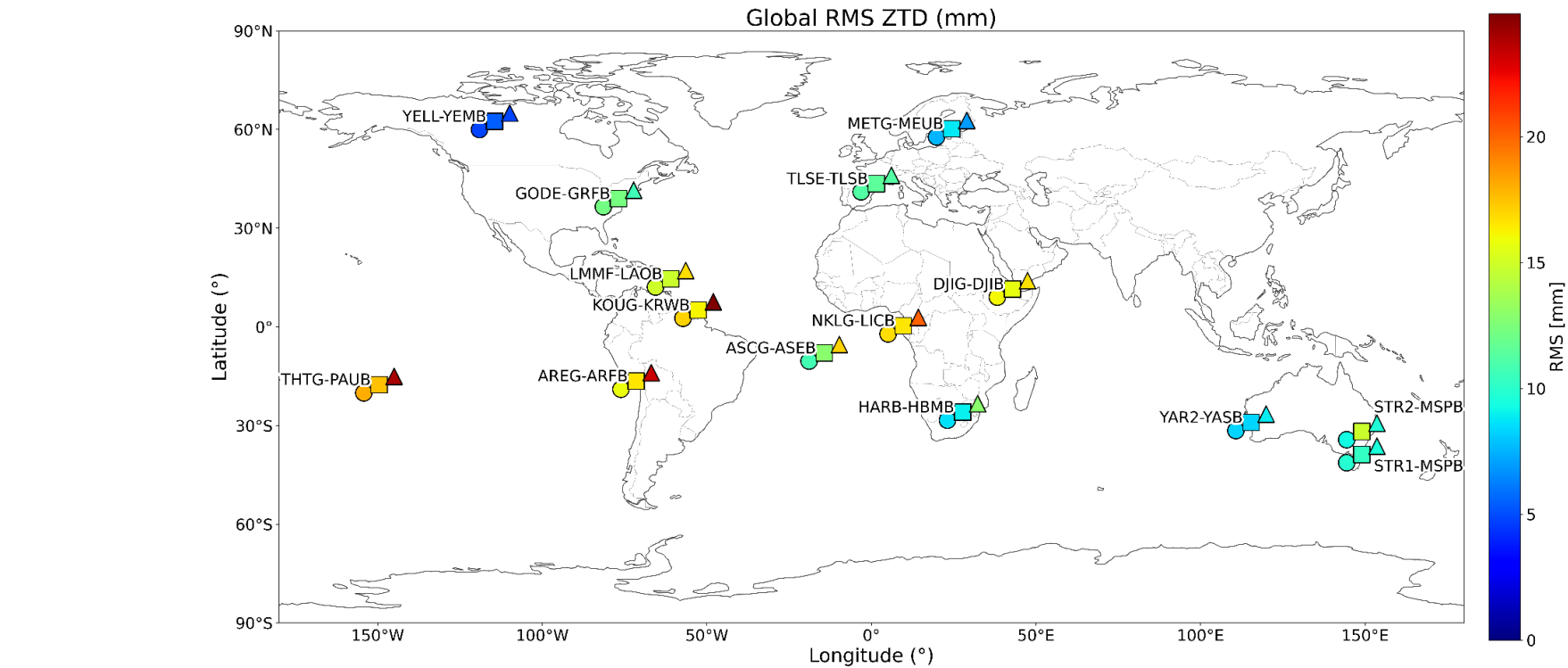


Bias Comparison with ERA5



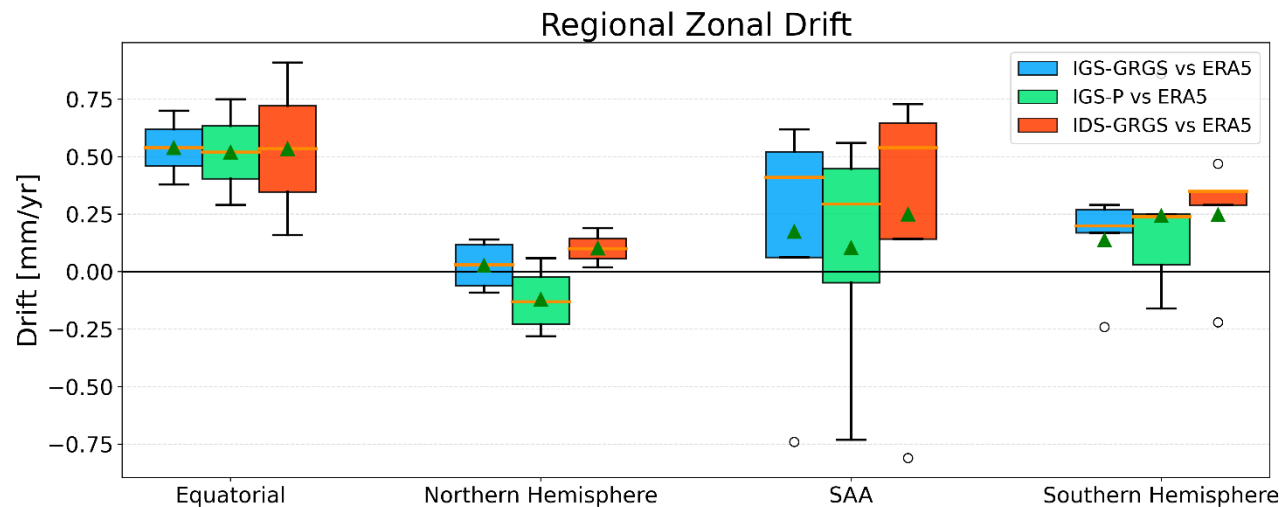
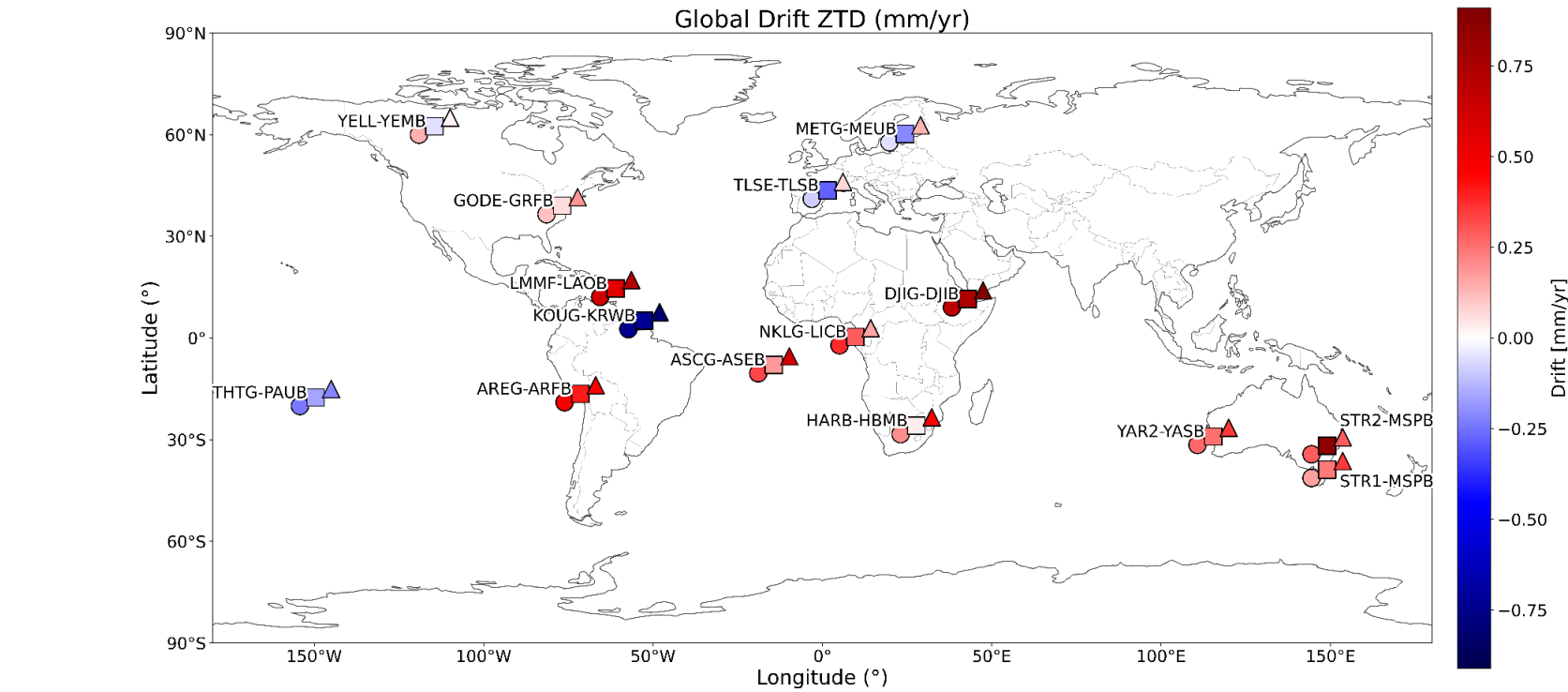
- All biases are negative w.r.t. ERA5, except for the Equatorial region (with more humidity), where the bias is positive. DORIS has the lowest biases w.r.t. ERA5.

RMS Comparison with ERA5



- It highlights geographic variability, with highest dispersion in the SAA and equatorial regions and lower RMS values at mid-latitudes.

Drift Comparison with ERA5



- Positive drifts are consistently seen by all solutions w.r.t. ERA5, apart from the Northern Hemisphere, where the trends are negligible w.r.t. ERA5.

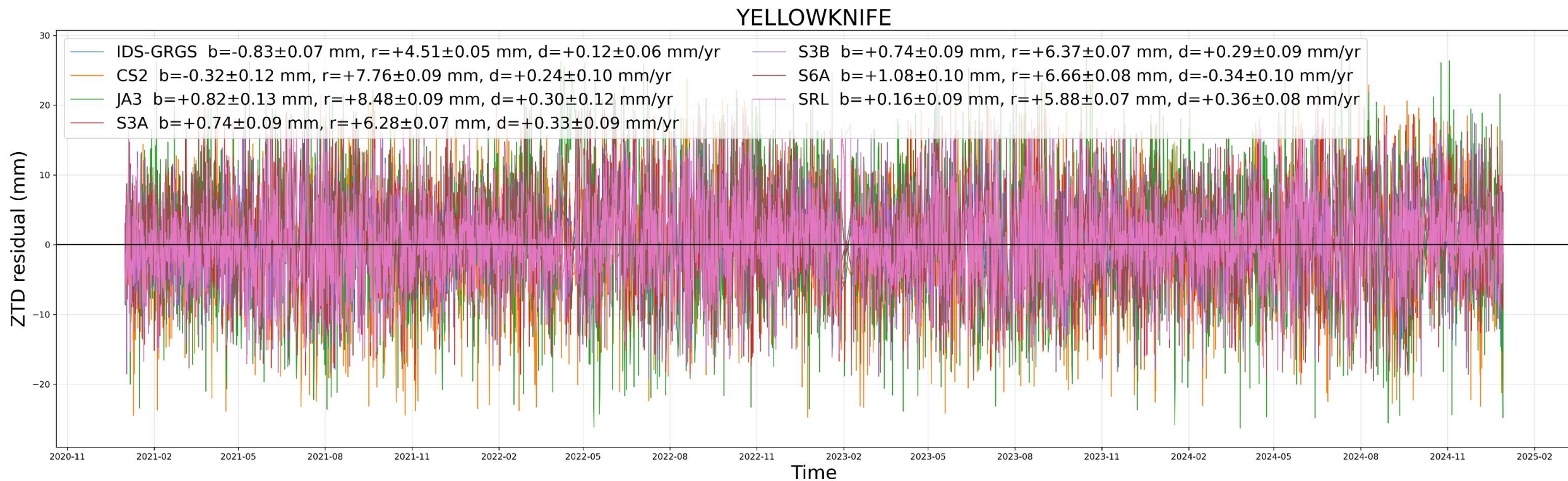
Solution's Comparison with ERA5

- ERA5 does not assimilate ground-based GNSS or DORIS ZTD observations, ensuring that the comparisons remain largely independent.
- Values in the table in blue color show the lowest bias, RMS, and drift along with their uncertainty for the solutions when compared with the ERA5 solution.
- **The DORIS solution has the highest number of the lowest biases.**

Table for solutions at IGS-GRGS epoch with ERA5 as the reference

Station	Bias (IGS-GRGS) mm	Bias (IGS-P) mm	Bias (IDS-GRGS) mm	RMS (IGS-GRGS) mm	RMS (IGS-P) mm	RMS (IDS-GRGS) mm	Drift (IGS-GRGS) mm/yr	Drift (IGS-P) mm/yr	Drift (IDS-GRGS) mm/yr
Arequipa	-10.92±0.06	-11.78±0.06	-10.52±0.10	15.82±0.05	16.56±0.05	23.26±0.09	0.49±0.05	0.41±0.05	0.46±0.07
Ascension	4.78±0.05	5.86±0.06	6.25±0.08	10.78±0.04	12.89±0.04	17.10±0.06	0.33±0.03	0.18±0.04	0.62±0.05
Djibouti	3.67±0.08	2.85±0.08	4.68±0.09	16.05±0.06	15.66±0.06	16.72±0.06	0.70±0.06	0.75±0.06	0.91±0.06
Greenbelt	-8.54±0.05	-8.67±0.05	-5.82±0.05	12.20±0.04	12.28±0.04	10.66±0.04	0.11±0.03	0.06±0.03	0.19±0.03
Hartebeesthoek	-1.37±0.04	-1.63±0.05	1.22±0.07	8.57±0.03	9.01±0.03	12.92±0.05	0.20±0.03	0.03±0.03	0.47±0.03
Kourou	-9.10±0.07	-8.32±0.07	-6.44±0.12	17.07±0.06	16.17±0.05	24.89±0.09	-0.74±0.05	-0.73±0.05	-0.81±0.07
Le-Lamentin	-3.25±0.07	-2.28±0.07	-1.49±0.08	14.90±0.05	14.80±0.05	16.75±0.06	0.62±0.05	0.56±0.05	0.73±0.06
Libreville	7.47±0.08	8.31±0.07	6.74±0.10	16.77±0.06	16.56±0.06	20.11±0.07	0.38±0.05	0.29±0.05	0.16±0.06
Metsahovi	-3.95±0.03	-4.40±0.04	-2.36±0.03	7.56±0.03	8.76±0.03	6.95±0.03	-0.05±0.02	-0.21±0.02	0.13±0.02
Mont-Stromlo-1	-4.57±0.04	-4.93±0.05	-3.23±0.05	9.86±0.03	10.25±0.04	9.56±0.03	0.17±0.03	0.24±0.03	0.35±0.03
Mont-Stromlo-2	-2.99±0.05	-8.24±0.07	-3.81±0.05	9.24±0.04	14.83±0.06	9.65±0.04	0.29±0.04	0.86±0.09	0.29±0.05
Papeete	-9.88±0.08	-10.28±0.07	-11.84±0.11	18.05±0.06	17.55±0.06	23.98±0.09	-0.24±0.05	-0.16±0.05	-0.22±0.06
Toulouse	-5.67±0.05	-4.91±0.05	-4.08±0.05	11.20±0.04	11.55±0.04	11.22±0.04	-0.09±0.03	-0.28±0.03	0.07±0.03
Yarragadee	0.94±0.04	0.12±0.04	-2.29±0.04	8.27±0.03	8.31±0.03	8.92±0.03	0.27±0.02	0.25±0.03	0.35±0.03
Yellowknife	-0.82±0.02	-0.86±0.03	-1.01±0.02	4.80±0.02	5.43±0.02	4.79±0.02	0.14±0.02	-0.05±0.02	0.02±0.01

ZTD Comparison with IGN Data



Single satellite DORIS tropospheric solutions (2021-2025) are from IGN's AC which when compared with ERA5 show mm-level bias, <10 mm RMS, and within ± 0.4 mm/yr drift, demonstrating stable and consistent ZTD performance.

Future Scope

- ❑ Our processing approach (GINS + piecewise-linear interpolation + GRGS or ERA5 reference framing) demonstrates that DORIS can deliver tropospheric delays consistent with IGS standards at a global level.
- ❑ We will explore the comparison of DORIS tropospheric data with altimetry and onboard radiometer data, aiming to evaluate its potential contribution to altimetric atmospheric corrections.

Co-located Sites between IDS and IGS GRG Solutions

Stations = 118, Sites = 46

Station	IDS ID	IGS ID	3-D Distance
ASCENSION	ASEB	ASCG	9.999
GRASSE	GR4B	GRAS	53.74
GRASSE	GR4B	GRAC	52.684
JIUFENG	JIWC	JFNG	12.043
JIUFENG	JIWC	WUH2	12973.038
JIUFENG	JIWC	WUHN	12972.657
JIUFENG	JIVB	WUHN	12972.647
KOUROU	KRWB	KOUG	16.882
KOUROU	KRWB	KOUR	25056.21
LE-LAMENTIN	LAOB	LMMF	24.359
MANILLE	MANB	PTGG	13.784
MANILLE	MANB	PTAG	41.929
MOUNT-STROMLO	MSPB	STR1	64.036
MOUNT-STROMLO	MSPB	STR2	17.185
RIO-GRANDE	RISC	RGDG	30.917
RIO-GRANDE	RISC	RIO2	40.817
RIO-GRANDE	RISC	RIOG	40.808
RIO-GRANDE	RIRB	RIOG	40.808
SAL	SARC	CPVG	12.672
SAL	SAQC	CPVG	12.669
SAL	SAPC	CPVG	12.671
SAL	SALB	CPVG	9.809
TOULOUSE	TLSB	TLSE	1272.012
TOULOUSE	TLSB	TLSG	16.049
YARRAGADEE	YASB	YARR	51.486
YARRAGADEE	YASB	YAR2	48.088
YARRAGADEE	YASB	YAR3	52.71
YELLOWKNIFE	YEMB	YEL2	56.676
YELLOWKNIFE	YEMB	YELL	48.84
TERRE ADELIE	ADHC	DUM1	12.678
TERRE ADELIE	ADHC	DUMG	6.798
AREQUIPA	ARFB	AREG	40.288
AREQUIPA	ARFB	AREQ	36.165
BADARY	BADB	BADG	4.291
CIBINONG	CIDB	CIBG	51.5
CIBINONG	CIDB	BAKO	42.011
CROZET	CRRC	CZTG	10.872
CROZET	CRQC	CZTG	10.891
CROZET	CRQB	CZTG	10.875

Station	IDS ID	IGS ID	3-D Distance
DIONYSOS	DIOB	DYNG	41.182
DJIBOUTI	DJIB	DJIG	61.881
FUTUNA	FUUC	FTNA	6.188
FUTUNA	FUUB	FTNA	6.189
GREENBELT	GRFB	GODE	206.029
GREENBELT	GRFB	GODS	70.418
GREENBELT	GRFB	GODN	141.45
GREENBELT	GRFB	USN3	23426.427
GREENBELT	GRFB	USN7	23426.485
GREENBELT	GRFB	USNO	23507.298
GREENBELT	GRFB	NRL1	27929.311
GREENBELT	GRFB	WDC5	23429.702
HARTEBEESTHOEK	HBMB	HARB	24.889
HARTEBEESTHOEK	HBMB	HRAG	2272.949
HARTEBEESTHOEK	HBMB	HRAO	2089.291
HOFN	HOGC	HOFN	42.747
HOFN	HOFC	HOFN	42.762
KERGUELEN	KEYC	KERG	25.976
KERGUELEN	KEYC	KRGG	17.438
KERGUELEN	KEYC	KETG	2728.364
KERGUELEN	KEXC	KETG	2728.365
KERGUELEN	KEWC	KETG	2728.365
KERGUELEN	KEVC	KETG	2728.358
KERGUELEN	KEUC	KETG	2728.354
KITAB	KIVC	KIT3	187.149
KITAB	KIVC	KITG	5.585
KITAB	KIUB	KITG	189.487
KAWAI	KOLB	KOKB	358.802
LIBREVILLE	LICB	NKLG	10.882
MAHE	MAIB	SEYG	16.868
MAHE	MAIB	SEY1	5726.638
MAHE	MAIB	SEY2	5722.396
MALE	MAMC	MALD	496.748
MALE	MALC	MALD	496.746
MALE	MALB	MALD	476.751
MANGILAO	MLAC	GUUG	23.602
MANAGUA	MNAC	MANA	102.74
METSAHOVI	MEUB	MET3	2789.426
METSAHOVI	MEUB	METG	18.871

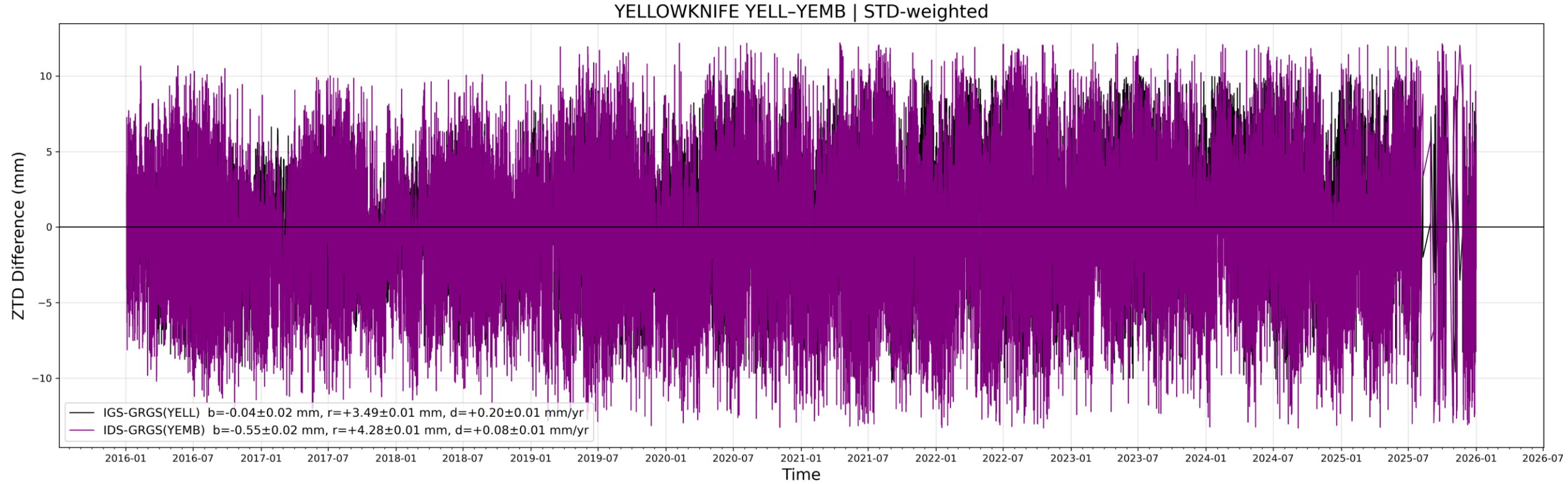
Station	IDS ID	IGS ID	3-D Distance
METSAHOVI	MEUB	METZ	2796.354
METSAHOVI	MEUB	METS	2797.081
NOUMEA	NOXC	NRMD	11.957
NOUMEA	NOXC	NOUM	8962.378
NOUMEA	NOXB	NOUM	8962.388
OWENGA	OWFC	OWMG	8.884
OWENGA	OWEC	OWMG	97.546
PAPEETE	PAUB	THTI	6.857
PAPEETE	PAUB	THTG	5.57
PAPEETE	PAUB	FAA1	2547.886
PAPEETE	PAUB	TAH1	21.65
PAPEETE	PAUB	PAPE	6037.344
PONTA-DELGADA	PDOC	PDEL	6.206
PONTA-DELGADA	PDNC	PDEL	6.203
LA-REUNION	REVC	REUN	84.564
LA-REUNION	REUC	REUN	84.562
LA-REUNION	REUB	REUN	16.179
RIKITEA	RIMC	GAMB	10.705
RIKITEA	RIMB	GAMB	14.772
ROTHERA	ROBC	ROTH	31.631
ROTHERA	ROZC	ROTH	31.636
ROTHERA	ROXC	ROTH	31.624
ROTHERA	ROWC	ROTH	67.553
ROTHERA	ROVB	ROTH	67.548
SAINT HELENE	HEMB	STHL	20.046
SANTA-CRUZ	SCSC	GLPS	104.203
SANTA-CRUZ	SCSC	GALA	34.645
SANTA-CRUZ	SCRC	GALA	91.091
SANTA-CRUZ	SCRB	GALA	91.091
ST-JOHN-S	STKC	STJ3	21.656
ST-JOHN-S	STKC	STJ2	20.604
ST-JOHN-S	STKB	STJ2	20.589
SYOWA	SYQB	SYOG	312.21
THULE	THUB	THU2	59.161
THULE	THUB	THU1	926.559
ULAANBAATAR	ULAC	ULAB	11.995
WETTZELL	WEUC	WTZA	277.936
WETTZELL	WEUC	WTZR	279.425
WETTZELL	WEUC	WTZT	280.397
WETTZELL	WEUC	WTZZ	278.5

Stations for Analysis

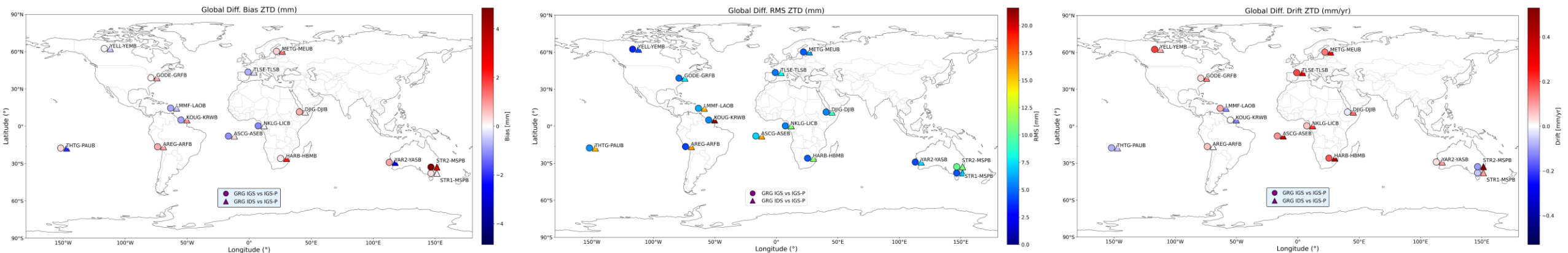
Colocation < 1 km
Stations = 15, Sites = 14

DORIS Station	DORIS ID	GPS ID	DORIS-GPS 3D Distance (m)
AREQUIPA	ARFB	AREG	40.288
ASCENSION	ASEB	ASCG	9.999
DJIBOUTI	DJIB	DJIG	55.717
GREENBELT	GRFB	GODE	239.095
HARTEBEESTHOEK	HBMB	HARB	24.889
KOUROU	KRWB	KOUG	16.882
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MOUNT-STROMLO	MSPB	STR2	17.185
PAPEETE	PAUB	THTG	5.57
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YELLOWKNIFE

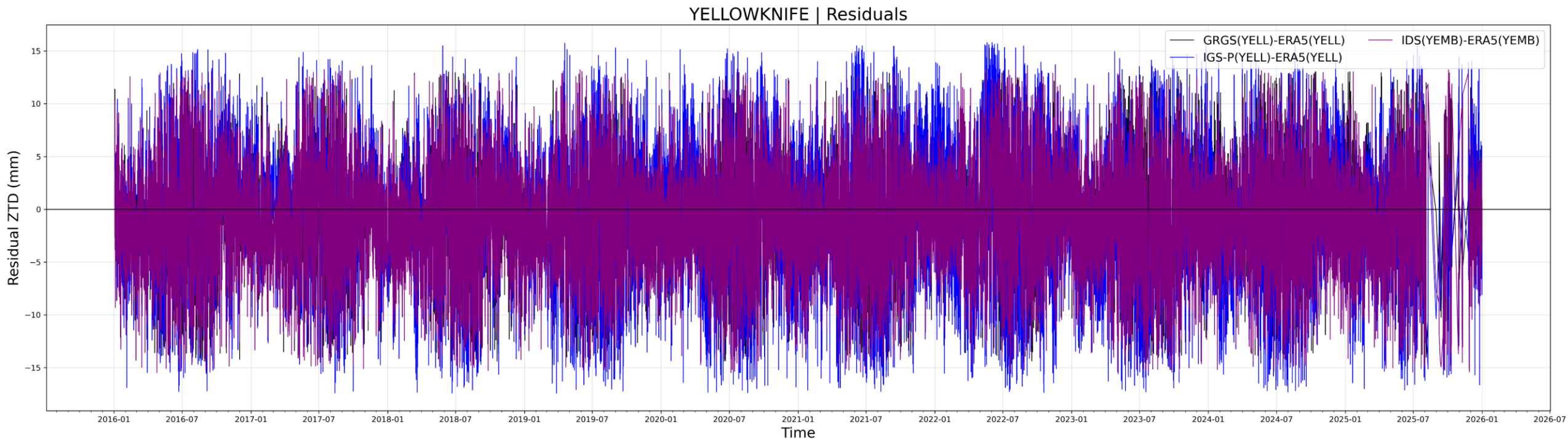


Solution's Comparison with IGS-P



Station	Bias (IGS-GRGS) mm	Bias (IDS-GRGS) mm	RMS (IGS-GRGS) mm	RMS (IDS-GRGS) mm	Drift (IGS-GRGS) mm/yr	Drift (IDS-GRGS) mm/yr
Arequipa	0.78±0.02	0.83±0.09	4.19±0.02	16.02±0.06	0.06±0.01	0.01±0.04
Ascension	-1.05±0.04	0.35±0.08	7.19±0.03	15.83±0.06	0.11±0.02	0.41±0.04
Djibouti	0.78±0.03	0.20±0.05	5.49±0.02	8.86±0.03	-0.02±0.01	0.15±0.02
Greenbelt	0.09±0.03	0.80±0.04	5.11±0.02	7.62±0.03	0.04±0.01	0.14±0.02
Hartebeesthoek	0.13±0.02	2.20±0.06	4.65±0.02	11.11±0.04	0.17±0.01	0.45±0.02
Kourou	-0.86±0.03	1.08±0.11	5.64±0.02	21.60±0.08	-0.00±0.01	-0.13±0.05
Le-Lamentin	-0.80±0.03	-0.57±0.08	6.41±0.02	15.53±0.06	0.09±0.02	-0.12±0.04
Libreville	-1.13±0.03	-0.10±0.06	5.48±0.02	11.00±0.04	0.06±0.01	0.21±0.02
Metsahovi	0.44±0.02	1.30±0.03	4.69±0.02	6.14±0.02	0.14±0.01	0.33±0.01
Mont-Stromlo-1	0.29±0.02	0.09±0.03	4.39±0.02	6.81±0.02	-0.06±0.01	0.10±0.01
Mont-Stromlo-2	4.86±0.05	3.28±0.06	10.23±0.04	10.83±0.05	-0.10±0.03	0.53±0.07
Papeete	0.36±0.03	-2.04±0.08	5.85±0.02	15.37±0.06	-0.08±0.02	-0.06±0.03
Toulouse	-0.73±0.03	-0.31±0.04	5.31±0.02	8.00±0.03	0.19±0.01	0.35±0.02
Yarragadee	0.85±0.02	-2.96±0.03	4.30±0.02	7.21±0.03	0.03±0.01	0.10±0.01
Yellowknife	-0.04±0.02	-0.55±0.02	3.49±0.01	4.28±0.01	0.20±0.01	0.08±0.01

YELLOWKNIFE



	Bias (mm)	RMS (mm)	Drift (mm/yr)
IGS - ERA5	-0.82 ± 0.02	4.80 ± 0.02	0.14 ± 0.02
IGS-P - ERA5	-0.86 ± 0.03	5.43 ± 0.02	-0.05 ± 0.02
IDS - ERA5	-1.01 ± 0.02	4.79 ± 0.02	0.02 ± 0.01

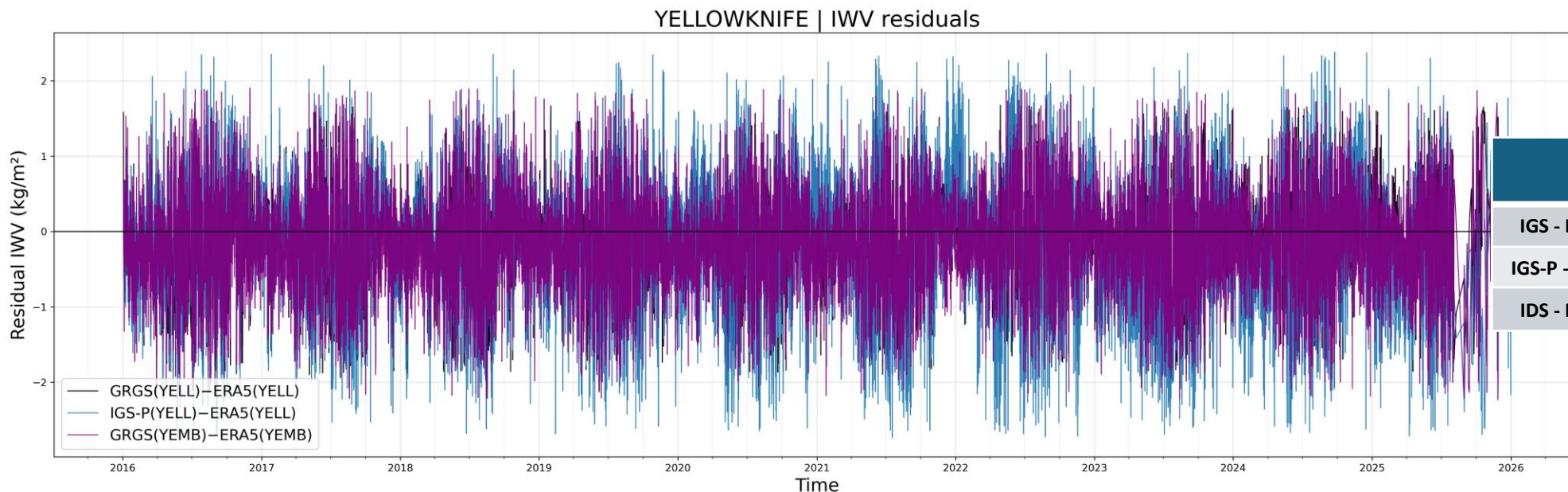
Integrated Water Vapour (IWV)

IWV is the total amount of water vapour contained in a vertical column of the atmosphere above a given location.

$$\text{IWD} = k(T_m) \cdot \text{ZWD}$$

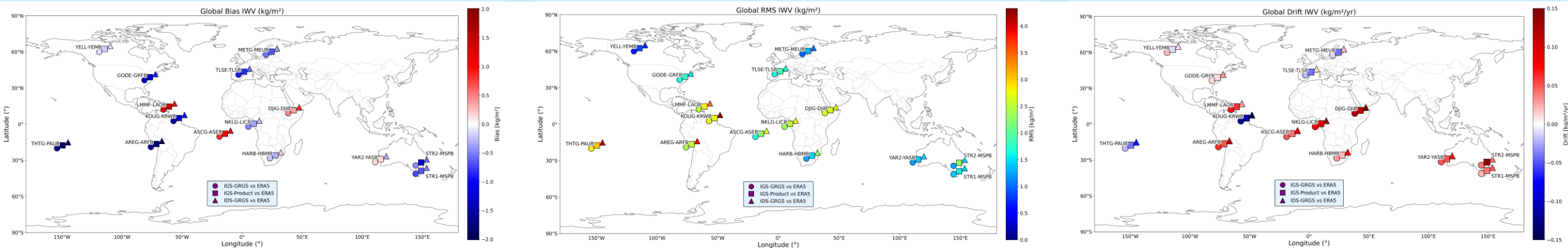
where $k(T_m)$ is the Water vapour weighted mean atm. temp of column above the station.

- **For IDS-GRGS:** ZTD from IDS-GRGS, ZHD from IDSERA5, and $k(T_m)$ from IDSERA5 data.
- **For IGS-GRGS:** ZTD from IGS-GRGS, ZHD from IGSERA5, and $k(T_m)$ from IGSERA5 data.
- **For IGS-Product:** ZTD from IGS-Product, ZHD from IGSERA5, and $k(T_m)$ from IGSERA5 data.



	Bias (kg/m ²)	RMS (kg/m ²)	Drift (kg/m ² /yr)
IGS - ERA5	-0.14±0.01	0.63±0.00	0.02±0.00
IGS-P - ERA5	-0.19±0.01	0.86±0.01	-0.01±0.00
IDS - ERA5	-0.14±0.01	0.68±0.00	0.01±0.00

IWV Solution's Comparison with ERA5



Station	Bias (IGS-GRGS) kg/m ²	Bias (IGS-P) kg/m ²	Bias (IDS-GRGS) kg/m ²	RMS (IGS-GRGS) kg/m ²	RMS (IGS-P) kg/m ²	RMS (IDS-GRGS) kg/m ²	Drift (IGS-GRGS) kg/m ² /yr	Drift (IGS-P) kg/m ² /yr	Drift (IDS-GRGS) kg/m ² /yr
Arequipa	-1.66±0.02	-1.73±0.02	-2.01±0.03	2.41±0.01	2.56±0.01	3.92±0.02	0.06±0.01	0.05±0.01	0.11±0.01
Ascension	0.82±0.01	1.07±0.02	1.07±0.02	1.65±0.01	2.26±0.01	2.71±0.02	0.05±0.01	0.04±0.01	0.09±0.01
Djibouti	0.46±0.02	0.37±0.02	0.82±0.02	2.61±0.02	2.65±0.02	2.80±0.02	0.12±0.01	0.11±0.01	0.15±0.01
Greenbelt	-1.34±0.01	-1.25±0.01	-0.91±0.01	1.67±0.01	1.77±0.01	1.57±0.01	0.01±0.00	0.01±0.00	0.03±0.00
Hartebeesthoek	-0.22±0.01	-0.30±0.01	0.17±0.02	1.24±0.01	1.45±0.01	2.27±0.02	0.03±0.00	0.02±0.01	0.08±0.01
Kourou	-1.50±0.02	-1.30±0.02	-1.09±0.04	2.75±0.01	2.74±0.02	4.33±0.03	-0.12±0.01	-0.11±0.01	-0.15±0.01
Le-Lamentin	1.21±0.02	1.41±0.02	1.10±0.03	2.51±0.02	2.81±0.02	3.48±0.03	0.07±0.01	0.06±0.01	0.03±0.01
Libreville	-0.49±0.02	-0.35±0.02	-0.24±0.02	2.33±0.01	2.50±0.02	2.78±0.02	0.08±0.01	0.09±0.01	0.13±0.01
Metsahovi	-0.58±0.01	-0.67±0.01	-0.38±0.01	0.97±0.01	1.33±0.01	1.03±0.01	-0.01±0.00	-0.04±0.00	0.02±0.00
Mont-Stromlo-1	-0.71±0.01	-0.67±0.01	-0.49±0.01	1.41±0.01	1.57±0.01	1.45±0.01	0.02±0.00	0.04±0.00	0.05±0.00
Mont-Stromlo-2	-0.44±0.01	-1.20±0.02	-0.59±0.01	1.25±0.01	2.28±0.02	1.47±0.01	0.04±0.01	0.14±0.01	0.04±0.01
Papeete	-1.67±0.02	-1.85±0.02	-1.86±0.03	2.82±0.02	3.03±0.02	4.05±0.03	-0.02±0.01	-0.04±0.01	-0.07±0.01
Toulouse	-0.90±0.01	-0.83±0.01	-0.60±0.01	1.63±0.01	1.88±0.01	1.71±0.01	-0.02±0.01	-0.04±0.01	0.01±0.01
Yarragadee	0.17±0.01	0.13±0.01	-0.32±0.01	1.19±0.01	1.39±0.01	1.46±0.01	0.05±0.00	0.05±0.00	0.07±0.01
Yellowknife	-0.14±0.01	-0.19±0.01	-0.14±0.01	0.63±0.00	0.86±0.01	0.68±0.00	0.02±0.00	-0.01±0.00	0.01±0.00