Geodesy and Geospatial Engineering

On Recent Activities at GNSS@TG Stations in the South Atlantic Ocean and the Tracking of Hurricanes Using GNSS

Norman Teferle

Geodesy and Geospatial Engineering
Institute of Civil and Environmental Engineering
University of Luxembourg

UNIVERSITÉ DU LUXEMBOURG

Geodesy is …

Fundamental for monitoring climate change

Dr. Rajendra Pachauri, Chairman of the Intergovernmental Panel on Climate Change, commented about geodesy at a recent climate symposium in Ny-Ålesund, Svalbard.

ARCTIC: IPCC Chairman Dr. Rajendra Pachauri supports the work on a draft UN resolution on global geodesy

"Geodetic Earth observation contributes significantly to strengthen the study of our changing planet and provides valuable information to policy makers who are exploring ways to address climate change," Dr. Pachauri said.

The geodesists around the globe measure and define the Earth's shape, rotation and gravitation and changes to these. Geodetic Earth observation provides a coordinate reference frame for the whole planet, which is fundamental for monitoring changes to the Earth.

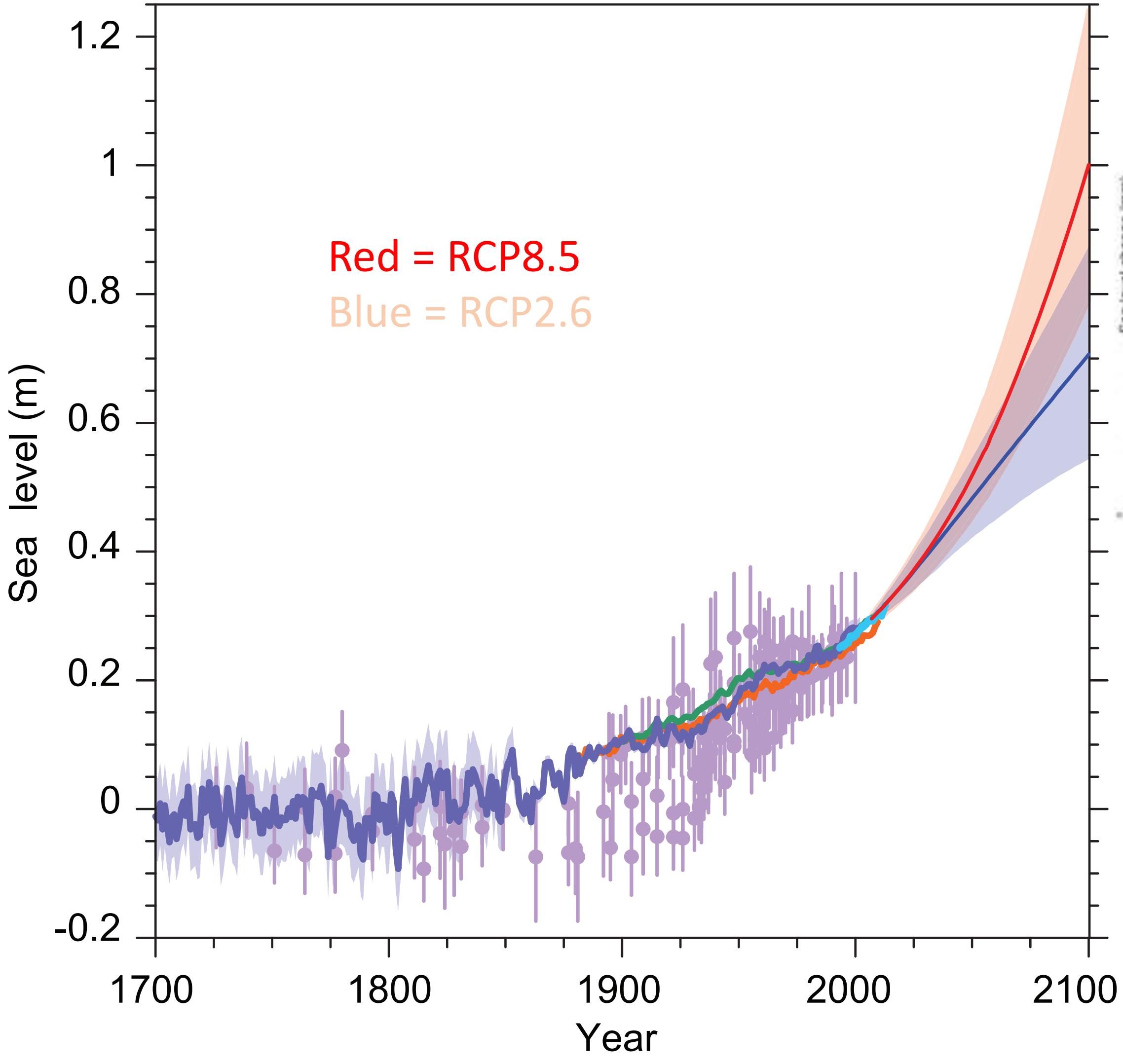
Dr. Pachauri said UN-GGIM and the Global Geodetic Reference Frame Working Group are making importan contributions to scientific understanding.

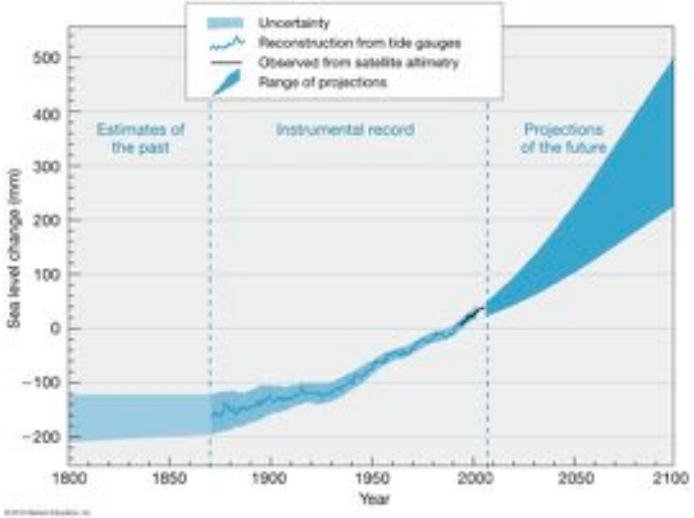
"I was gratified to learn about their work on a draft UN resolution o global geodesy," he said. "Their work is making a vital contribution to our understanding of climate change."

Contents

- Present-Day Land and Sea Level Changes around South Georgia Island: Results from Precise Levelling, GNSS, Tide Gauge and Satellite Altimetry Measurements
- Recent Activities on Tristan da Cunha Island: Geodetic Installations, Local Tie Measurements and their Analysis
- Tracking Hurricanes using GPS Atmospheric Integrated Water Vapour Fields

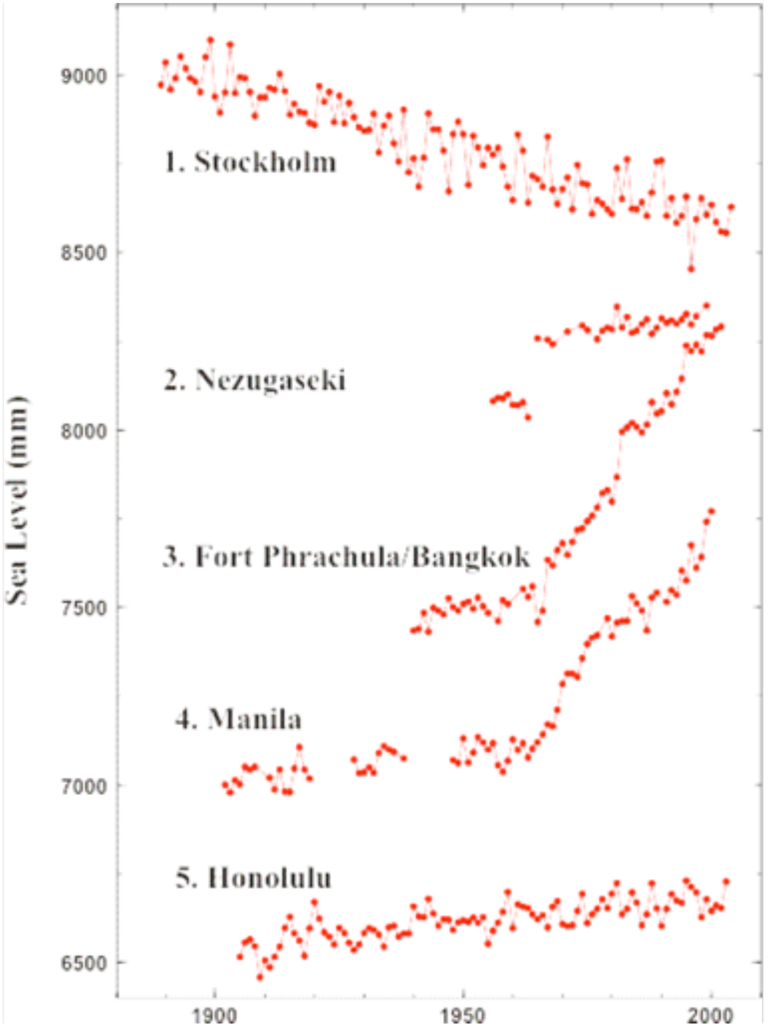
Sea Level Projections (IPCC, 2013)





Geodesy and Geospatial Engineering

Mean Sea Level (MSL) Records from PSMSL



- **Stockholm - Glacial Isostatic Adjustment** (GIA; sometimes called Post Glacial Rebound or PGR): Site near Stockholm shows large negative trend due to crustal uplift.
- **Nezugaseki - Earthquakes**: This sea level record from Japan, demonstrates an abrupt jump following the 1964 earthquake.
- **Fort Phrachula/Bangkok - Ground water extraction**: Due to increased groundwater extraction since about 1960, the crust has subsided causing a sea level rise.
- **Manila - Sedimentation**: Deposits from river discharge and reclamation work load the crust and cause a sea level rise.
- **Honolulu - A 'typical' signal** that is in the 'far field' of GIA and without strong tectonic signals evident on timescales comparable to the length of the tide gauge record.

(PSMSL, 2015)

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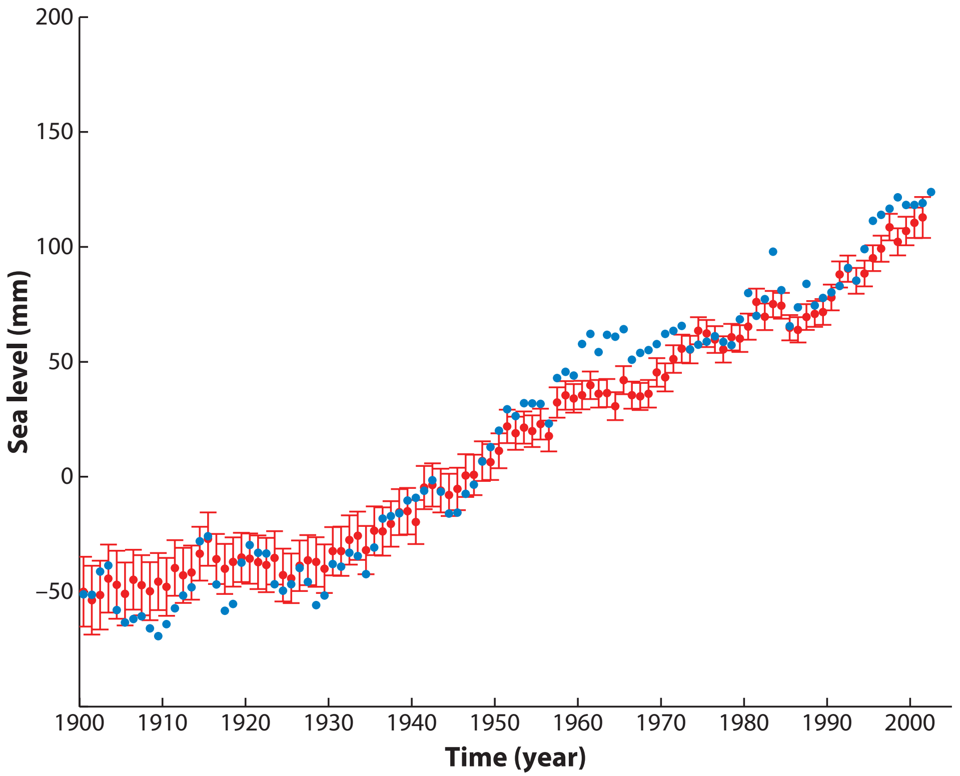
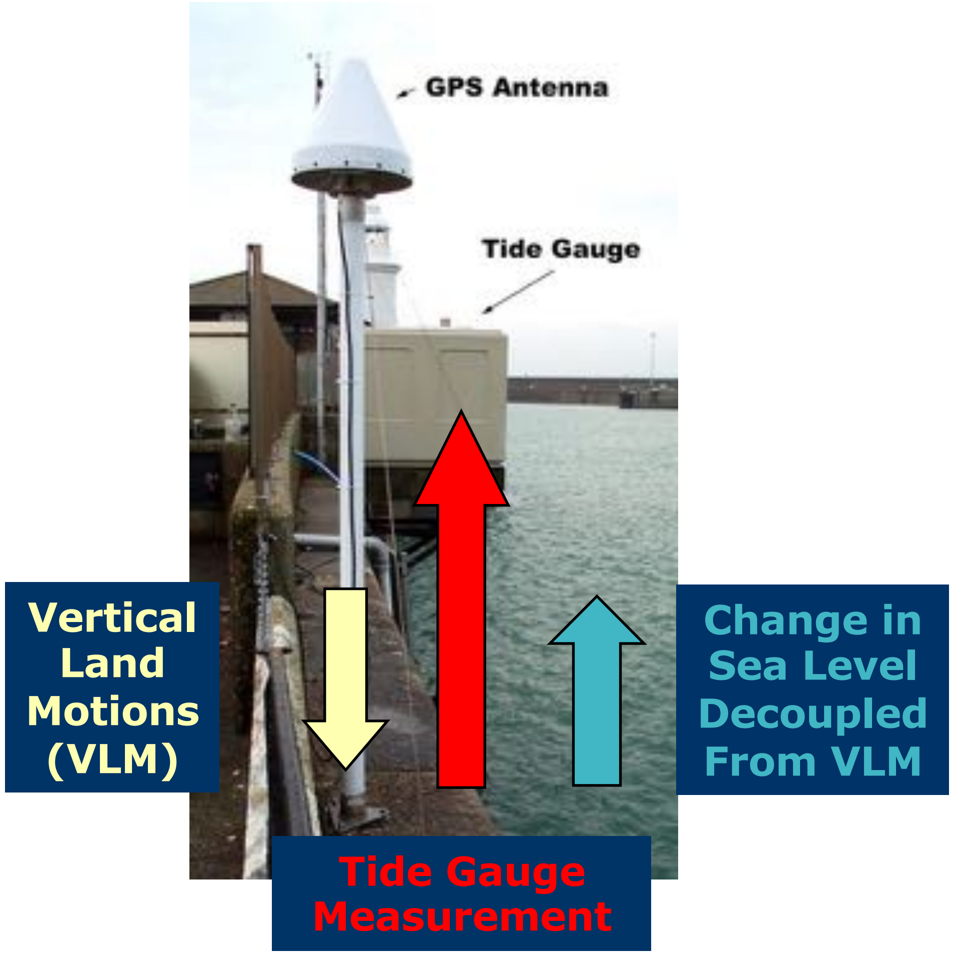
20th Century Sea Level Record from Tide Gauges

- Observed global mean sea level (from tide gauges) between 1900 and 2001
- Red dots are from Church et al. (2004). Blue dots are from Jevrejeva et al. (2006).

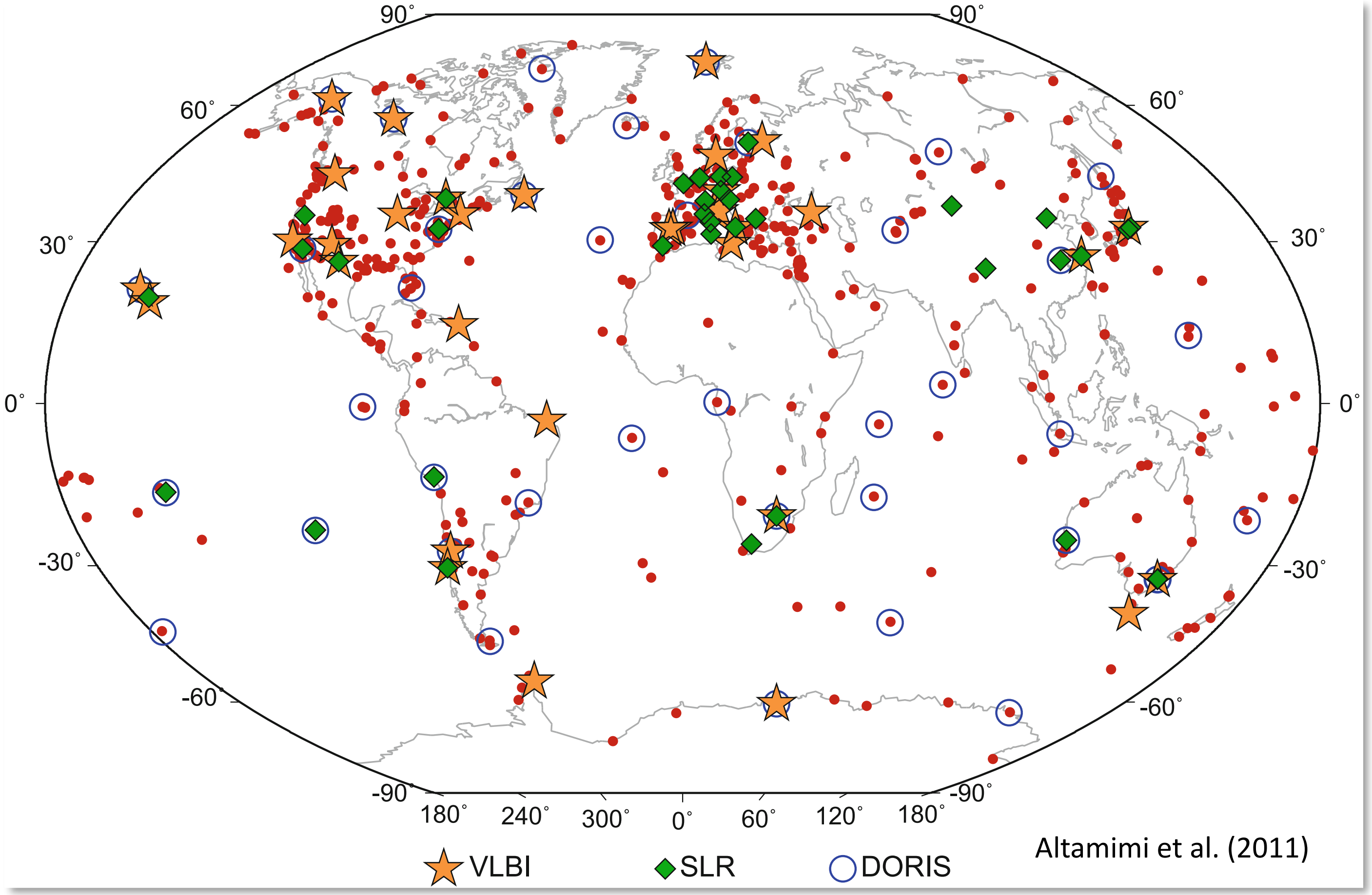


Why monitor Vertical Land Motions at Tide Gauges ?



- Tide gauges (TG) measure local sea level
- Vertical land motions (VLM) are determined from CGPS and AG at or close to the tide gauge
- The change in sea level de-coupled from VLM can be inferred

The ITRF2008 Network



ITRF2008:
934 Stations
580 Sites
463 N. Hem.
117 S. Hem.
84 co-location Sites

Accuracy:
Origin: 1 cm Scale: 1.2ppb

Co-location of Instruments

- None of space geodetic techniques is able to provide all the parameters necessary to completely define a TRF
  - **VLBI** strength(orientation), **SLR** strength(geocentre) , **GPS** strength (crustal movements)

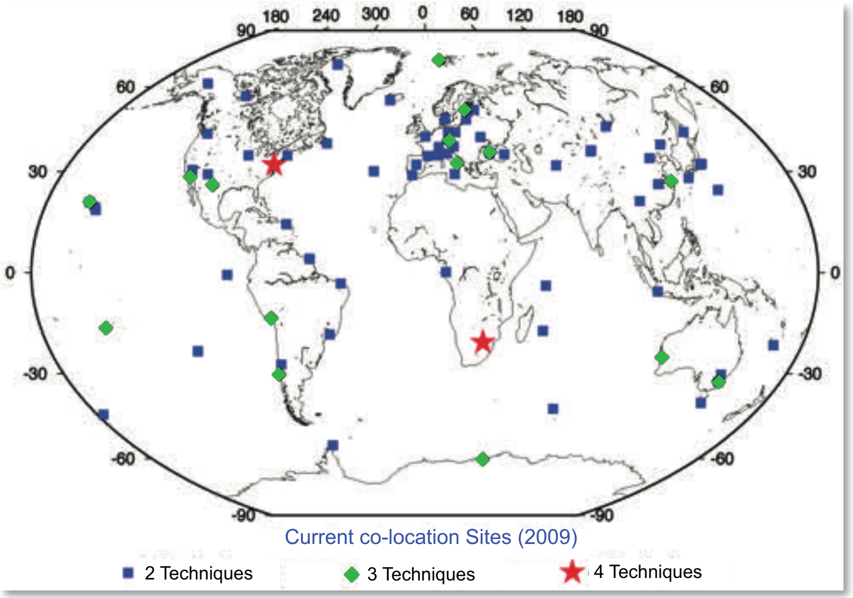
- To define an accurate ITRF (Source GGOS 2020):
  - < 1 mm reference frame accuracy
  - < 0.1 mm/yr stability

- Measurement of sea level is the primary driver improvement over current ITRF performance by a factor of 10-20.

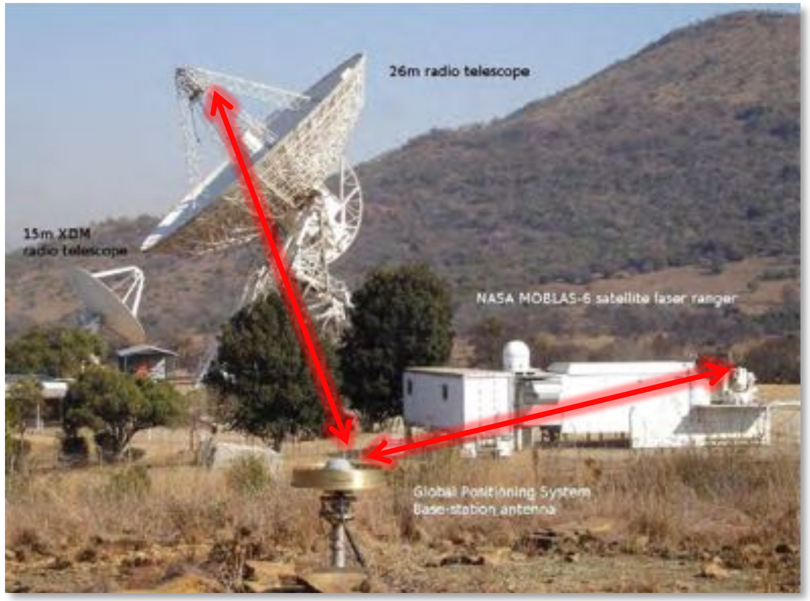
- The co-location of different and complementary instruments is crucial for several reasons:

- Without co-location sites and highly accurate local tie information, it is impossible to establish a unique and common global reference frame (TRF) for all major space geodetic techniques to answer key geophysics science questions.

Co-location of Geodetic Techniques



Altamimi et al. (2011)



Hartebeesthoek, South Africa

UK South Atlantic Tide Gauge Network

- Established since 1985
- British Overseas Territories (BOTs) and Antarctica
- Affords long sea level records from an under-sampled region
- Used for:
  - Monitoring ACC variability
  - ‘Ground truthing’ satellite altimetry
  - Understanding climate variability on various timescales incl. longer term changes
  - Design and testing of tide gauge (TG) equipment for remote and hostile locations

Present-Day Land and Sea Level Changes around South Georgia Island: Results from Precise Levelling, GNSS, Tide Gauge and Satellite Altimetry Measurements

F.N. Teferle[1], I.W.D. Dalziel[2], A. Hunegnaw[1],

A. Hibbert[3], S.D.P. Williams[3] , P.L. Woodworth[3], R. Smalley[4] and L. Lawver[2]

[1]Geodesy and Geospatial Engineering, Department of Engineering, FSTC, University of Luxembourg, Luxembourg

[2]University of Texas at Austin, Jackson School of Geosciences, USA

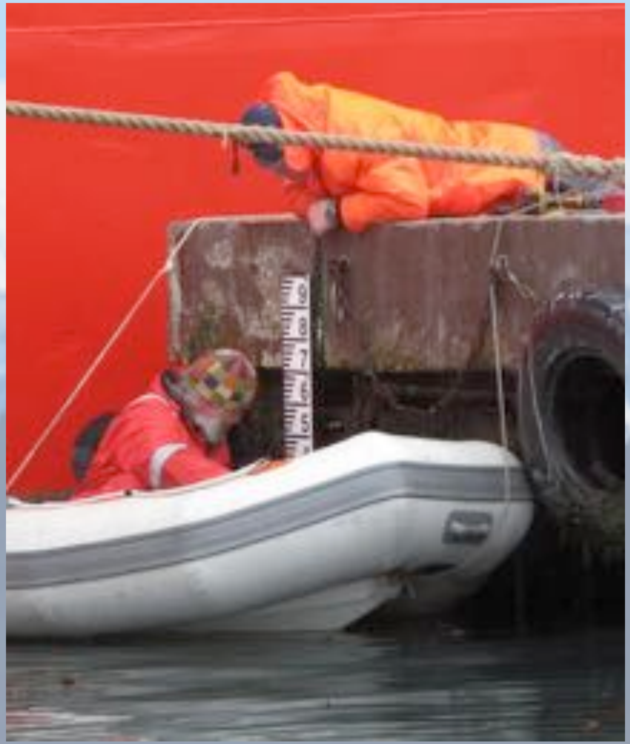
[3]National Oceanography Centre, Liverpool, United Kingdom

[4]University of Memphis, Center for Earthquake Research and Information, USA

13th International Symposium on Antarctic Earth Science (ISAES), July 22-26, 2019, Incheon, Republic of Korea

Overview

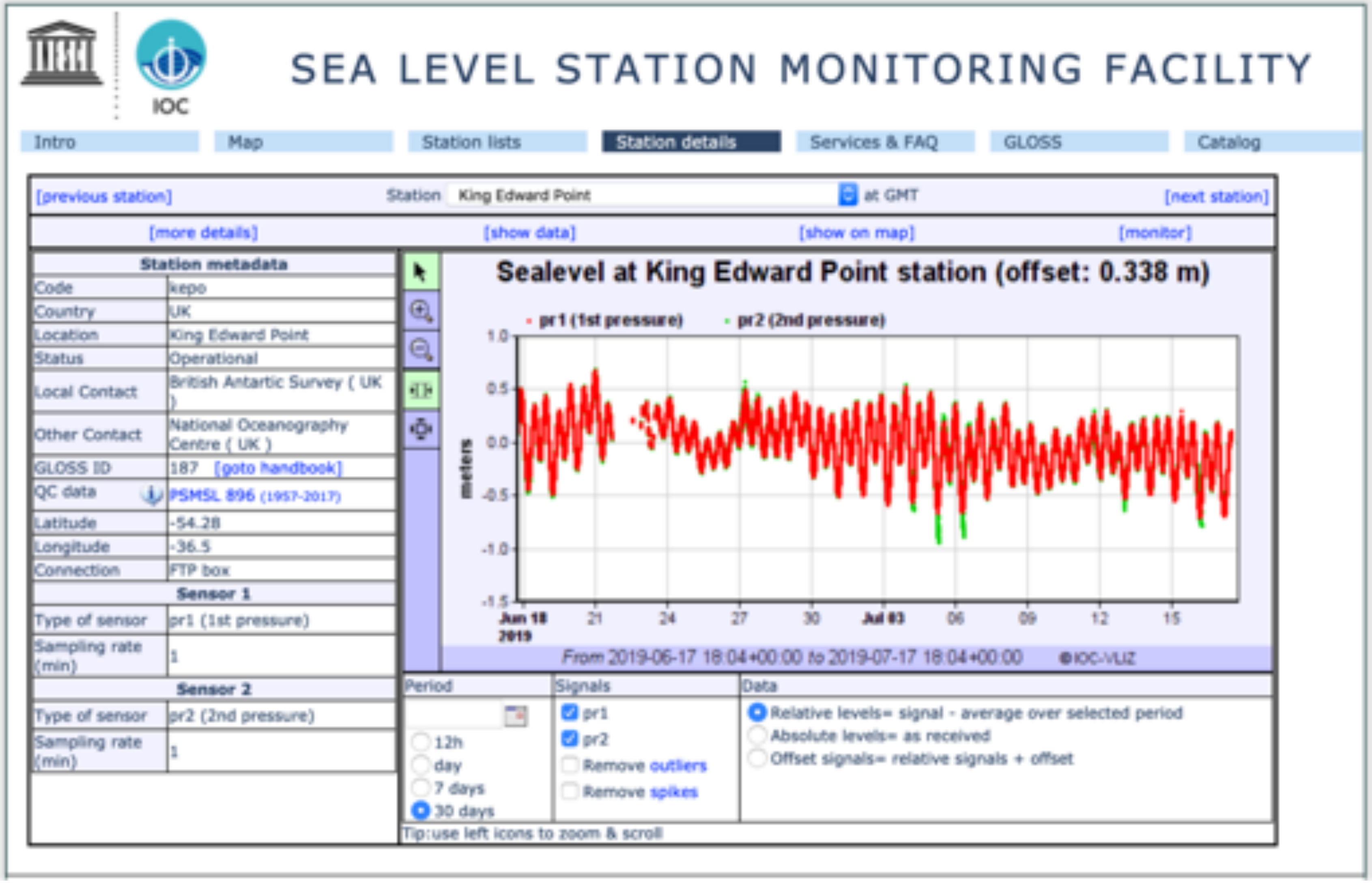
- UK South Atlantic Tide Gauge Network
- GNSS Installations
- Benchmark Network
- Results
  - GNSS Height Time Series
  - Sea Level Observations
- Conclusions



Tide board installation at King Edward Point (KEP) Research Station, South Georgia Island in 2014.

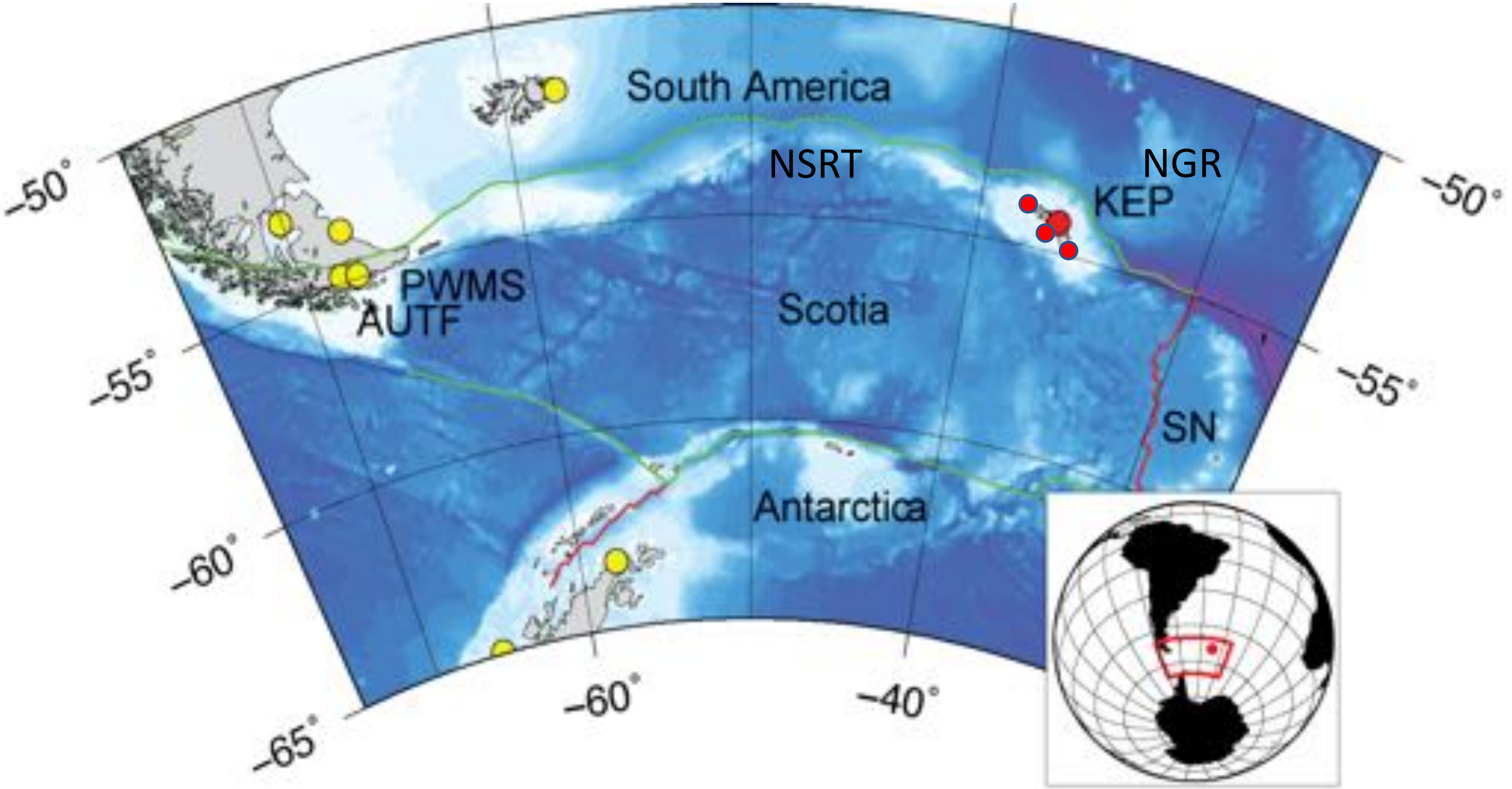
KEP Tide Gauge History

- Early tide gauge data 1957-1959
- New tide gauge since 2008
- Right hand shows the recent TG data at the IOC Sea Level Station Monitoring Facility



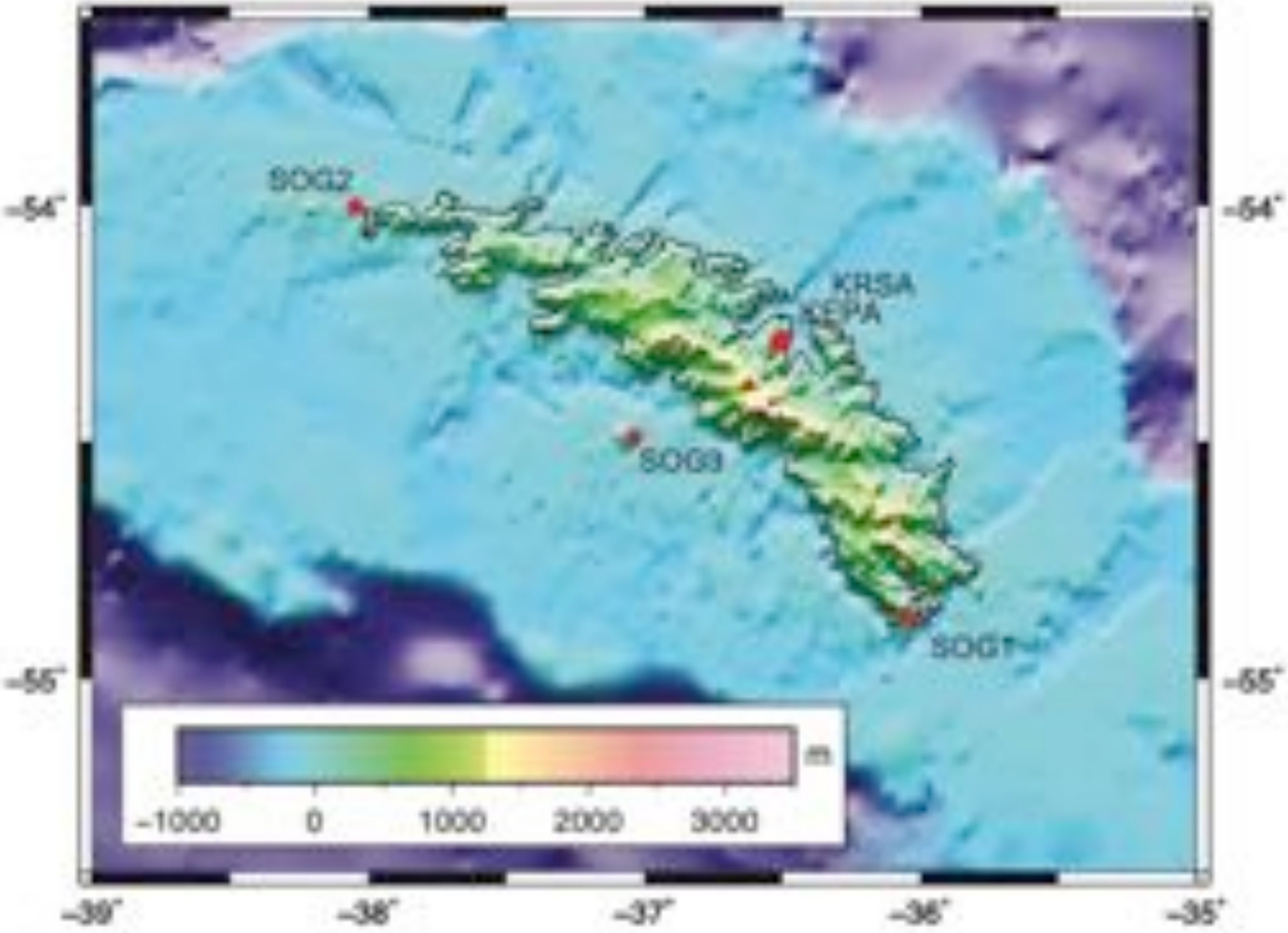
Tectonic Plates and Continuous GNSS Stations

- Location of South Georgia (SG
  Island and tectonic plates in t
  South Atlantic Ocean
- Transforms/fracture zones (green), ridges (red) and trenches (blue)
- continuous GNSS stations (rec
  and yellow circles)
- King Edward Point (KEP)
- NSRT: North Scotia Ridge Transform, NGR: Northeast Georgia Rise, SN: the South Sandwich plate



Presented on July 25, 2019 at the 13th ISAES, July 22-26, 2019, Incheon, Republic of Korea

South Georgia GNSS Network



The continuous GNSS Stations KEPA and KRSA

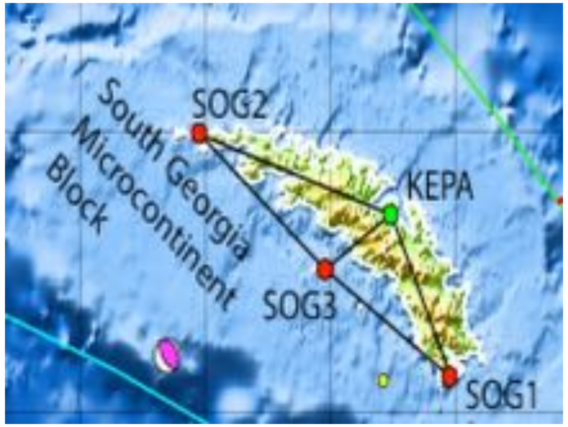
GNSS antenna and mast with unobstructed sky view on top of Brown Mt. Solar power system, enclosures with batteries and electronics, structural frame, radio antenna and weather station in 30m distance to mast.

Antenna location on bedrock.

GNSS antenna and mast with obstructed sky due to Mt. Duse. Mains power and communications to KEP radio room in 120 m distance. Many problems since early 2017 with not all data having been recoverable. Antenna location on concrete monument in gravel beds.

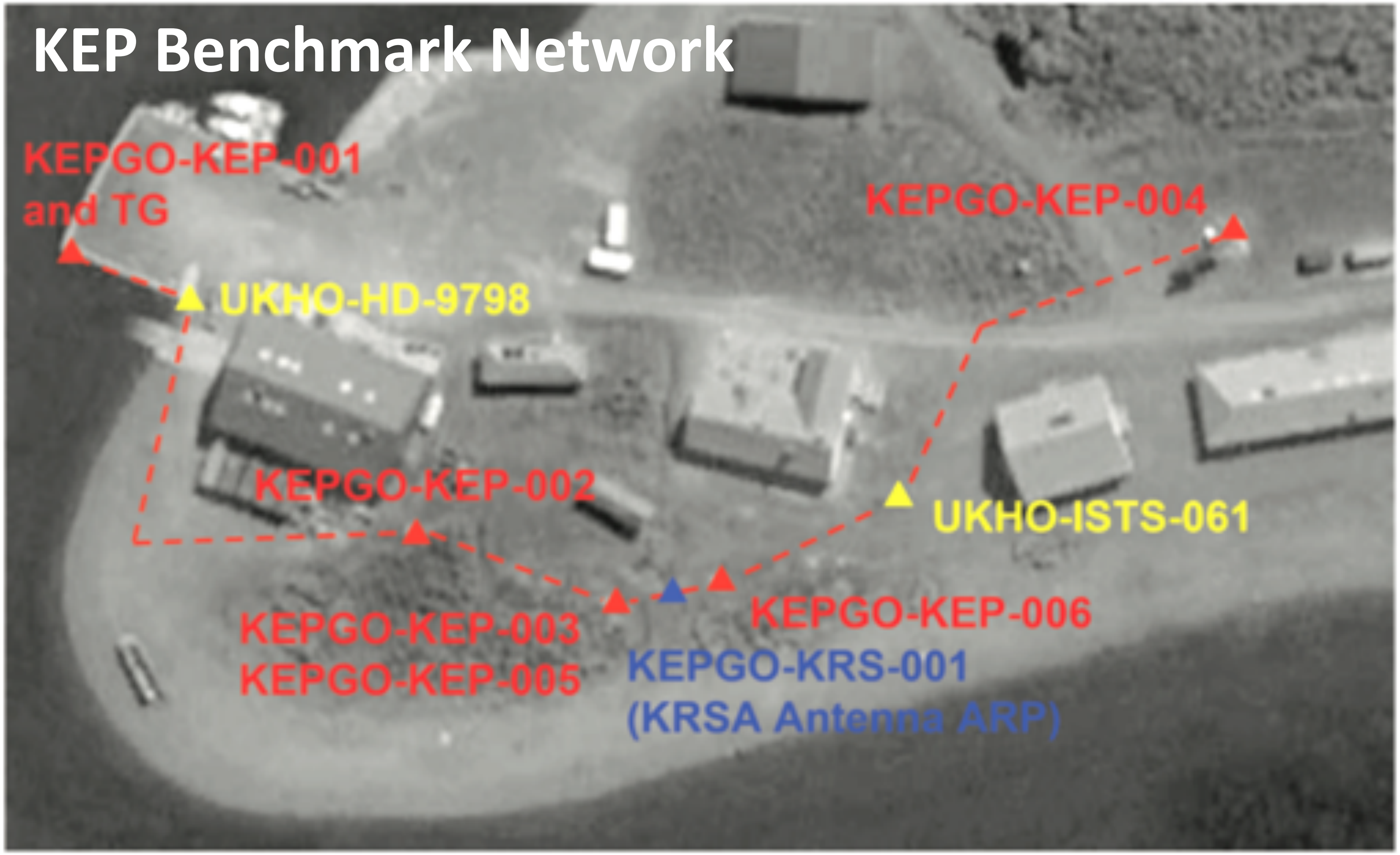
Other GNSS Installations

- Consortium of the University of Texas at Austin and Memphis University
- NSF Project
- Installed 3 stations in late 2014
- At periphery of main island



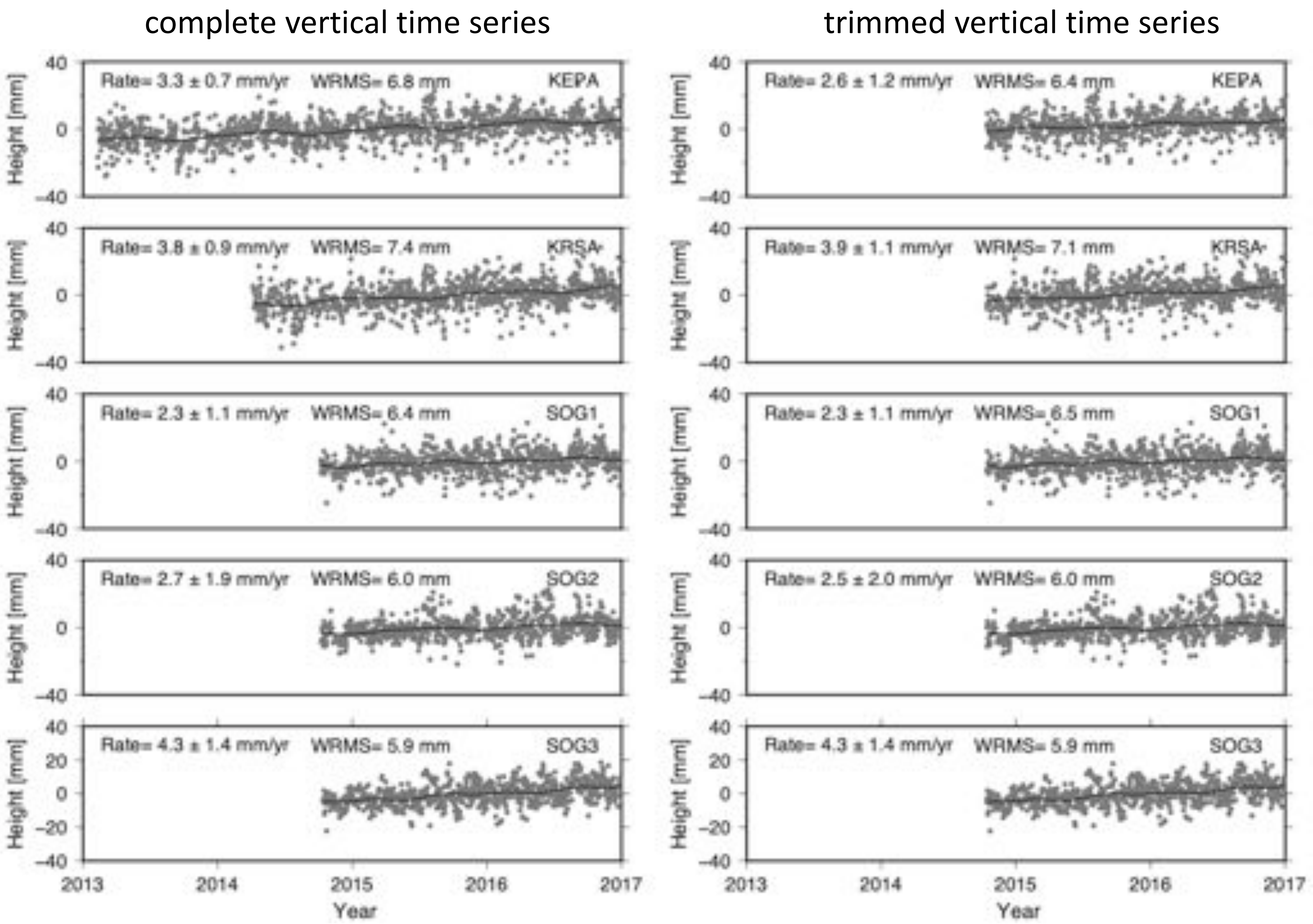
Benchmark Networks

- Two Benchmark networks were established: on Brown Mountain and at KEP
- At KEP to provide geodetic reference for the tide gauge and tie it to the GNSS station KRSA
- On Brown Mt. enable a tie if monument of KEPA gets destroyed by severe weather



Previous GNSS Results (<2017)

- Based on global Bernese GNSS Software DD solution (IGS Repro 2 Standards)
- Indicate general uplift of SG
- As expected, some vertical rate changes due to time series length



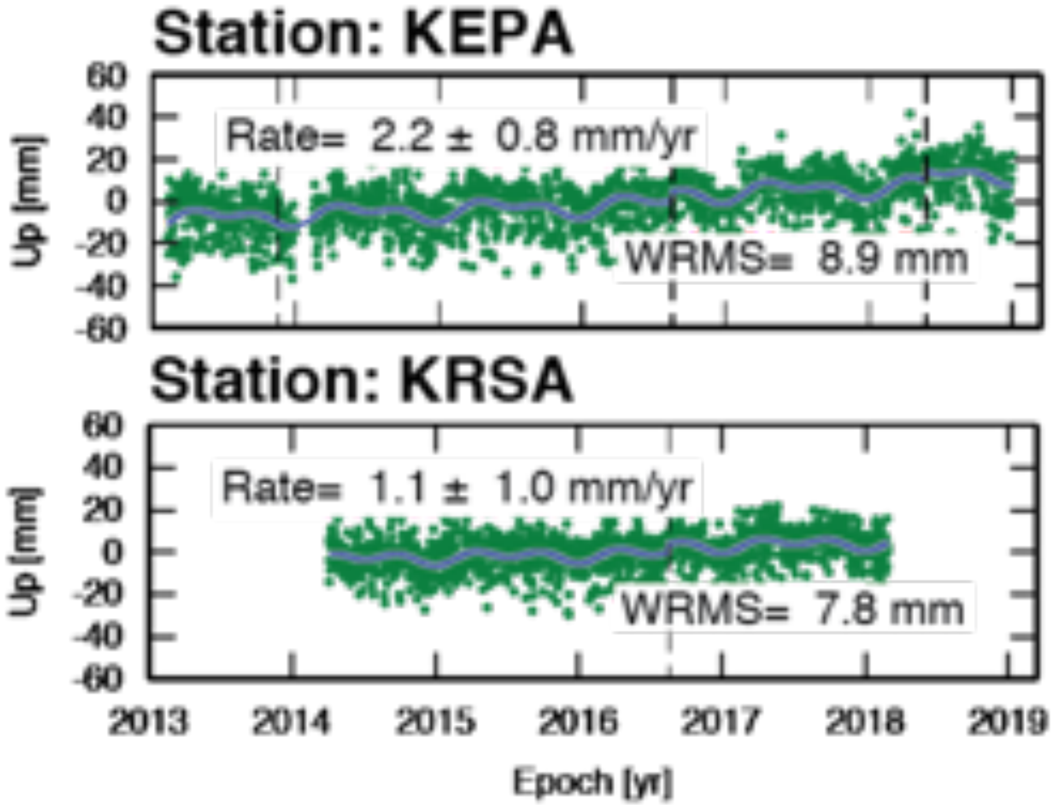
Updated GPS Solution

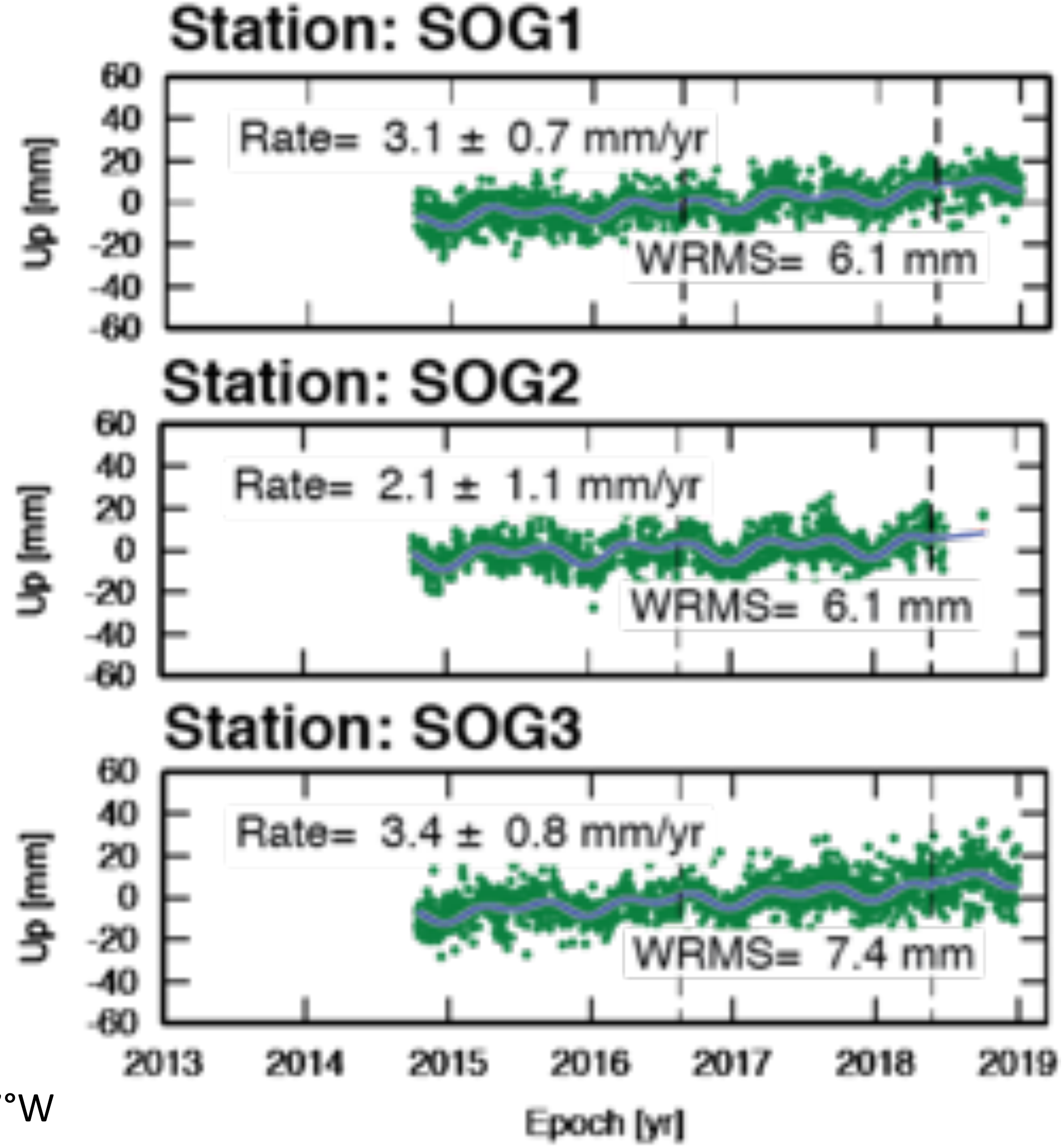
- Based on PRIDE Software and follow IGS repro2 strategy
  - Elevation angle cut off: 3 degrees
  - Weighting: Elevation-dependent data weighting
  - A priori hydrostatic delay, Vienna Mapping functions
  - Satellite orbit and clocks products by IGS
  - Solid Earth tides, Ocean tides, pole tides, relativistic effects IERS Conventions 2003
- Estimated parameters
  - Station coordinates
  - Receiver clocks
  - 2-hour zenith tropospheric delays
  - 12-hour horizontal tropospheric gradients
  - Integer phase ambiguities

PRIDE Software

- Developed and maintained by The PRIDE Lab at the GNSS Research Center of Wuhan University
- Open source software
- Follows Precise Point Positioning (PPP) strategy with integer ambiguity resolution (AR)
- The implementation of the AR, needs external phase bias products derived from a global network solution

What do the latest GNSS Results show?





Offsets:

Nov 13, 2013: M7.7 Scotia Sea EQ, 60.274°S 46.401°W

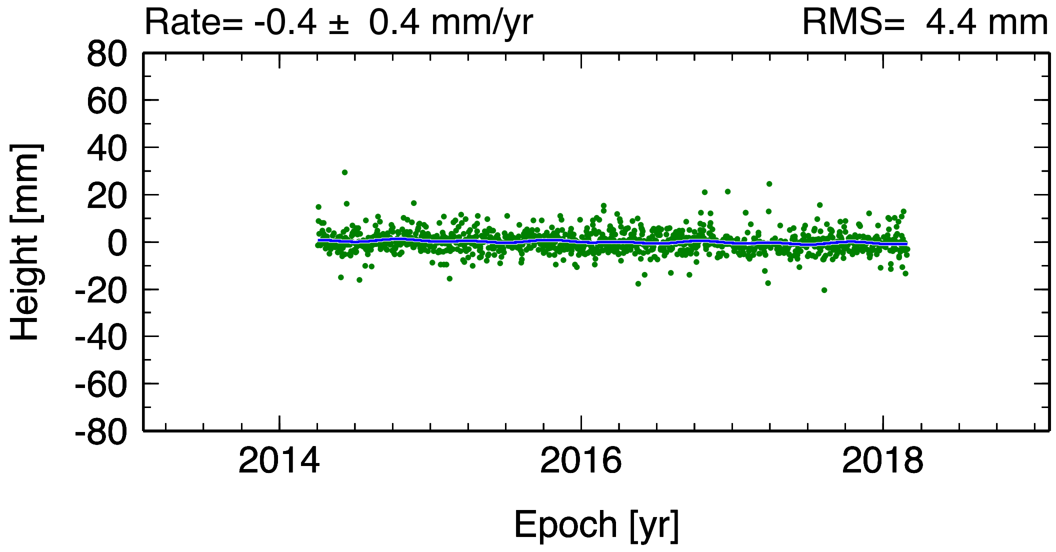
Aug 19, 2016: M7.4 South Georgia Island Region EQ, 55.285°S 31.877°W

May 27, 2018: Reference Frame Change ITRF2008 to ITRF2014

Is the rate difference due to the different time spans for KEPA and KRSA?

- Using Dual-CGPS Station Analysis (Teferle et al., 2002) investigate relative motion KEPA to KRSA
- The vertical rate difference from the "absolute" results is -1.1 ± 1.3 mm/yr
- The vertical rate difference from the "relative" results is -0.4 ± 0.4 mm/yr
- Judging by the 1-σ uncertainties the rate differences may indicate some relative vertical motion but they are statistically not significant

Height Difference Time Series KEPA - KRSA



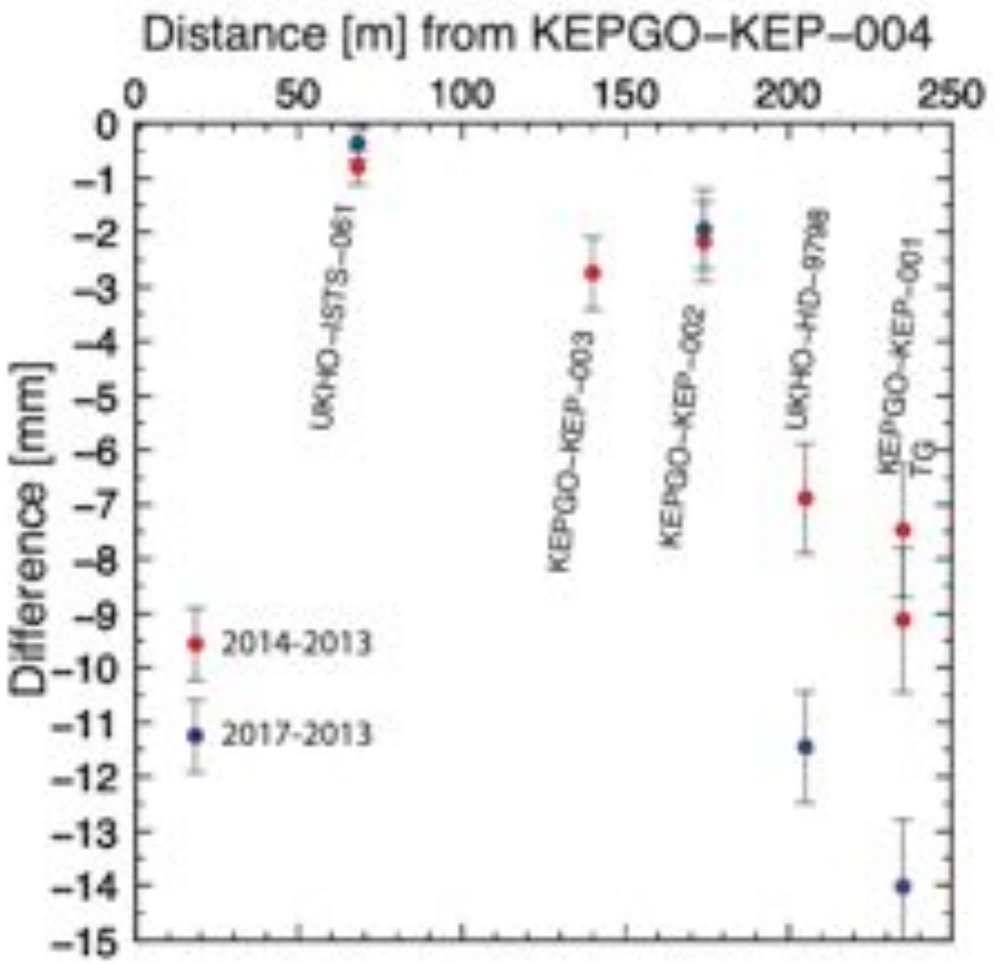
For any technical questions:
norman.teferle@uni.lu

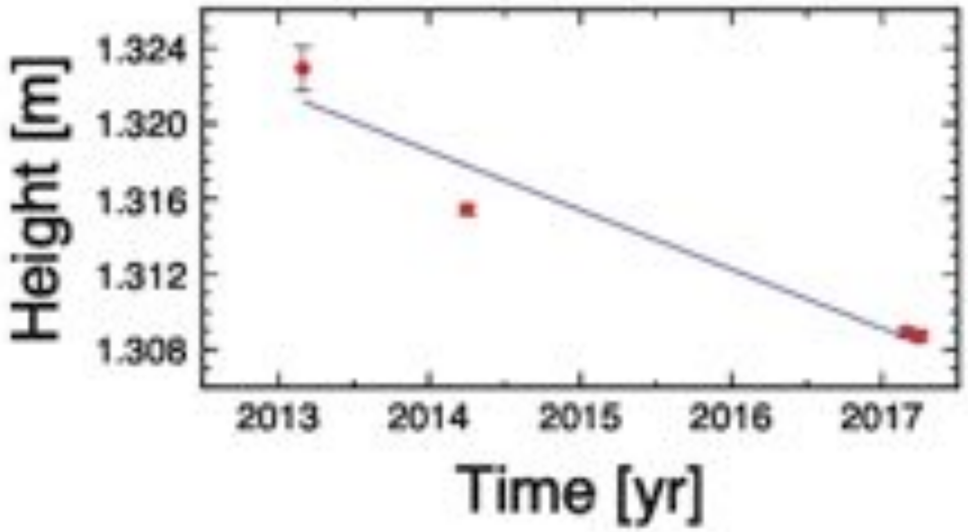
What do the Precise Levelling Results show?

- Starting from KEPGO-KEP-004 towards the tide gauge (TG) we have stability up to KEPGEO-KEP-002
- UKHO-HD-9798 and the tide gauge, tide board and KEPGEO-KEP-001 are subsiding
- Subsidence can be computed to be between 2.9 to 3.6 mm/yr

	Distance [m] from	Campaign 2013		Campaign 2014		Campaign 2017a		Campaign 2017b	
Benchmark	KEPGO-KEP-004	Height [m]	SD [m]	Height [m]	SD [m]	Height [m]	SD [m]	Height [m]	SD [m]
KEPGO-KEP-004	0	3,7600		3,7600		3,7600		3,7600	
UKHO-ISTS-061	68	3,0757	0,0003	3,0749	0,0001	3,0753	0,0001	3,0753	0,0001
KEPGO-KEP-003	140	2,7704	0,0006	2,7676	0,0002				
KEPGO-KEP-002	174	2,8145	0,0007	2,8124	0,0002	2,8126	0,0002	2,8128	0,0002
UKHO-HD-9798	205	1,3465	0,0010	1,3396	0,0003	1,3350	0,0003	1,3349	0,0003
KEPGO-KEP-001	235	1,3229	0,0012	1,3154	0,0003	1,3089	0,0003	1,3087	0,0003
Tide Board	235			1,1531	0,0003	1,1469	0,0003	1,1466	0,0003
TG	235	0,6560	0,0012	0,6469	0,0005				

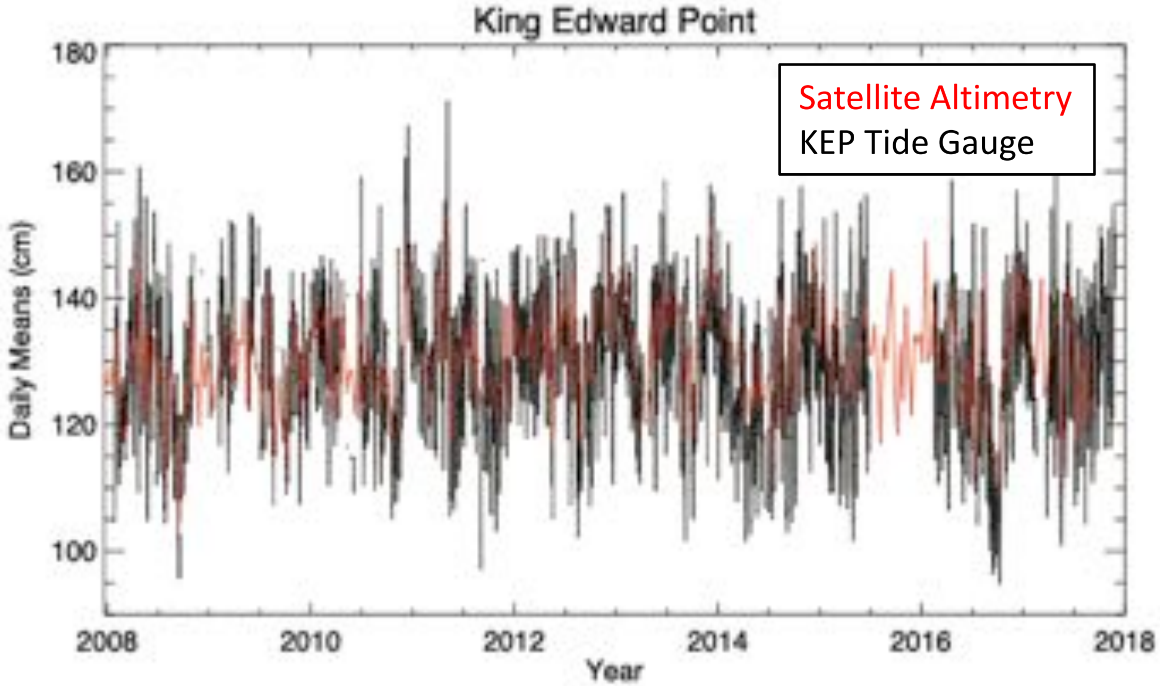
What is the TG Subsidence Rate?



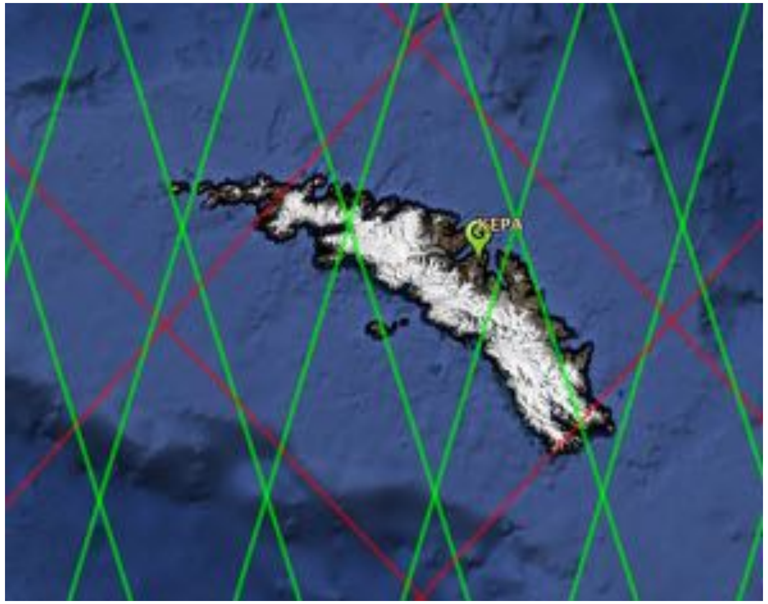


Height changes at TG from 2013 to early 2017. Over the 4 years the tide gauge subsided by 1.4 cm, which indicates an average subsidence rate of 3.6 mm/yr.

What do the Sea Level Time Series Show?



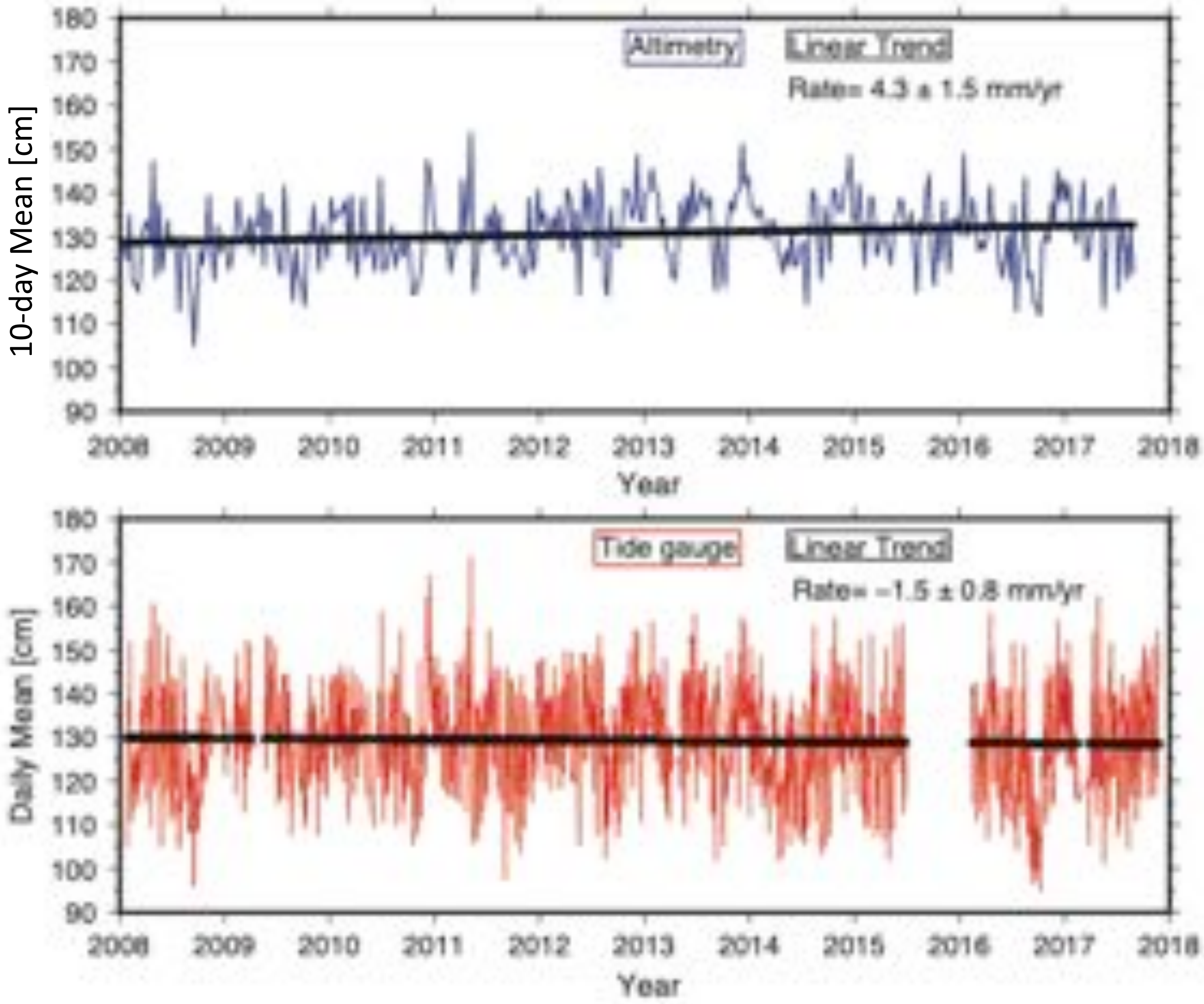
Sea level data for King Edward Point from daily mean tide gauge records (black line) and 10-day average satellite altimeter data (red line). Several data gaps in the tide gauge record are visible. The satellite altimeter data was provided by Brian Beckley and Xu Yang of NASA and was derived from the NASA MEaSUREs v4.2 data set of merged TOPEX/JASON/OSTM altimetry. No inverted barometer (IB) and dynamic atmospheric correction (DAC) combined correction were applied to the data.



KEP tide gauge and satellite altimetry mission ground tracks for TOPEX/POSEIDON/- JASON (red lines) and Sentinel-3 (green lines - for future reference)

A closer look at Sea Level ?

- Rate difference in the sea level records of 5.8 ± 1.7 mm/yr (2008-2018)
- SL fall indicated by the TG would be in line with land uplift, but what about subsidence at TG?
- Local TG subsidence needs a larger regional uplift than indicated
- More investigations are needed



What about the RRS Sir David Attenborough ?

- New Royal Research Ship (RRS) owned by UK Natural Environment Research Council (NERC)
- Substantially larger vessel than the RRS James Clark Ross and RRS Ernest Shackleton which currently serve KEP
- Vessel requires a new KEP jetty
- New KEP tide gauge will be installed

Conclusions

- We have updated the GNSS results since 2018
- The picture of uplift over South Georgia Island of 2-3 mm/yr continues while local subsidence of ~3 mm/yr at the tide gauge is indicated
- 2008-2018 altimeter and TG sea level rates differ substantially and cannot be explained by observed uplift/subsidence processes
- No new levelling information is available for 2018 or 2019, but
- in the Austral Summer 2019/2020 works on a new jetty will start and a new tide gauge will be installed
- This highlights once more the importance of the levelling information connecting the tide gauge and the GNSS station and new campaigns will be necessary in the future

Geodesy and Geospatial Engineering

Thank you for your attention!

- Acknowledgments
  - UL Funding – GSCG Project “New Geodetic Infrastructure and Reprocessed GPS Solutions for Sea Level, Climate Change and Geodynamics”
  - GSGSSI Administration and BAS
    - Mr Keiron Fraser, Mrs Sarah Lurcock, Mr Pat Lurcock, Mr Richard Cable, Mr Jason Wood, Mrs Vickie Foster, Mr Keiran Love, Mr Leslie Whittamore, Mr Dickie Hall, Mr Gerry Gillham and Mr Rod Strachnan
  - University of Luxembourg
    - Dr Kibrom Abraha, Mr Cedric Bruyere, Mr Vincente Adonis and Mr Marc Seil
  - National Oceanography Centre
    - Mr Peter R Foden

Recent Activities on Tristan da Cunha Island: Geodetic Installations, Local Tie Measurements and their Analysis

F.N. Teferle[1], A. Hunegnaw[1], D. Backes[1],

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[1]Geodesy and Geospatial Engineering, Department of Engineering, FSTC, University of Luxembourg, Luxembourg

[2]National Oceanography Centre, Liverpool, United Kingdom

JULY 8-18 JUILLET 2019 I MONTRÉAL, CANADA

27th IUGG General Assembly

27e Assemblée Générale de l'UGGI

International Union of Geodesy and Geophysics I Union Géodésique et Géophysique Internationale

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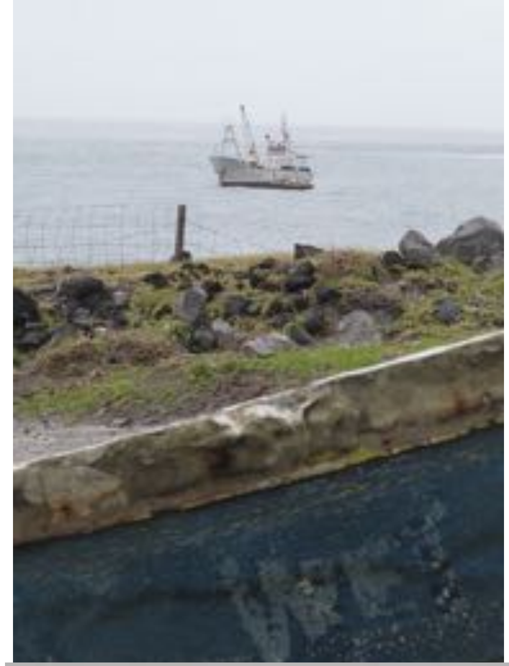



TRISTAN DA CUNHA
POLICE STATION

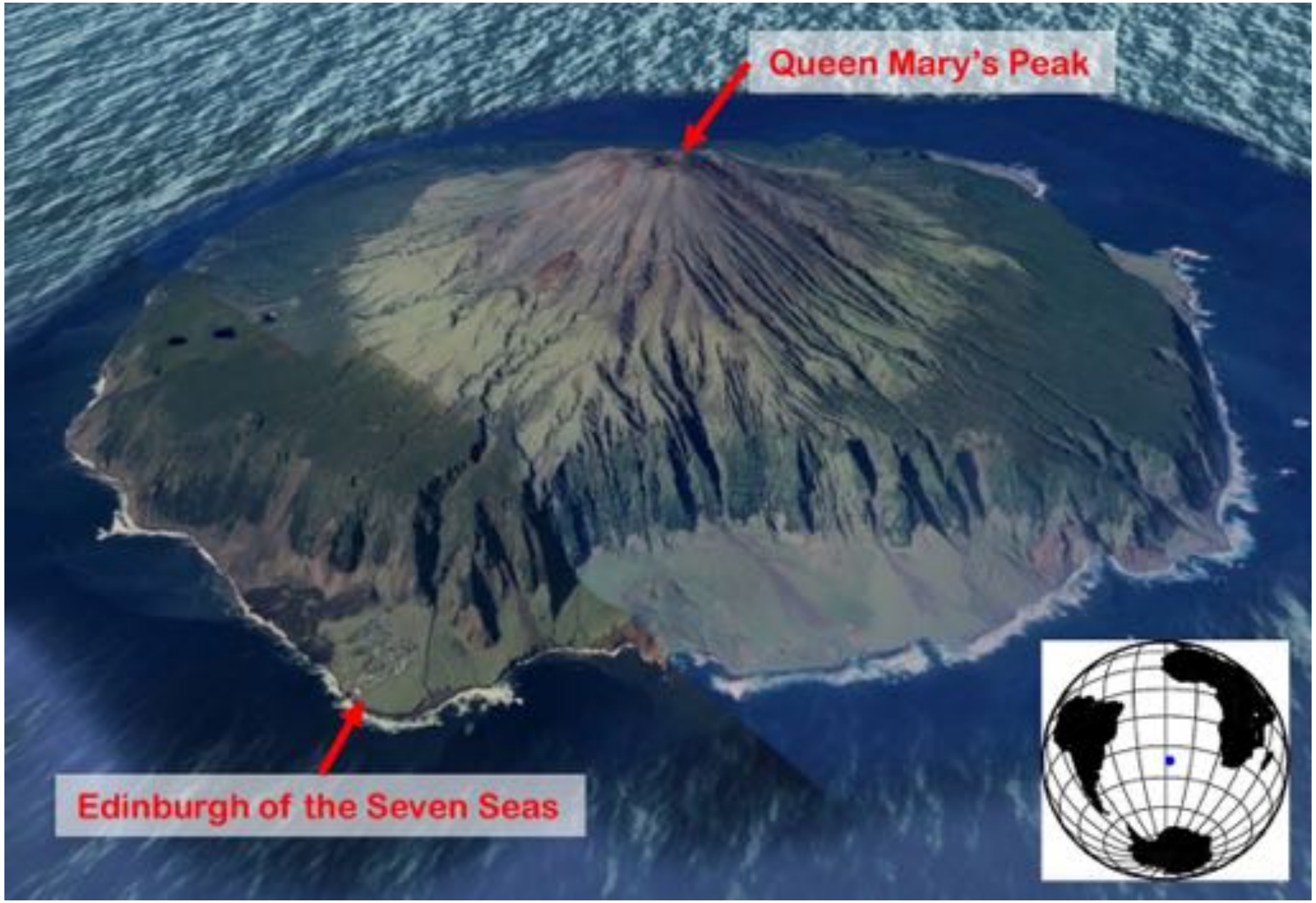

WELCOME
TO THE
REMOTEST
ISLAND

Overview

- Background
- Objectives
- GNSS Installation
- Tide Gauge Installations
- Benchmark Network
  - Existing Benchmarks
  - New and GNSS Benchmarks
- Tie Measurements – Site survey
- Results
- Conclusions and Outlook

Tristan da Cunha Island

- Main island of the Tristan da Cunha archipelago
  - 4 islands (3+1)
  - Gough Island – 400 km south - IGS station (decommissioned)
- Near circular volcanic island with ~12 km diameter
- Volcano with highest point at ~2000 m
- Last eruption 1961
- ~260 Inhabitants



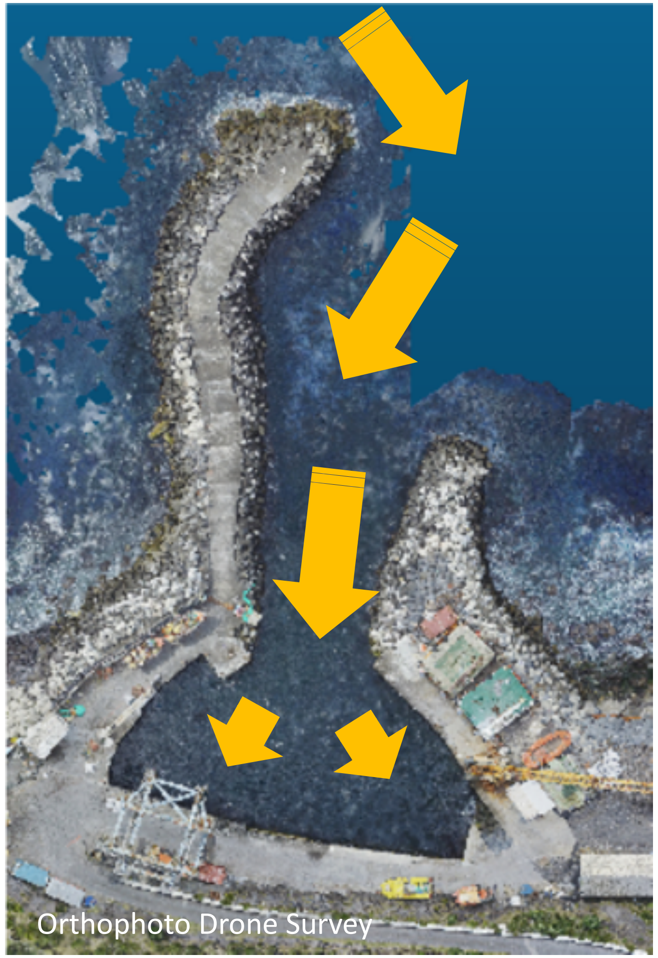
Tristan da Cunha - Logistics

- No flight option
- 5-day ship journey from Cape Town
- Extreme weather conditions with rough seas - landing is only possible on average on 60 days a year
- Little geospatial information, only satellite imagery
- International scientific interest (CTBTO, British Geological Survey, IGN/CNES and NOC-UL)

Daily Mail (2014)

Objectives

- Establish a scientific, state-of-the-art GNSS station to measure vertical land movements for sea level studies (IGS TIGA WG and GGOS Theme 3 missions)
  - Naturally GNSS enables a range of other scientific applications
- Establish two tide gauges to test which performs better in the remote location and hostile conditions: wave action
- Perform a site survey to reference
  - Tide gauges with respect to existing and new benchmarks
  - New GNSS Station TCTA (DOMES 30604M004) to current DORIS Station TRJB (DOMES 30604S003)

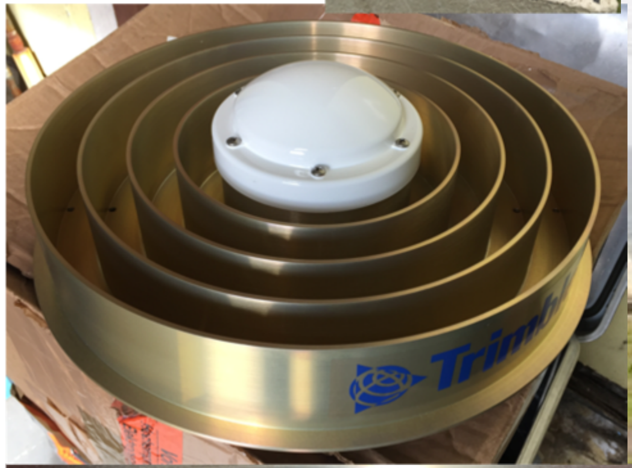


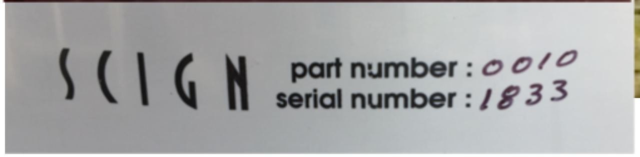
Orthophoto Drone Survey

GNSS Installation

- First attempt in 2016
- Success in 2017
- Trimble NetR9 and Trimble TRM59900.00 + SCIS radome (TCTA DOMES 30604M004)
- Antenna absolute calibration by Geo++ (GPS+GLONASS)
- Uses concrete pillar of decommissioned DORIS station TRIB
- RCV in enclosure with power and DSL Modem connected to comms box inside radio hut – LAN ready
- No data link at the moment !

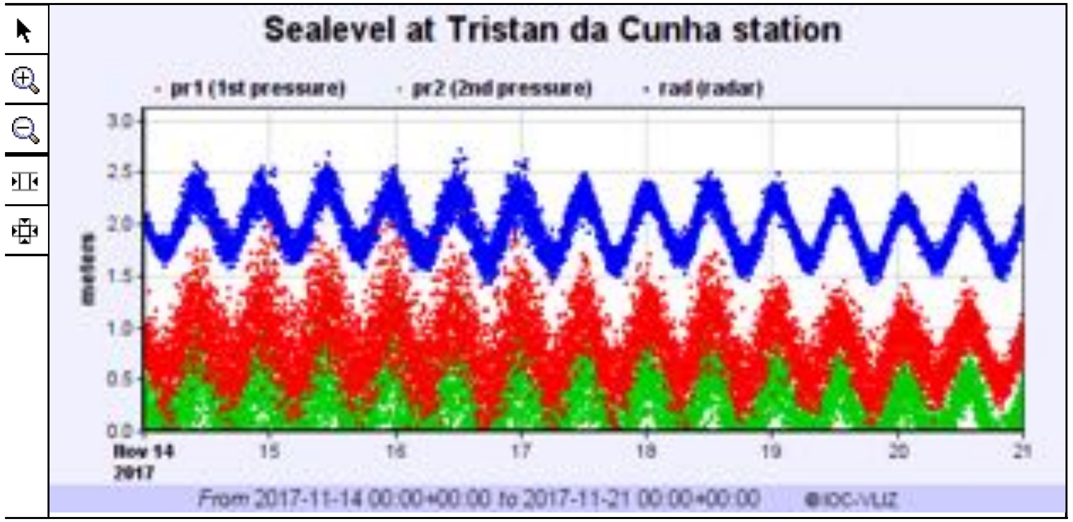
DORIS BM Station TRIB (DOMES 30604M001)



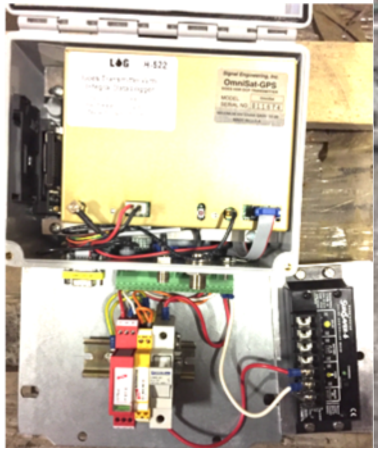


Tide Gauge Installations

- OTT Radar gauge + OTT pressure gauge with sensors at roughly full tide and half tide levels
- Data logger, power system and communication module in nearby boat shed

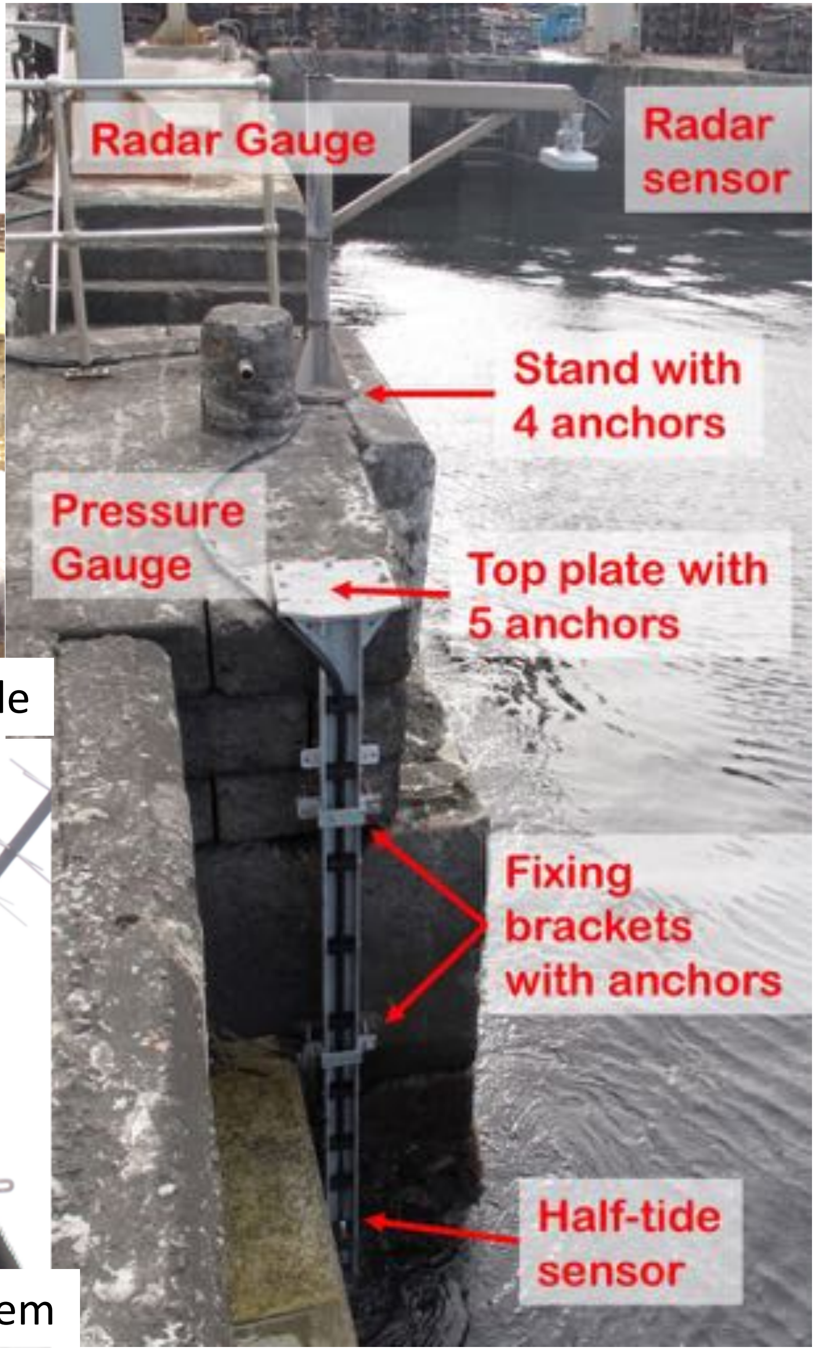


http://www.ioc-sealevelmonitoring.org/station.php?code=tdcu



Data Logger Module

Comms & Power System



Benchmark Network

▲ Tide Gauge Benchmarks

Benchmark Network

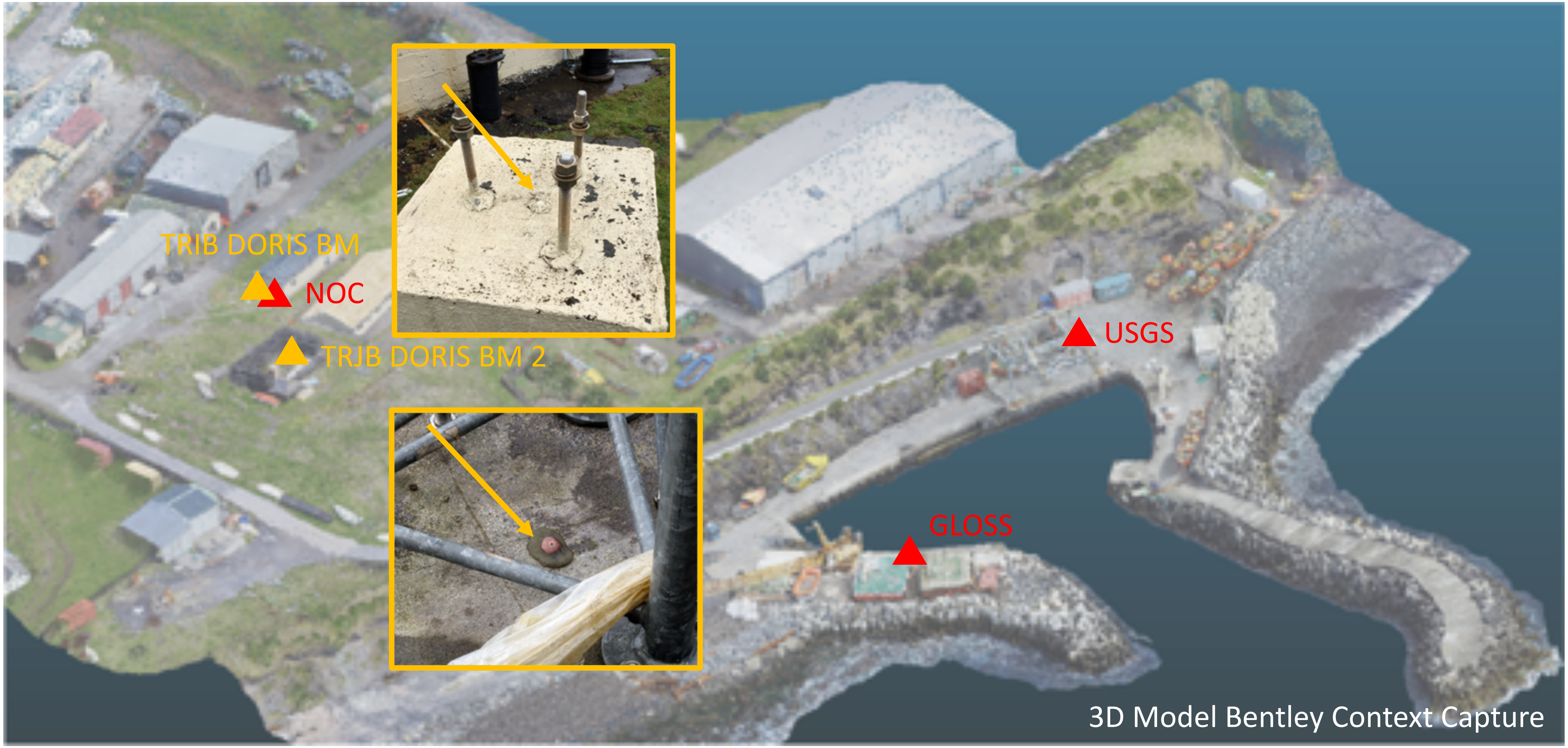
▲ Tide Gauge Benchmarks

Benchmark Network

Tide Gauge Benchmarks
DORIS Benchmarks at TRJB and TRIB

Benchmark Network

Tide Gauge Benchmarks
DORIS Benchmarks at TRJB and TRIB

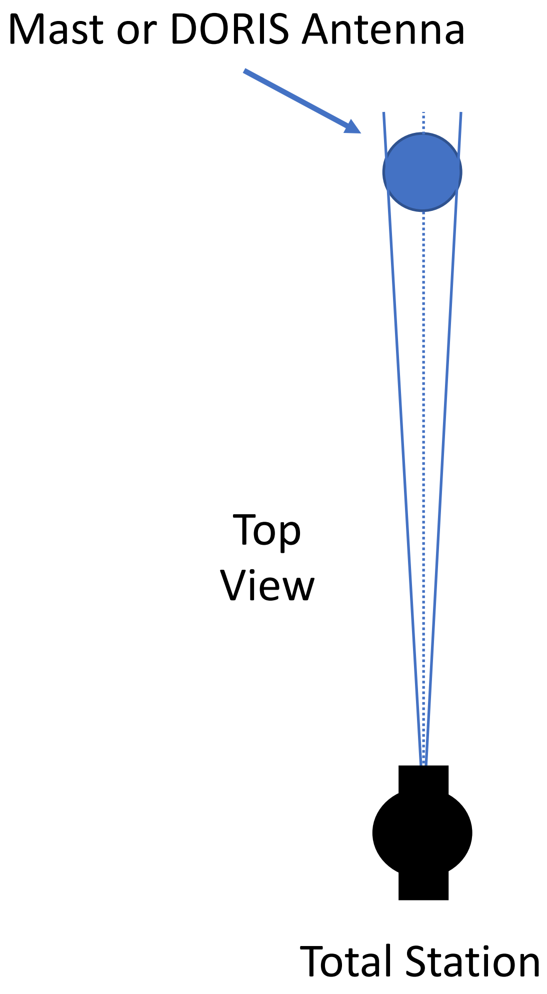


Benchmark Network

Tide Gauge Benchmarks
DORIS Benchmarks at TRJB and TRIB
GNSS/new Benchmarks

Site Survey

- Data Sets
  - 3 x 24 hours of GNSS observations at TCTA and 1003 (DoY 279-281, 2017)
    - To provide absolute position of TCTA and azimuth TCTA-1003
  - 1 x 1 hour of GNSS observations at 1002, 1003, 1004, 1005 and 1006
    - To provide approximate coordinates
    - Tripods remained in place for site survey (except at 1005)
  - Survey using Leica Total Station TS30
    - 3 full rounds of horizontal directions, vertical angles and slope distances
  - Precise levelling using Leica DNA03 and 3m Invar staff/3m telescopic staff
    - Differences between forward and backward runs <0.2mm
    - Bias between staffs when mixing of upright and inverted staff position
  - Drone photogrammetry and terrestrial laser scan for documentation purposes

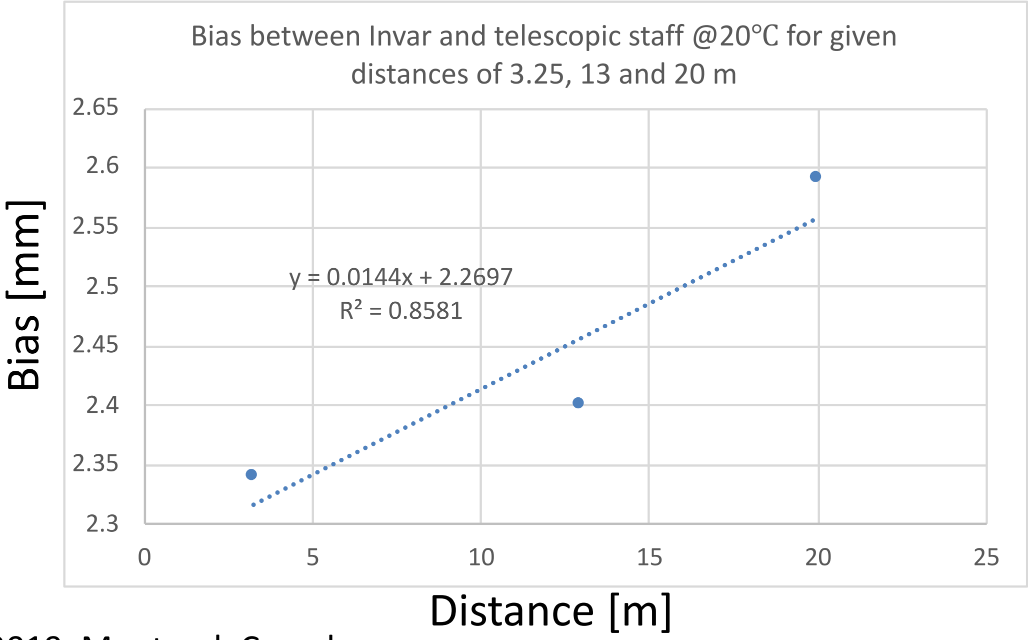


Precise Levelling

- Mix of staffs
  - Normal levelling runs with 3m Invar staff – high accuracy
  - Sections to GNSS antenna, DORIS station and radar gauge with 3 m telescopic staff – lower accuracy
- Laboratory tests show bias between staffs when mixing upright and inverted position
- As a consequence, when using the telescopic staff, the height difference observed is too small, ~2,45 mm, sight distance dependent





Pre-processing and Least Squares Adjustment

Observation Pre-processing:

- GNSS 3-day solution of TCTA and 1003 (Azimuth) using Bernese GNSS Software v5.2
- GNSS 1-hour solutions of baselines TCTA to 1002, 1003, 1005 and 1006 using Leica GeoOffice v8.2
- Terrestrial survey data were pre-processed in rmGeo
  - Adjusted rounds of angles and slope distances
  - Averaged height differences
- Least Squares Adjustment using GeoLab 2017 V2017.2.6

PARAMETERS		OBSERVATIONS	
Description	Number	Description	Number
No. of Stations	32	Directions	34
Coord Parameters	70	Distances	21
Free Latitudes	19	Azimuths	0
Free Longitudes	19	Vertical Angles	0
Free Heights	32	Zenithal Angles	21
Fixed Coordinates	26	Angles	0
Astro. Latitudes	0	Heights	0
Astro. Longitudes	0	Height Differences	53
Geoid Records	0	Auxiliary Params.	0
All Aux. Pars.	6	2-D Coords.	0
Direction Pars.	6	2-D Coord. Diffs.	14
Scale Parameters	0	3-D Coords.	6
Constant Pars.	0	3-D Coord. Diffs.	15
Rotation Pars.	0		
Translation Pars.	0		
	--------		--------
Total Parameters	76	Total Observations	164
Degrees of Freedom = 88			

Local Geodetic Datum Implementation

- Cartesian coordinates from TCTA and azimuth TCTA - 1003

```
*COORDINATE SOLUTION OF TCTA_ARP (IGS14/ITRF2014 EPOCH 2017:279)
*BERNESE GNSS SOFTWARE V5.2 PPP OVER 3 DAYS (DOYS 279-281)
 3DC
 XYZ  000 TCTA_ARP          4978463.5247      -1086616.9773    -3823205.2619   m  0
 COV  CT DIAG                           1
 ELEM                0.000001                0.000001                0.000001
```

Average Coordinates for TCTA

```
*AZIMUTH DERIVED FROM TCTA_ARP AND 1003 (IGS14/ITRF2014 EPOCH 2017:279)
*BERNESE GNSS SOFTWARE V5.2 PPP OVER 3 DAYS (DOYS 279-281)
 3DD
 PLH  000 TCTA_ARP     S 37  3 55.000588 W 12 18 44.943277      47.9919 m       0
 PLH  000 1003_ARP     S 37  3 53.498850 W 12 18 44.188425      42.5524 m       0
 COV  LG DIAG
 ELEM                0.000001                0.000001                    0.01
```

Azimuth TCTA to 1003 over 3 days

DORIS TRJB Coordinate Observation DPOD2014 V1.0 @Epoch 2017 Doy 279

```
* PLH   000 TRJB          S 37   3 54.411577 W 12 18 44.639851      46.9286 m       0
 GRP   DORIS TRJB DPOD2014 V1.0 @EPOCH 2017.76164
 3DC
 XYZ   000 TRJB                  4978474.98663     -1086611.80654     -3823190.13201 m  0
 COV   CT DIAG                             1
 ELEM                      0.0001                      0.0001                      0.0001
```

www.ids-doris.org

Centering Equations

- Various centering equations were introduced into the adjustment, e.g. at TCTA and TRJB

```
*TCTA_ARP AND CENTER OF MAST (1035) ARE VERTICALLY ALIGNED
 2DD
 PL   00  TCTA_ARP     S 37  3 55.000588 W 12 18 44.943277
 PL   00  1035         S 37  3 55.000588 W 12 18 44.943277
 COV  LG DIAG
 ELEM                0.000001               0.000001
```

```
*TCTA_ARP AND 1030 (TRIB DORIS BM) ARE NOT FULLY VERTICALLY ALIGNED
 2DD
 PL   00  TCTA_ARP     S 37  3 55.000588 W 12 18 44.943277
 PL   00  1030         S 37  3 55.000300 W 12 18 44.943076
 COV  LG DIAG
 ELEM               0.0000250               0.0000250
* PL   00  1030         S 37  3 55.000588 W 12 18 44.943277
```

Statistics Summary

Stochastic model:

- Errors from pre-processing where introduced a priori
- Variance factors of observation groups were equal at the beginning and updated accordingly:
    - GNSS vectors
    - DORIS coordinates
    - Height differences
    - Horizontal directions
    - Vertical Angles
    - Slope distances
- GeoLab 2017 uses theory for blunder detection as in Ghilani (2010)

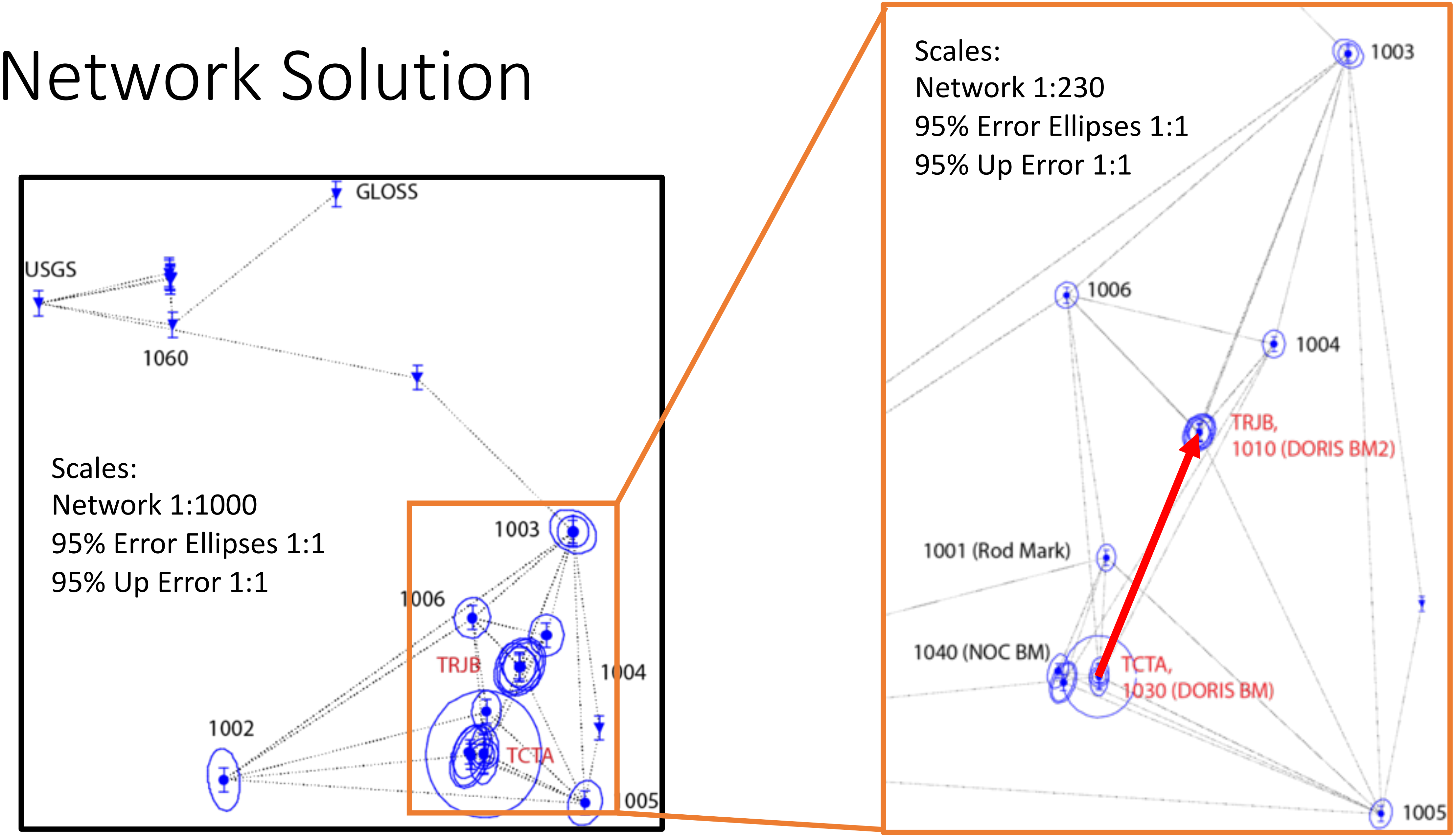
Residual Critical Value Type	Tau Max
Internal reliability	No
External reliability type	None
Reliability significance level	1.0
Reliability power of test	80
Residual Critical Value	3.6666
Number of Flagged Residuals	0
Convergence Criterion	0.0001
Final Iteration Counter Value	3
Confidence Level Used	95.0000
Estimated Variance Factor	0.9036
Number of Degrees of Freedom	88

Chi-Square Test on the Variance Factor:

6.8646e-01 < 1.0000 < 1.2437e+00 ?

THE TEST PASSES

Network Solution



Extracted Main Coordinate Results (Co-location GNSS – DORIS)

X-COORDINATE			Y-COORDINATE	Z-COORDINATE			
CODE	FFF	STATION	STD DEV	STD DEV	STD DEV		
----	---	------------	------------------	------------------	------------------		
XYZ		TCTA_ARP	4978463.5247 0.0009	-1086616.9773 0.0009	-3823205.2619 0.0009	m	0
XYZ		TRIB	4978462.2906 0.0038	-1086616.7026 0.0049	-3823204.2916 0.0045	m	0
XYZ		TRJB	4978474.9572 0.0020	-1086611.8044 0.0019	-3823190.1433 0.0020	m	0
XYZ		TRJB2GHZ	4978475.3368 0.0020	-1086611.8873 0.0021	-3823190.4369 0.0022	m	0
XYZ		1010 (DORIS BM2)	4978472.2984 0.0018	-1086611.2241 0.0016	-3823188.0878 0.0018	m	0
XYZ		1030 (DORIS BM)	4978461.9077 0.0022	-1086616.6190 0.0013	-3823203.9956 0.0023	m	0

Using these we can cross-evaluate vector results from this study with the previous ones, Poyard (2012).

DORIS TRIB-TRJB Vector Cross-Evaluation

Benchmark	Poyard 2012			This Study			Difference			
Vector	dX	dY	dZ	dX	dY	dZ	dX	dY	dZ	3D RMS
DORIS BM - DORIS BM 2	10,3904	5,3951	15,9064	10,3907	5,3949	15,9077	-0,0003	0,0002	-0,0013	0,0013
	0,0027	0,0031	0,0030	0,0018	0,0021	0,0029				
DORIS BM - TRJB	13,0470	4,8182	13,8525	13,0495	4,8146	13,8522	-0,0025	0,0036	0,0003	0,0044
	0,0029	0,0031	0,0031	0,0030	0,0023	0,0030				
DORIS BM 2 - TRIB	-10,0074	-5,4787	-16,2025	-10,0078	-5,4784	-16,2038	0,0004	-0,0003	0,0013	0,0014
	0,0024	0,0028	0,0027	0,0042	0,0052	0,0048				
TRIB - TRJB	12,6647	4,9018	14,1486	12,6666	4,8981	14,1483	-0,0019	0,0037	0,0003	0,0042
	0,0027	0,0028	0,0028	0,0043	0,0053	0,0049				

All units are m.

- Sub-mm to -1,3 mm agreement for DORIS BM – DORIS BM2 vector.
- Overall 3D RMS ranges from 1,3 to 4,4 mm.

Internal Vector Evaluation

- Several vectors can be evaluated for adhering to the given centering equations

Benchmark Vector	dN	dE	dU
TCTA_ARP - 1030 (DORIS BM)	0,0122	0,0052	-2,0849
TCTA_ARP - 1035 (TCTA_BCR)	0,0000	0,0004	0,0350
TRJB - 1010 (DORIS BM 2)	0,0000	0,0000	-3,4104
TRJB - TRJB2GHz	0,0000	0,0000	0,4870
1010RFL - 1010 (DORIS BM 2)	0,0051	-0,0017	1,2999

All units are in m.

- The solution suggests that
  - TCTA – DORIS BM are not vertically aligned
  - The handheld 1010RFL is not vertically aligned with DORIS BM 2.
  - There is no 3 mm East offset for TRJB – DORIS BM 2 (Poyard, 2012)

Extracted Main Levelling Results

CODE	FFF	STATION	LATITUDE	STD DEV	LONGITUDE	STD DEV	ELIP-HEIGHT	STD DEV	
PLH		TCTA_ARP	S 37 3 55.000588	0.0009	W 12 18 44.943277	0.0009	47.9920 m	0.0009	0
PLH		1001 (Rod Mark)	S 37 3 54.713534	0.0018	W 12 18 44.921636	0.0012	44.8213 m	0.0013	0
PLH		1010 (DORIS BM 2)	S 37 3 54.412446	0.0021	W 12 18 44.640022	0.0017	43.5017 m	0.0013	0
PLH		1030 (DORIS BM)	S 37 3 55.000193	0.0025	W 12 18 44.943065	0.0012	45.9071 m	0.0020	0
PLH		1040 (NOC Ball Mark)	S 37 3 54.987178	0.0023	W 12 18 45.068113	0.0014	44.5356 m	0.0013	0
PLH	110	GLOSS (Ball Mark)	S 37 3 51.222914	0.0000	W 12 18 46.192530	0.0000	24.4629 m	0.0013	0
PLH	110	1060 (BM)	S 37 3 52.103319	0.0000	W 12 18 47.577926	0.0000	25.5697 m	0.0013	0
PLH	110	USGS	S 37 3 51.958381	0.0000	W 12 18 48.712091	0.0000	25.4732 m	0.0013	0

Using these we can cross-evaluate height differences from this study with the previous ones, Poyard (2012).

Levelling Results – Cross-Evaluation

- Levelling results can be compared to two previous surveys in 2002 and 2012 (Poyard, 2012)

Benchmarks	N#	Elevation Differences [m]			Difference
		2002	Poyard 2012	This Study	2012-This Study
1030 (DORIS BM)	1				
1001 (Rod Mark)	2		-1,0840	-1,0858	0,0018
1040 (NOC Ball Mark)	3		-0,2860	-0,2857	-0,0003
1010 (DORIS BM 2)	4		-1,0350	-1,0399	0,0049
1050 (GLOSS Ball Mark)	5		-19,0310	-19,0388	0,0078
Total 1-5		-21,4600	-21,4360	-21,4502	0,0142
Total 2-5			-20,3520	-20,3644	0,0124
Direct 2-5 (no DORIS BMs)			-20,3515	-20,3584	0,0069
Direct 3-5 (no DORIS BMs)			-20,0656	-20,0727	0,0071

All units are m.

Tide Gauge Benchmark Heights

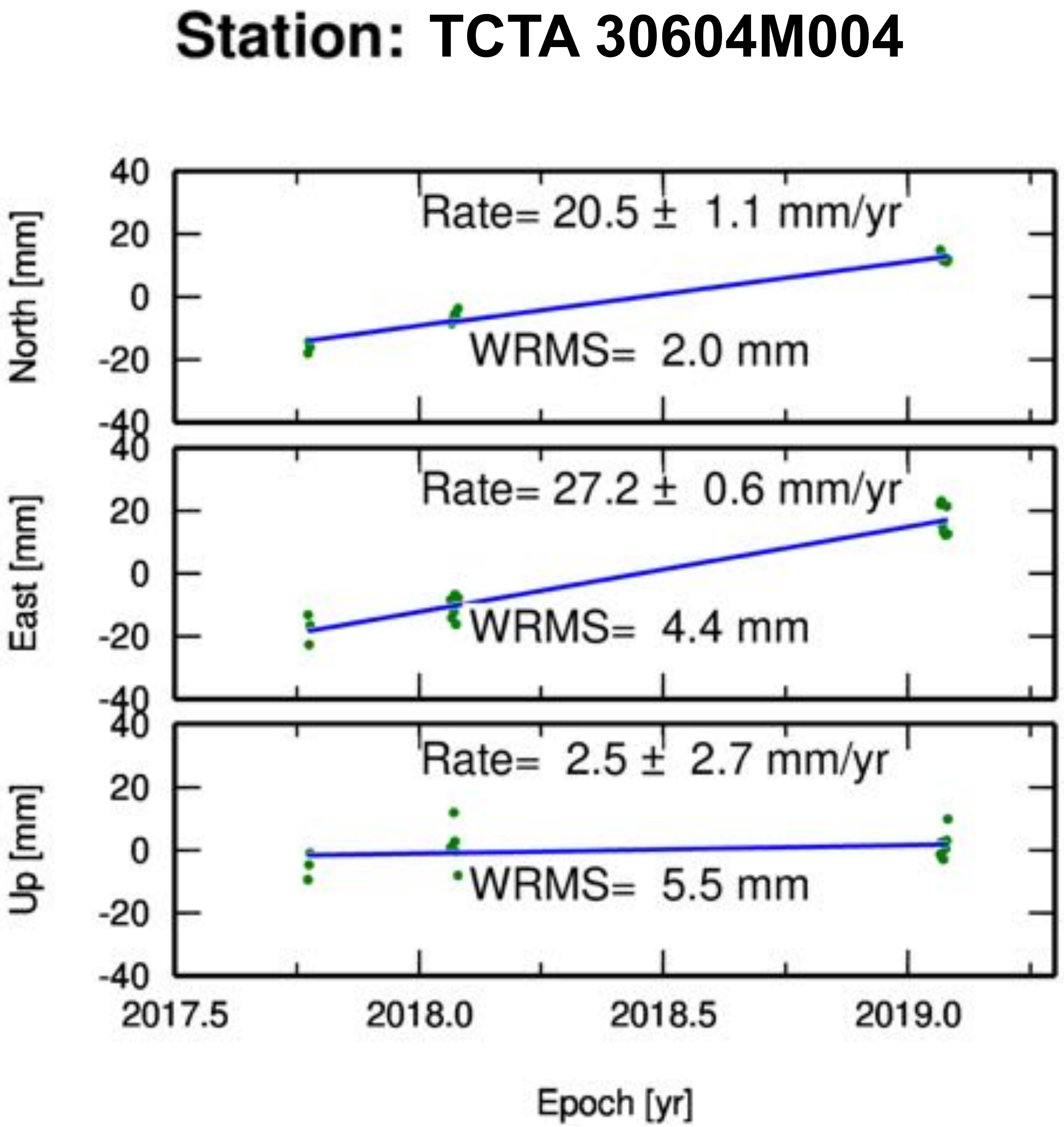
CODE	FFF	STATION	LATITUDE STD DEV	LONGITUDE STD DEV	ELIP-HEIGHT STD DEV	
PLH		1040 (NOC BALL MARK)	S 37 3 54.987178	W 12 18 45.068113	44.5356 m	0
			0.0023	0.0014	0.0013	
PLH	110	1050 (GLOSS BALL MARK)	S 37 3 51.222914	W 12 18 46.192530	24.4629 m	0
			0.0000	0.0000	0.0013	
PLH	110	1060 (New TGBM)	S 37 3 52.103319	W 12 18 47.577926	25.5697 m	0
			0.0000	0.0000	0.0013	
PLH	110	1061 (PG TOP PLATE)	S 37 3 51.792237	W 12 18 47.593764	24.7625 m	0
			0.0000	0.0000	0.0013	
PLH	110	1062 (PG PLATE BOLT)	S 37 3 51.790781	W 12 18 47.601102	24.7811 m	0
			0.0000	0.0000	0.0013	
PLH	110	1063 (RG MAINTENANCE)	S 37 3 51.780521	W 12 18 47.592153	25.8099 m	0
			0.0000	0.0000	0.0013	
PLH	110	1064 (RG OPERATION)	S 37 3 51.756197	W 12 18 47.606775	25.8234 m	0
			0.0000	0.0000	0.0014	
PLH	110	1070 (USGS BM)	S 37 3 51.958381	W 12 18 48.712091	25.4732 m	0
			0.0000	0.0000	0.0013	
PLH	110	PG_Sensor_1	S 37 3 51.792237	W 12 18 47.593764	21.7280 m	0
			0.0000	0.0000	0.0016	
PLH	110	PG_Sensor_2	S 37 3 51.792237	W 12 18 47.593764	22.2845 m	0
			0.0000	0.0000	0.0016	
PLH	110	RG_Sensor	S 37 3 51.756197	W 12 18 47.606775	25.5621 m	0
			0.0000	0.0000	0.0017	

Conclusions

- The GNSS and tide gauge installations, the benchmark network and the site co-location survey on Tristan da Cunha have been presented
- The adjustment results have been cross-evaluated with the previous ones from Poyard (2012). This shows:
  - 3D RMS agreements of 1.3 to 4.4 mm for various vectors
  - Height differences between NOC BM – GLOSS BM of -20,0727 ± 0,0018 m, which differs by 7,1 mm from Poyard (2012).
- Cartesian coordinate vector TCTA_ARP – TRJB of dX= 11,4325 ± 0,0022 m
  dY= 5,1729 ± 0,0021 m
  dZ= 15,1186 ± 0,0022 m
- Height differences between the GNSS station and the new tide gauges have been determined at the few mm-level (not shown)
- For many GNSS@TG stations similar studies are missing / no levelling information is made available to the IGS TIGA Archive at www.sonel.org

Outlook

- Installation of dedicated satellite communications
- Once routine data communication has been established - application for inclusion as IGS station
- Contributions to the ITRF
- Unfortunately: a move of the GNSS station might become necessary once a new radio hut has been erected



Geodesy and Geospatial Engineering

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  - **National Oceanography Centre**
    - **Mr Peter R Foden**
  - **IGN, France**
    - **Dr Bruno Garayt, Mr Jean-Claude Poyard**

- **References**

  - **Donal, Th., July 2016, Ascencion ITRF Co-location Site Survey, IGN Report 28654.**
  - **Poyard, J-C., June 2012, Tristan da Cunha Co-location Survey, IGN Report 28431.**
  - **Ghilani, C.D., 2010, Adjustment Computations: Spatial Data Analysis, 5th Ed.**

Tracking Hurricanes Using GPS Atmospheric Integrated Water Vapour Fields

Yohannes Getachew Ejigu[1], Felix Norman Teferle[2], Anna Klos[3], Janusz Bogusz[3] and Addisu Hunegnaw[2]

[1]Department of Space Science and Application Research Development, Ethiopian Space Science and Technology Institute, Addis Ababa, Ethiopia

[2]Geodesy and Geospatial Engineering, Institute of Civil and Environmental Engineering, University of Luxembourg, Luxembourg, Luxembourg.

[3]Faculty of Civil Engineering and Geodesy, Military University of Technology, Warsaw, Poland

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UNIVERSITÉ DU LUXEMBOURG

Ethiopian Space Science & Technology Institute

Military University of Technology

Luxembourg National Research Fund

Outline

1. Introduction
    - Hurricanes
    - Water Vapour
    - GPS Processing
2. Data and Methods
    - Retrieval of IWV from GPS ZTD
    - Precipitation data set
3. Results
    - Tracking of hurricanes using GPS-derived IWV
4. Summary

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Hurricanes

Hurricanes are the most powerful hydro-meteorological hazards

1. Intense low pressure disturbances, intense winds and very strong convective activity
2. Major damage potential/loss of life; about 10,000 death per year since 1971
3. $700 billion in damage annually since 1971
4. Global population exposed to hurricane hazard has tripled since 1971

2017 Atlantic hurricane season was the most active record, the third highest number of major hurricanes of the past century

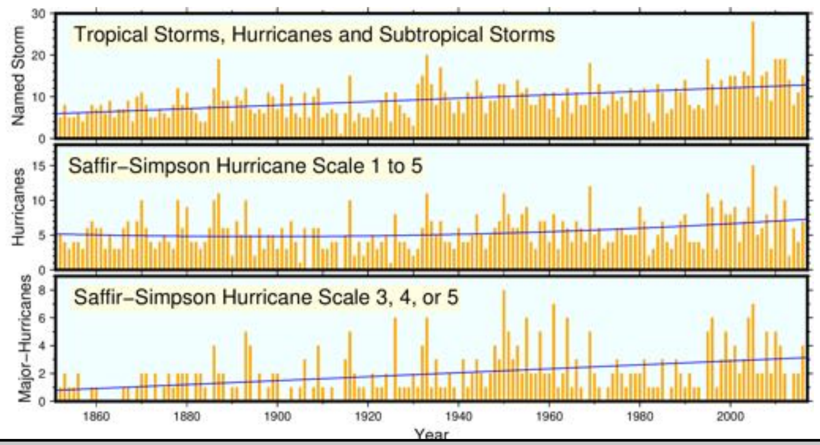


Fig.1. Named storms and Hurricanes in North Atlantic Basin, 1851--2017. (https://www.aoml.noaa.gov/hrd/tcfaq/E11.html)

Hurricane Physics

1. Natural perfect ideal Carnot heat engine
2. Spreads over a radius of a few hundred kilometers
3. The working fluid consists of dry air and water vapor
4. Air undergoes isothermal expansion A →B (entropy ↑)
5. Adiabatic ascent of the air along constant temperature B → C
6. Isothermal compression is radiated to outer C → D
7. Adiabatic compression (loosing altitude fast) D → A

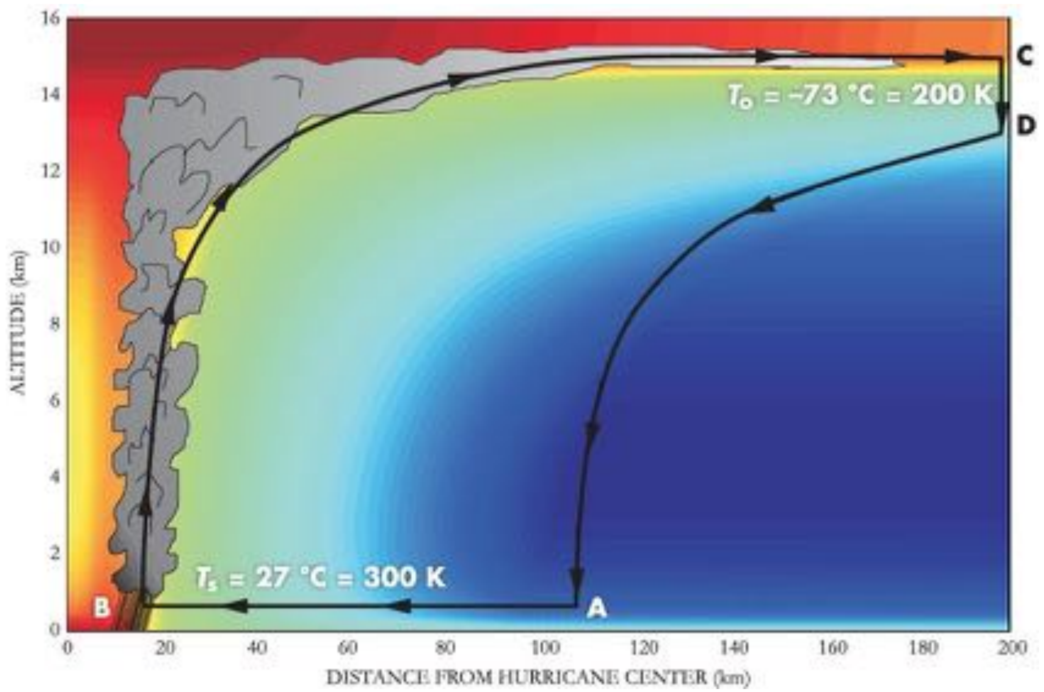


Fig.2 The hurricane as a Carnot heat engine.

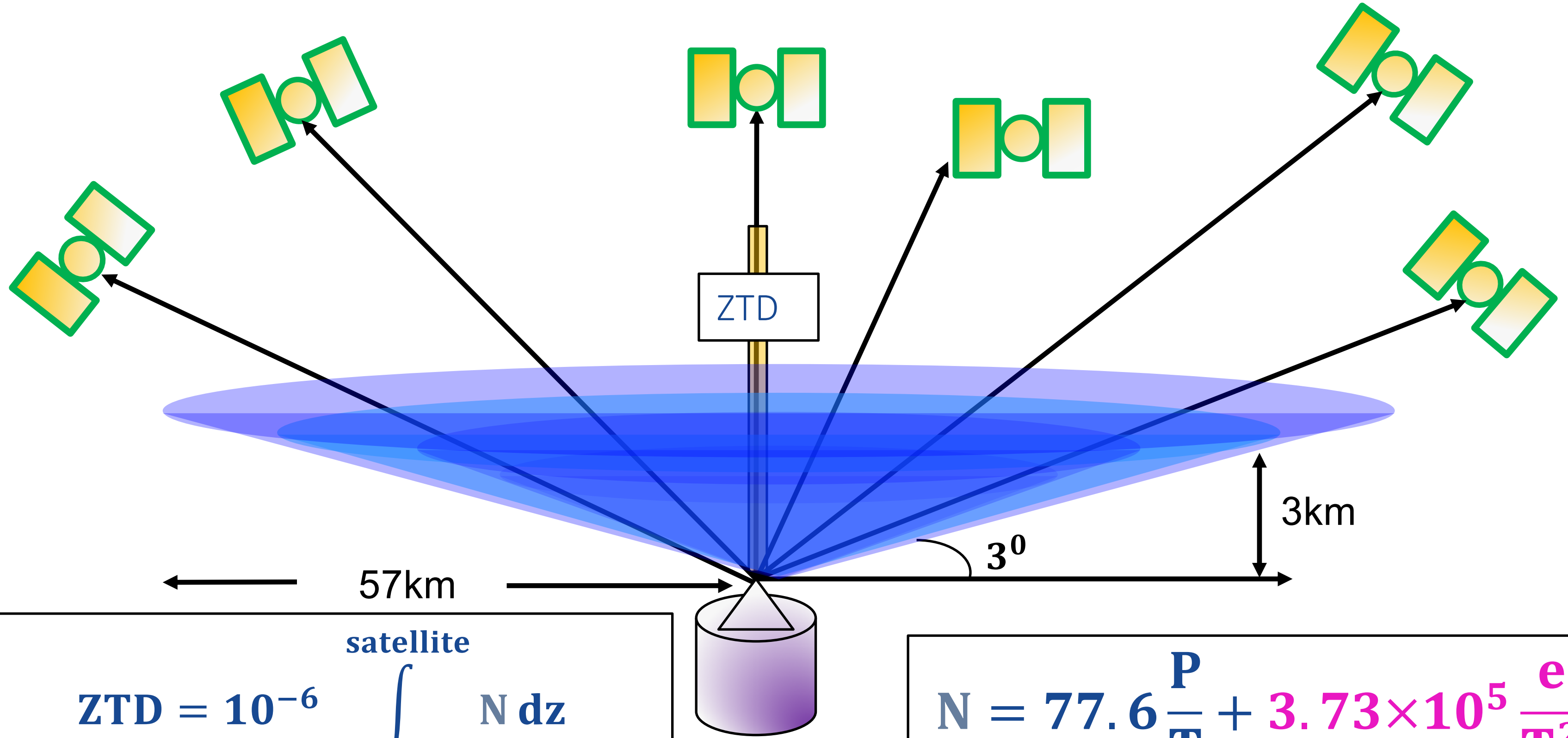
The process mainly responsible for driving the storm is the evaporation of seawater, which transfers energy from sea to air.

(Emanuel,2006).

Water Vapour

1. Water vapor arguably at the heart of all key terrestrial atmospheric processes
2. It is the source of clouds and precipitation, and an ingredient in most major weather events
3. It moves rapidly through the atmosphere, redistributing energy (latent heat) through evaporation and condensation
4. Hurricane will produce substantially more rain: Clausius-Clapeyron yields 7% increasing in water vapor per 1 degree Celsius Warming
5. It is acknowledged that water vapor can play an important role in the modeling and forecasting of hurricanes due to its role in their development (Businger et al., 1996).
6. Currently, the GPS tropospheric products can be used to determine the distribution of, and temporal changes of water vapor.

Water Vapour from GPS Observations



$$ZTD = 10^{-6} \int_{\text{anetnna}}^{\text{satellite}} N \, dz$$

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

Fig 3. GPS ZTD (IWV) estimate is considered as averaged values of inverse-cone with radius of 57 km at a height of 3 km

Retrieval of IWV from GPS ZTD

2 — We partitioned the GPS stations into different sub regional networks based on the impacts of the hurricanes

2 — Hurricane Harvey includes 360 GPS stations, 562 Hurricane Irma and 839 Hurricane Florence

3 — Most stations are distributed nearly 20-km apart

4 — We have used for a period of two months data for each Hurricanes

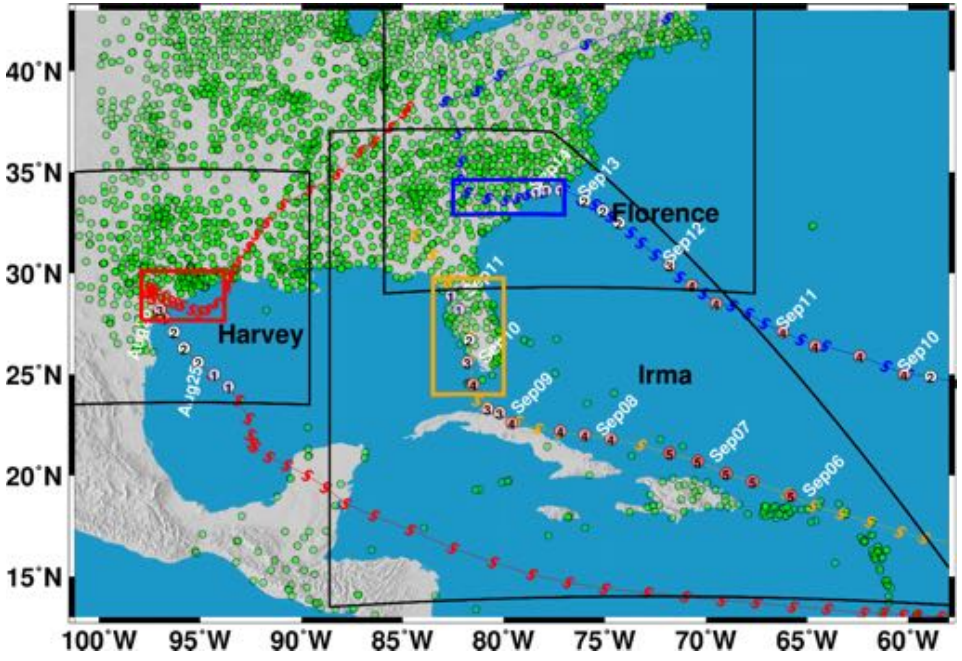


Fig.4. Distribution of GPS stations

GPS Processing Strategy

- **The observation cut-off angle at 7-degree**
- **We have used the ZTD Tropo-SINEX obtained at the Nevada Geodetic Laboratory using GIPSY/OASIS-II PPP strategy**
- **We calculated ZHDs using model available from the Vienna Mapping Functions (VMF) gridded files**
- **We extract ZWD directly by subtracting ZHD from the estimated ZTD**
- **Further, we calculated the IWV using atmospheric column mean temperature, converting IWV from the ZWD.**

$$IWV = \Pi \times ZWD$$

Precipitation Data Set/External Validation

For validation purpose, two types of precipitation dataset were used

- **The latest Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (GPM/IMERG) satellite mission (Huffman et al.,2017)**
- **Tropical Rainfall Measuring Mission (TRMM) satellite (Huffman and Bolvin, 2015)**
- **The Integrated Multi-satellite Retrievals for GPM (IMERG) 0.1 degree spatial resoluteness & 30 minute temporal resolutions**
- **The Tropical Rainfall Measuring Mission (TRMM): 0.1 degree spatial resolutions and 3 hours temporal resolutions**

Monitoring of Hurricanes using GPS-derived IWV

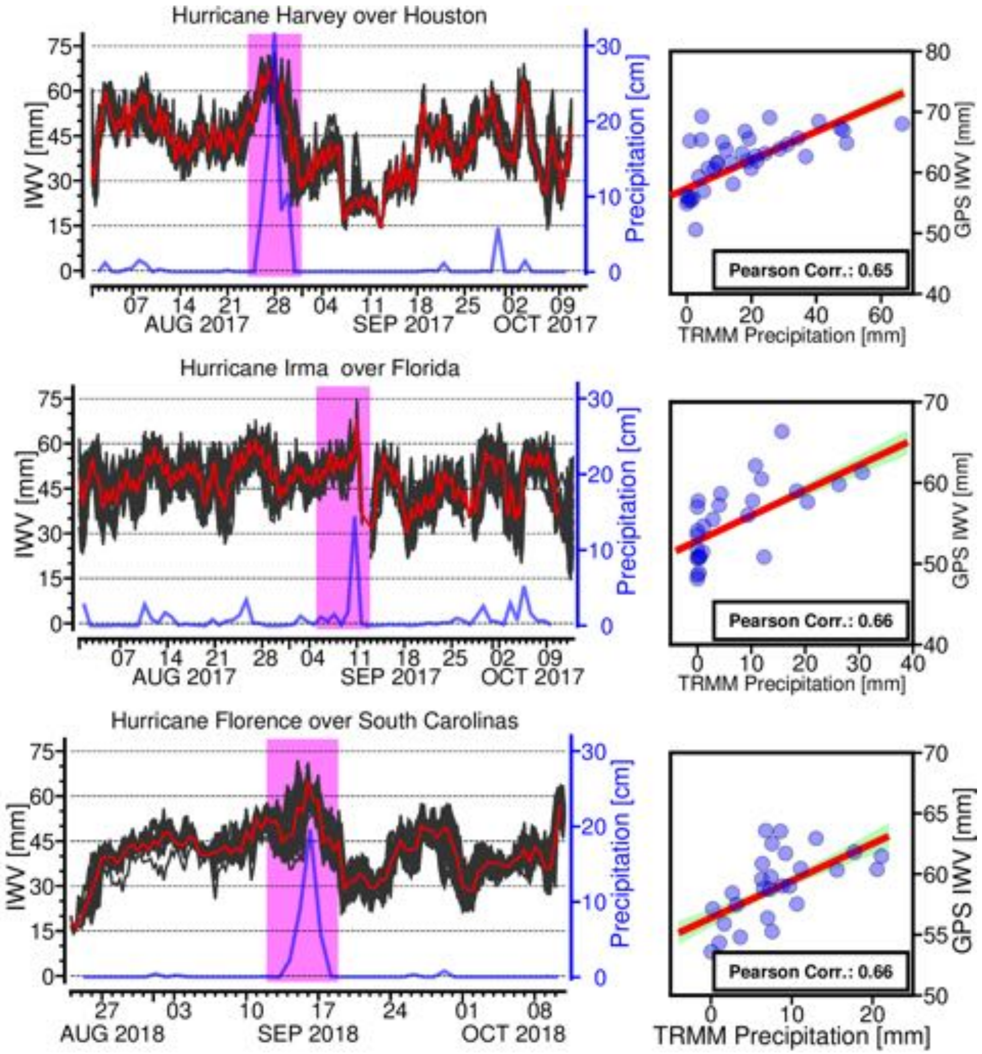
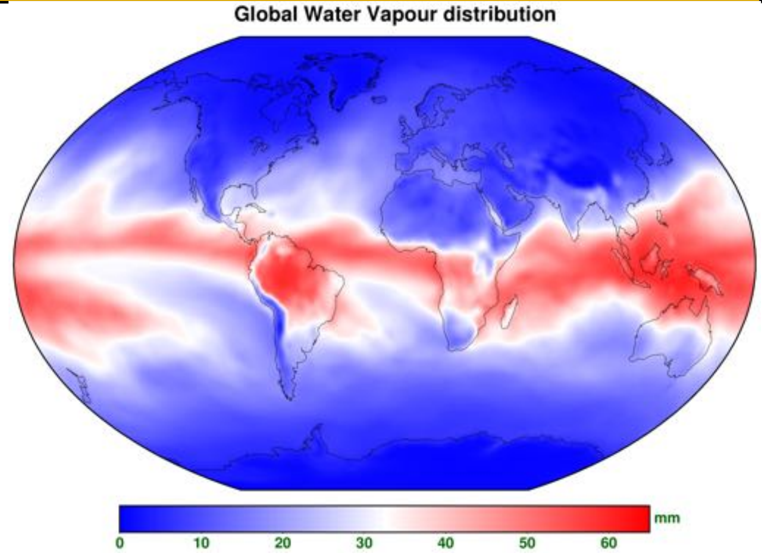


Fig.5: [Left] Stacked time series of GPS-IWV superimposed on daily GPM/IMERG precipitation. [Right] regression between TRMM satellite derived precipitation and GPS-IWV.



IWV Distribution Maps for Hurricane Harvey

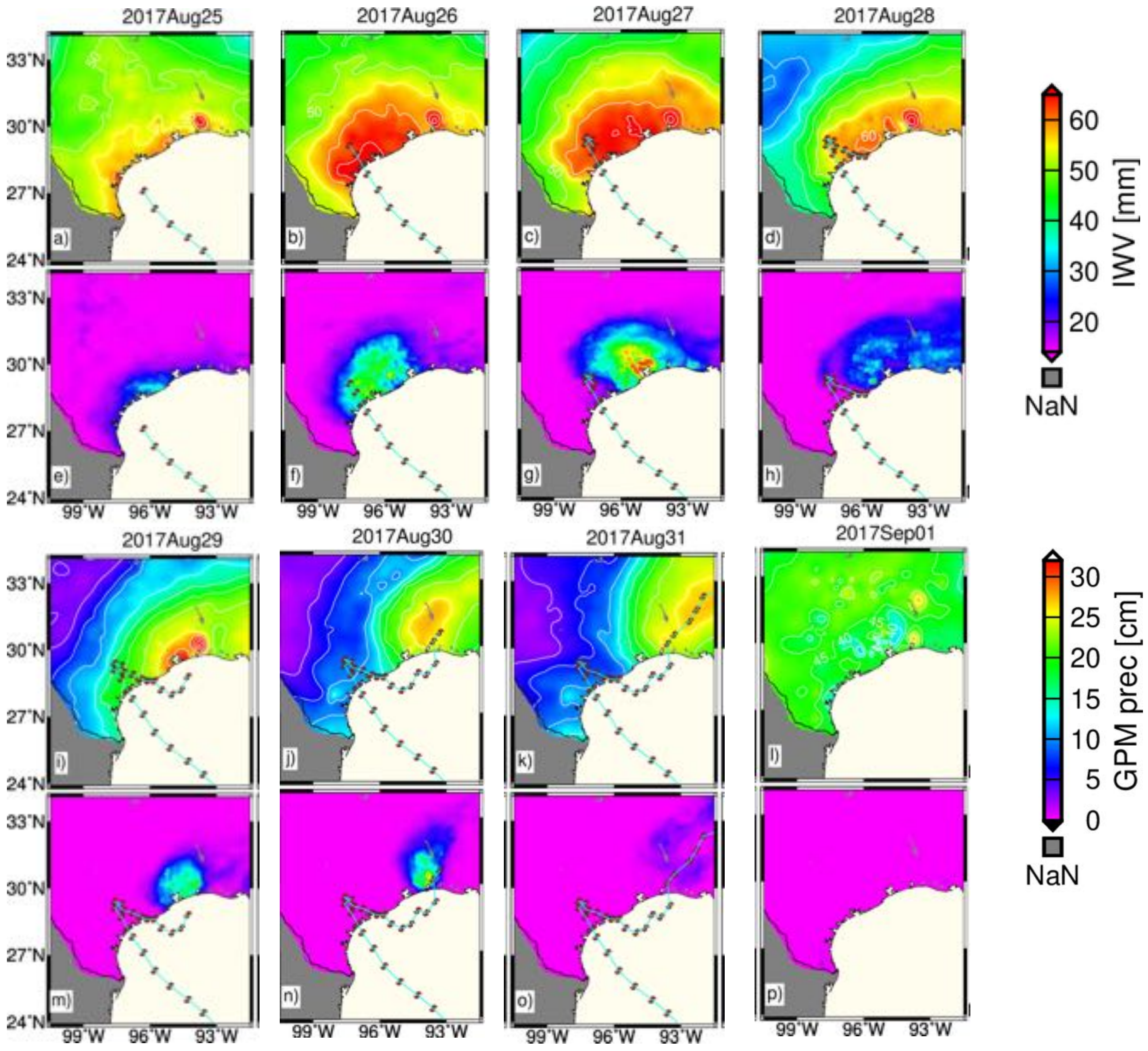
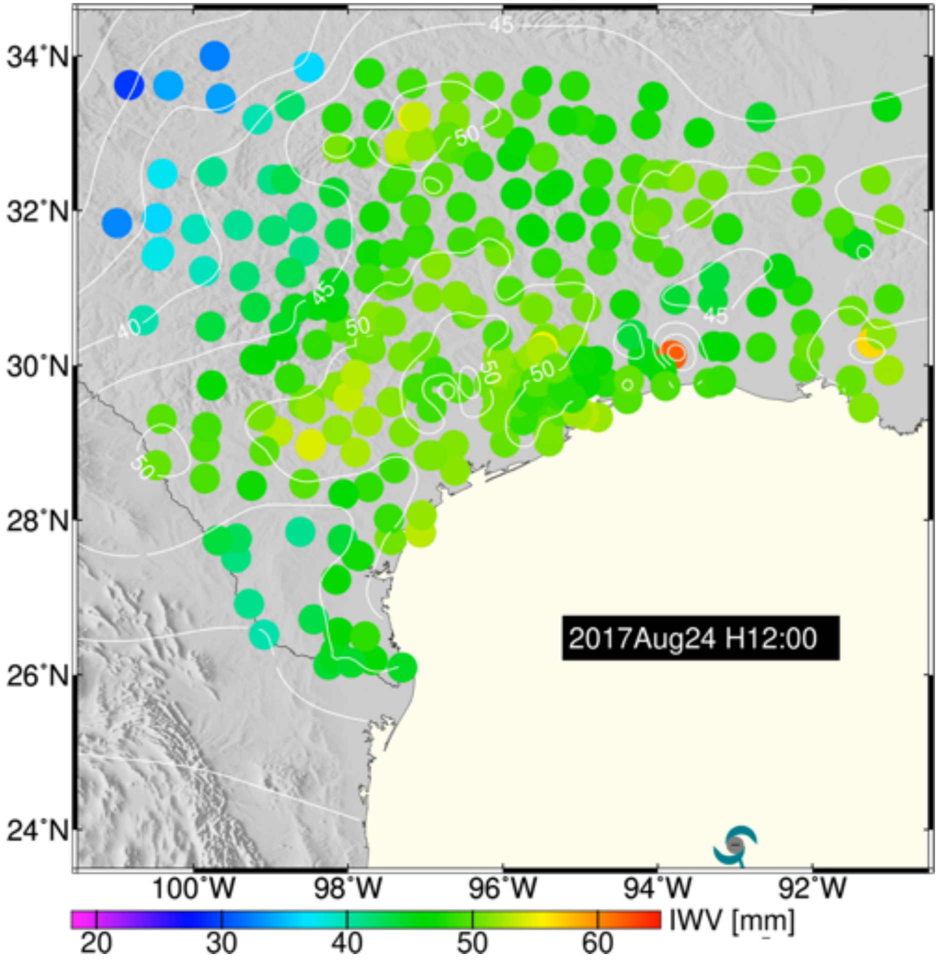


Fig.6: Distribution maps for Hurricane Harvey between 25-Aug to 1-Sep 2017. The contour interval of the GPS-IWV is 10 mm. Harvey's path is plotted as the cyan line and hurricane symbol as brown.

IWV Animation – Hurricane Harvey



IWV Distribution Maps for Hurricane Irma

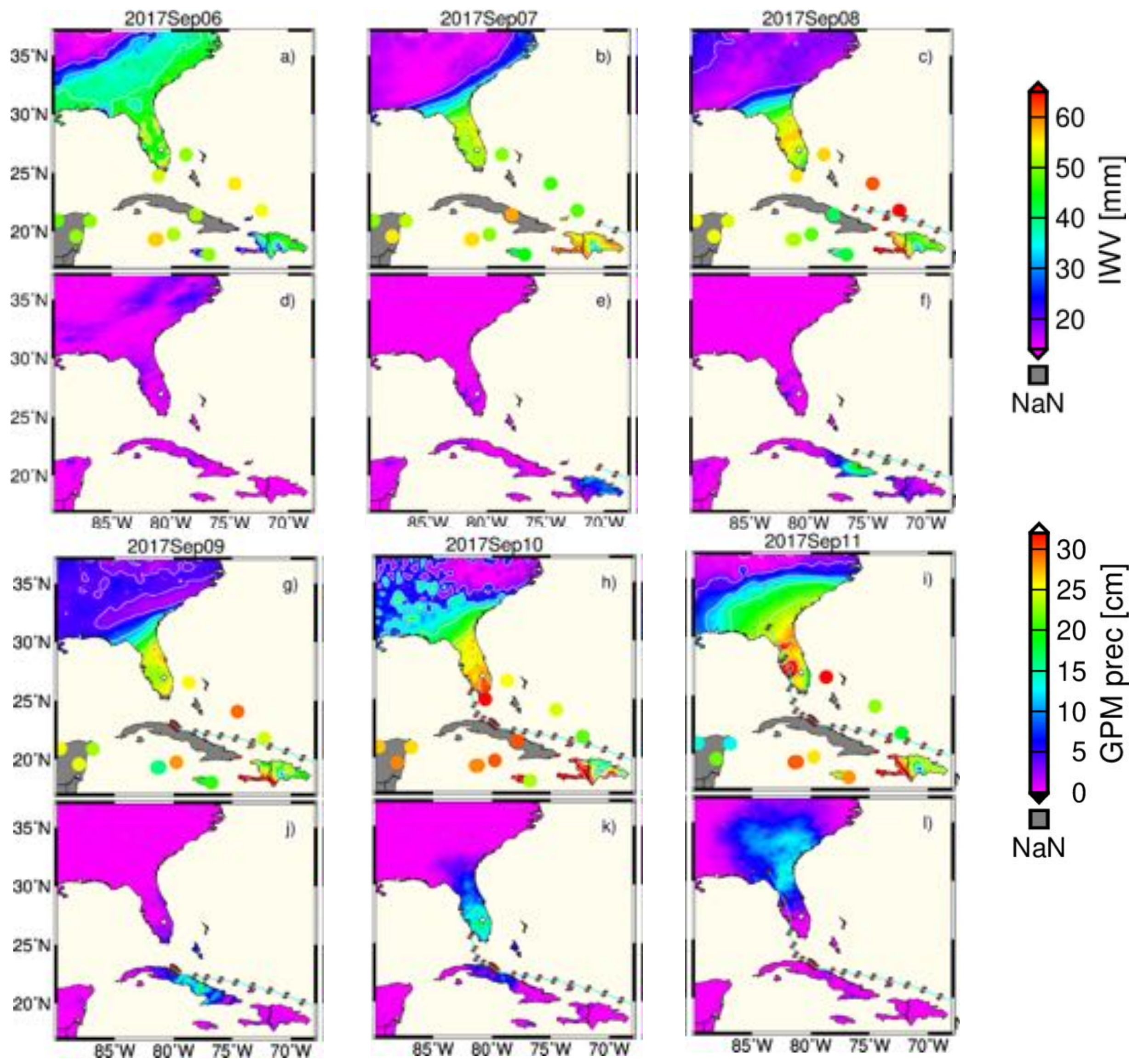
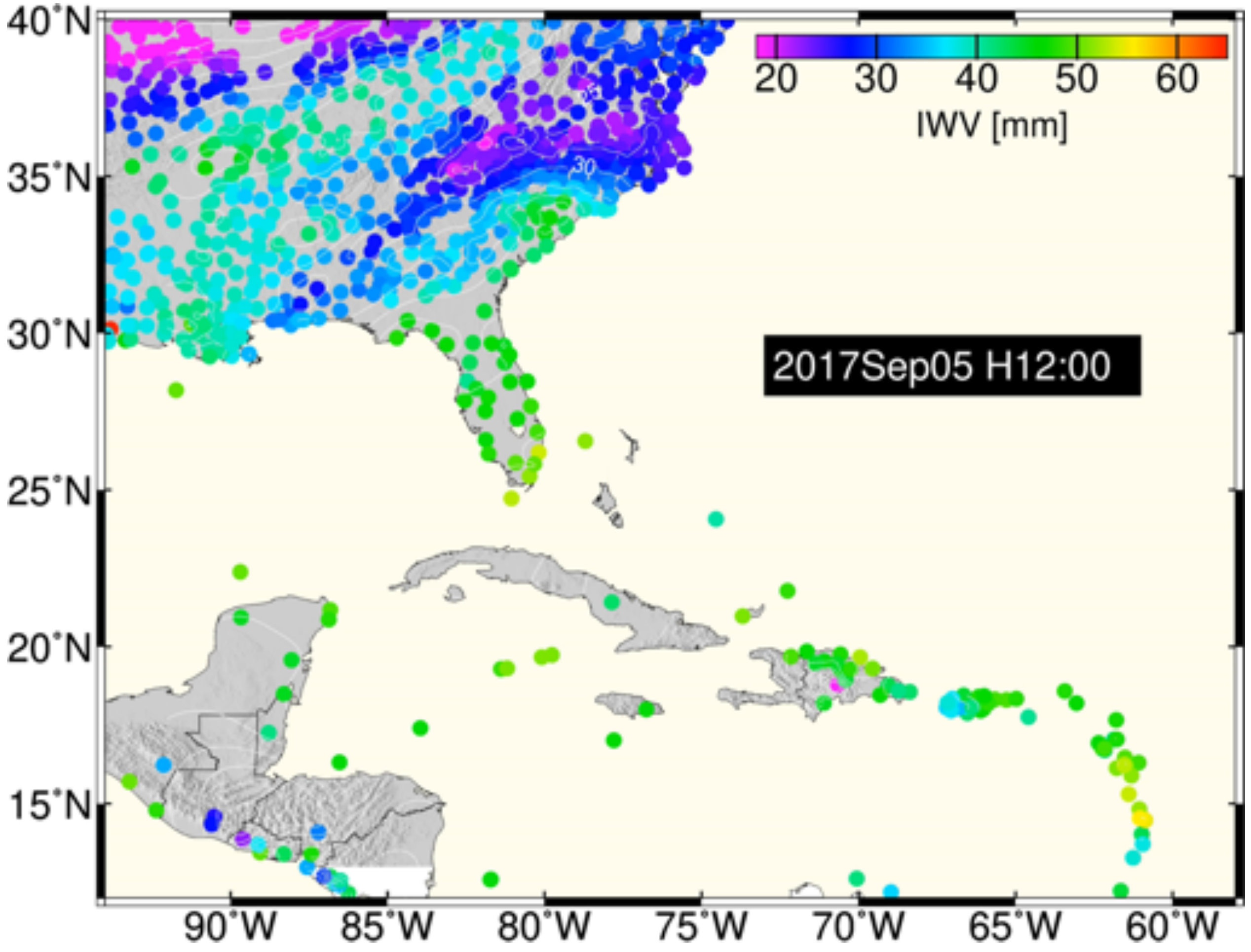


Fig.7: Distribution maps for Hurricane Irma between 06--11 Sep 2017. The contour interval of the GPS-IWV is 10 mm. Irma's path is plotted as the cyan line and the hurricane symbol as brown.

Animation – Hurricane Irma



Animation – Hurricane Florence

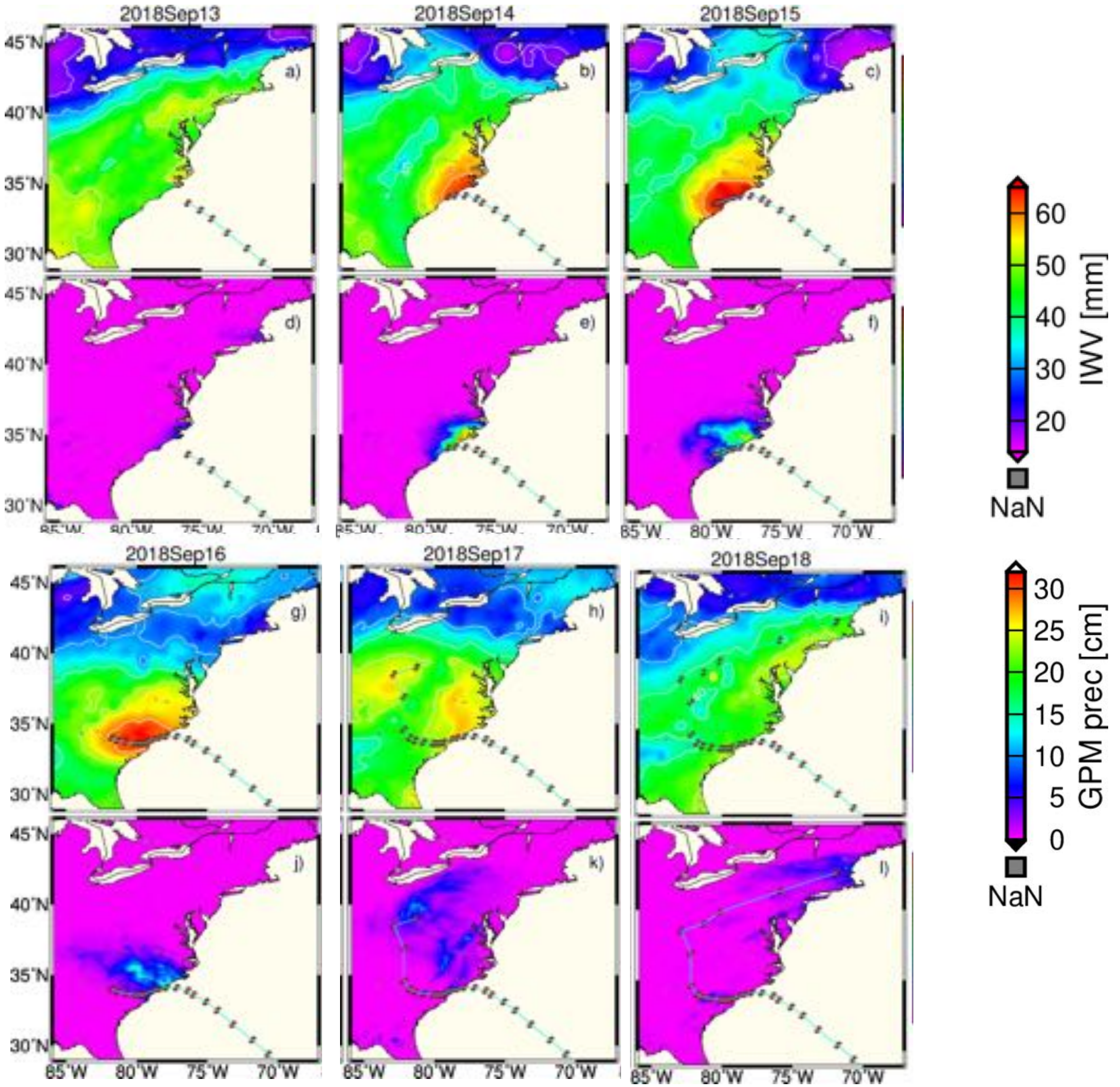
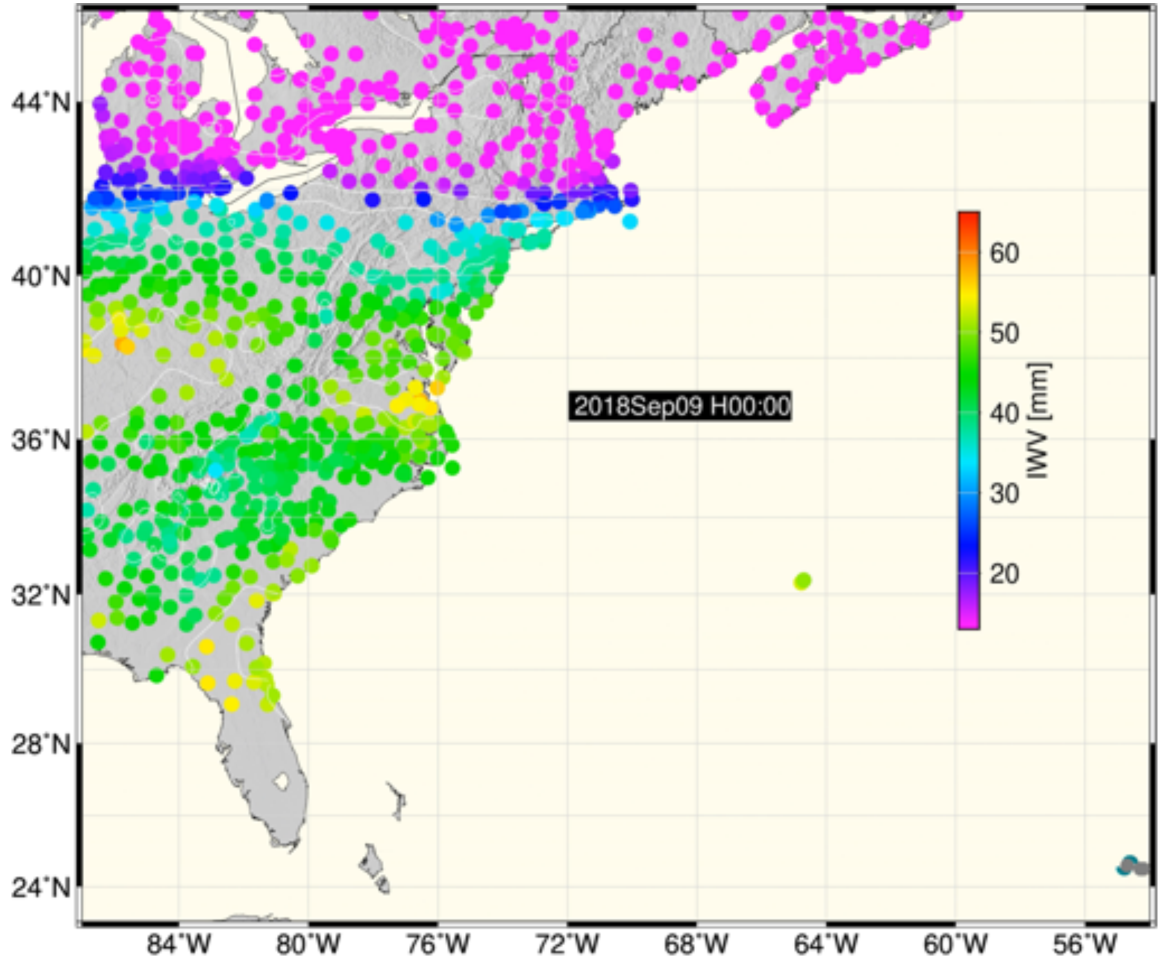


Fig.8: Distribution maps for Hurricane Florence between 14-18 Sept 2018. The contour interval of the GPS-IWV is 5 mm.

Harvey's path is plotted as the cyan line and the hurricane symbol as brown

Animation Hurricane Florence



Tracking Hurricane Paths using GPS

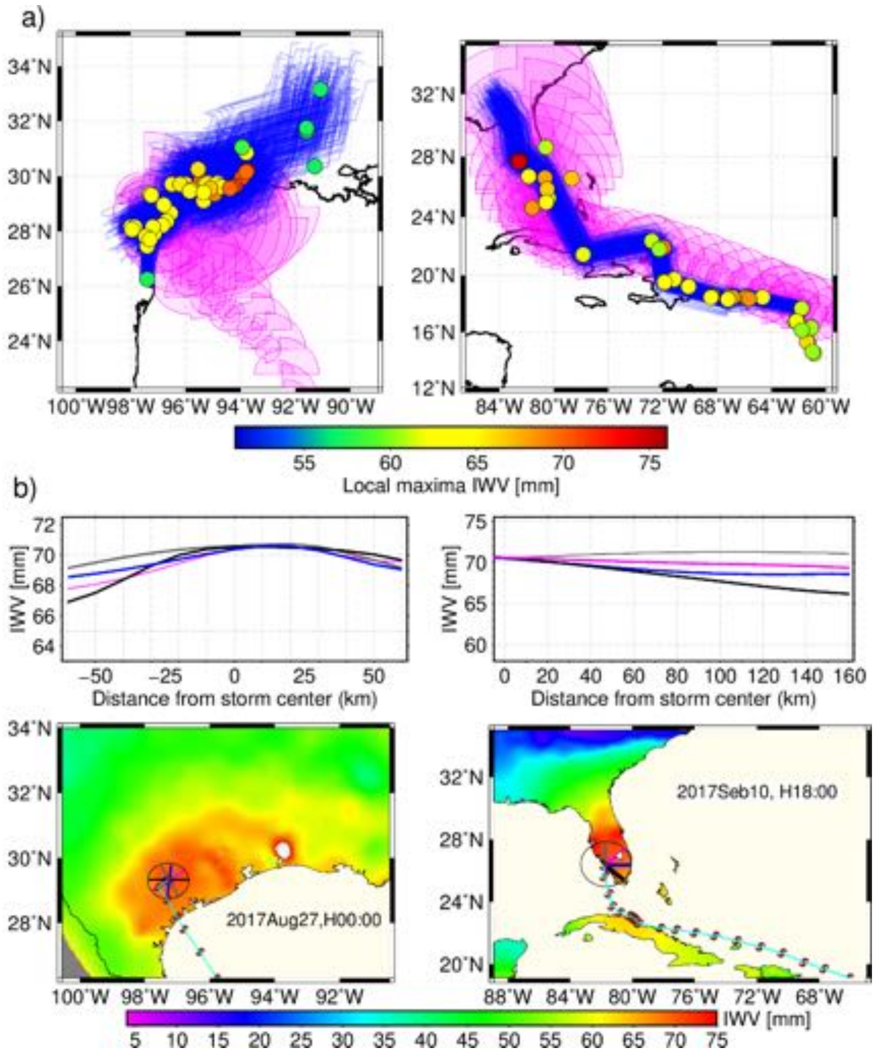


Fig.9: a) Spaghetti-line plots (blue-lines) transect GPS-IWV maxima for Harvey (left) and Irma (right). The light magenta polygons show the best tracks from NHC model, based on a post-storm analysis of all available data, presented at six-hourly intervals.

b) GPS-IWV crossing profiles along a straight line and sampled every 1-km grid on 27 Aug 2017 at 00:00 (left, top), and on 10Sep 2017, at 180:00 (right, top).

Summary

- We observed a sudden and significant increase and decrease in GPS-IWV during and post events
- We analyzed the map of maximum possible GPS-derived IWV distribution maps
- The results confirmed that the temporal change in GPS-IWV is strongly linked to the hurricane's path.
- Basing local-maxima of IWV field as an input to spaghetti model, underscores the potential for GPS predicting hurricane paths, at least six-hours prior to storm's arrival.
- Overall, our findings show that the use of GPS-IWV could significantly advance the monitoring of hurricane activity in dense GPS stations regions.
- These developments provide the background for the inclusion of real-time GPS in nowcasting models for severe events.