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 understand ing.

"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."

UNIVERSITÉ DU LUXEMBOURG

Faculty of Sciences,
Technology
and Communication

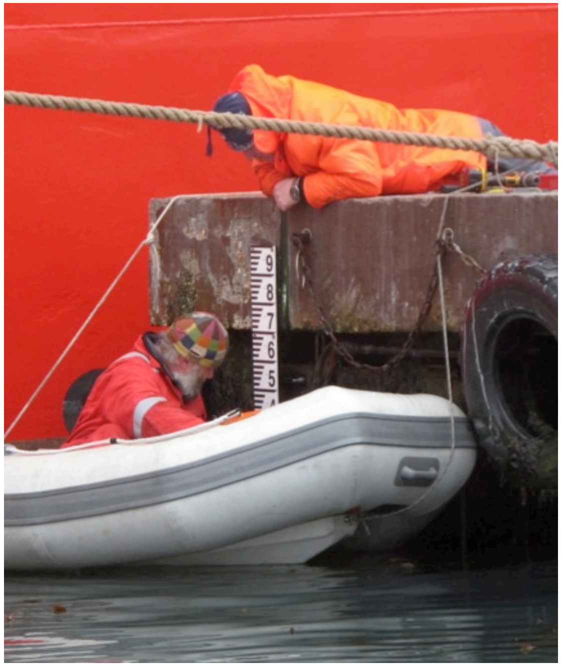
Sea Level Changes, Monitoring of Vertical Land Movements and TIGA Activities

Prof Norman Teferle
Geophysics Laboratory, RUES,
Faculty of Sciences, Technology and Communication
Campus Belval, MNO-E04-0415100

UNIVERSITÉ DU LUXEMBOURG

Overview

- Introduction
- Sea level changes in the past
- Sea level changes during the instrumental record
  - Tide gauges
  - Satellite Altimetry
- Monitoring of vertical land movements and TIGA activities



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

What do we know about climate change?

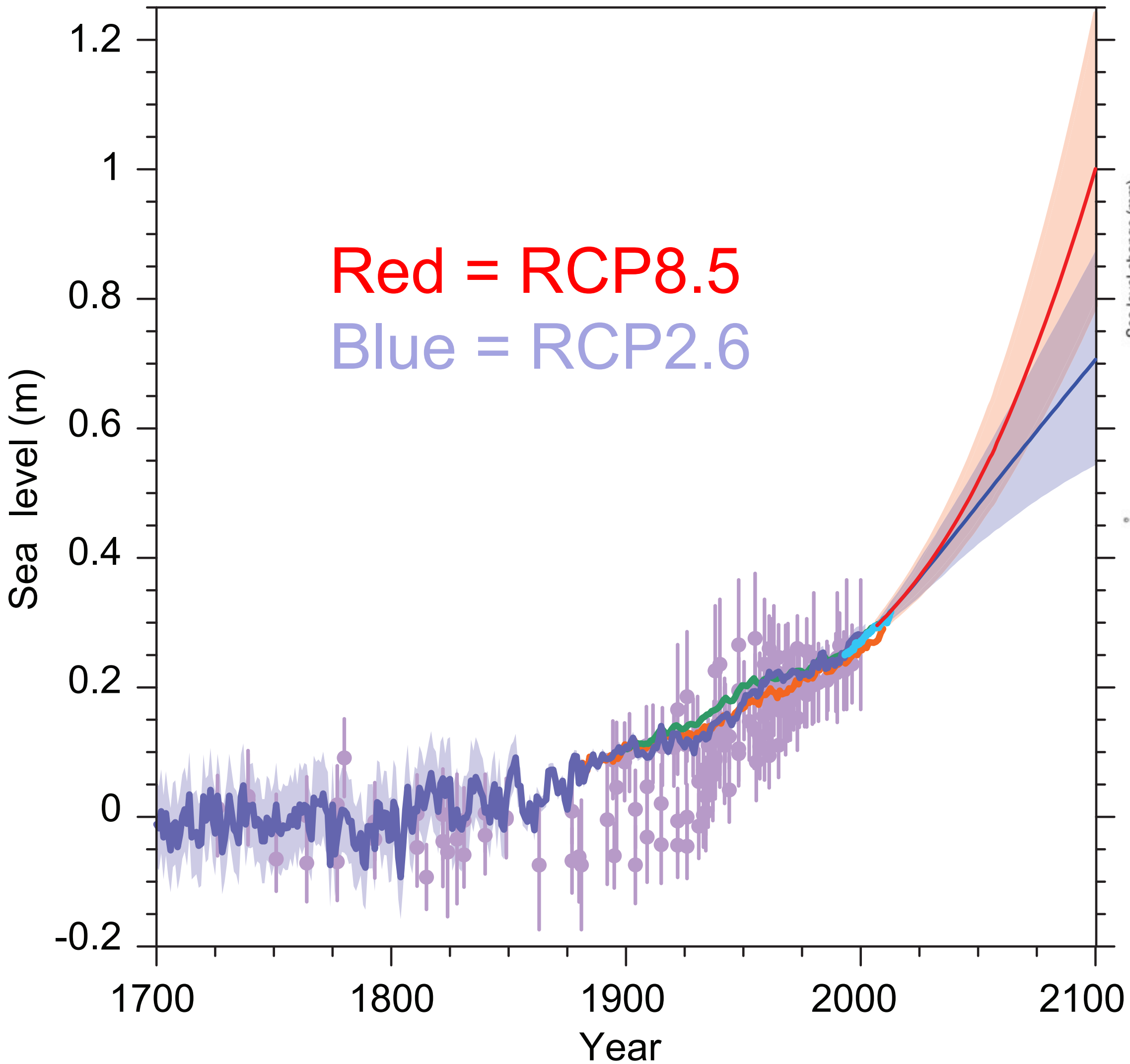
- The Earth is warming!
  - surface temperature is 0.8° C warmer during first decade of the 21st century than during the first decade of the 20th century
- Most of the warming can be attributed to human activities that release carbon dioxide (CO_2) and other heat-trapping greenhouse gases (GHG)
- Natural climate variability leads to
  - year-to-year or decade-to-decade fluctuations
  - large regional differences, but
  - cannot explain or offset long-term trends
- Global warming is closely associated with a broad spectrum of other changes
  - increased frequency of intense rainfall
  - decreased Northern Hemisphere snow cover
  - Arctic sea ice loss
  - sea level rise
  - …

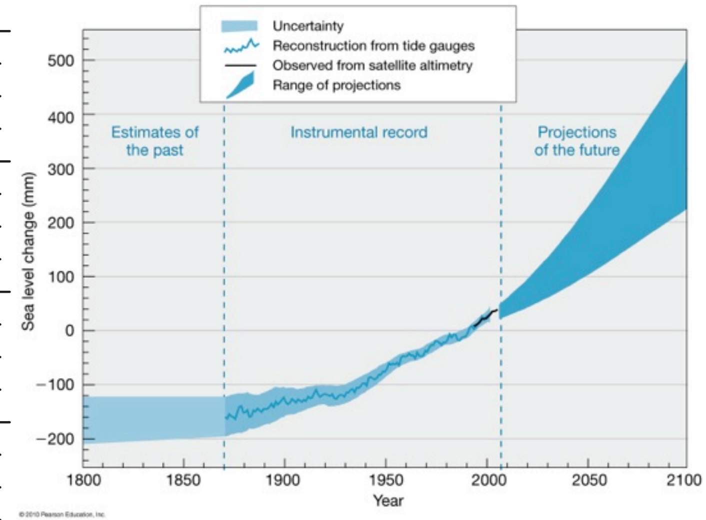
What do we know about future climate?

- All attempts to stabilize or reduce GHG concentrations have failed!
- Projections of future climate change anticipate an additional warming of 1.5° C to 6.4° C over the 21st century.
- It is reasonable to expect that the magnitude of future climate change and the severity of its impacts will be larger if actions are not taken to reduce GHG emissions and adapt to impacts.
- Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.
- The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation.
- It is *very likely* that the Arctic sea ice cover will continue to shrink and thin and that Northern Hemisphere spring snow cover will decrease during the 21st century as global mean surface temperature rises. Global glacier volume will further decrease.
- Global mean sea level will continue to rise during the 21st century. Under all emission scenarios the rate of sea level rise will *very likely* exceed that observed during 1971–2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets.

IPCC 5th AR, 2013

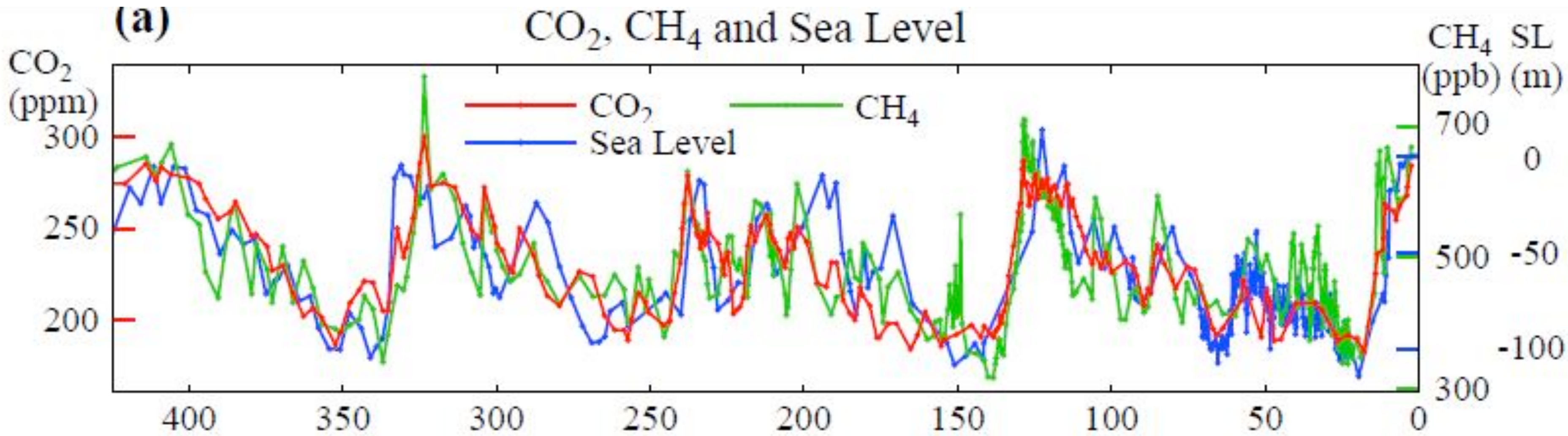
Sea Level Projections (IPCC, 2013)



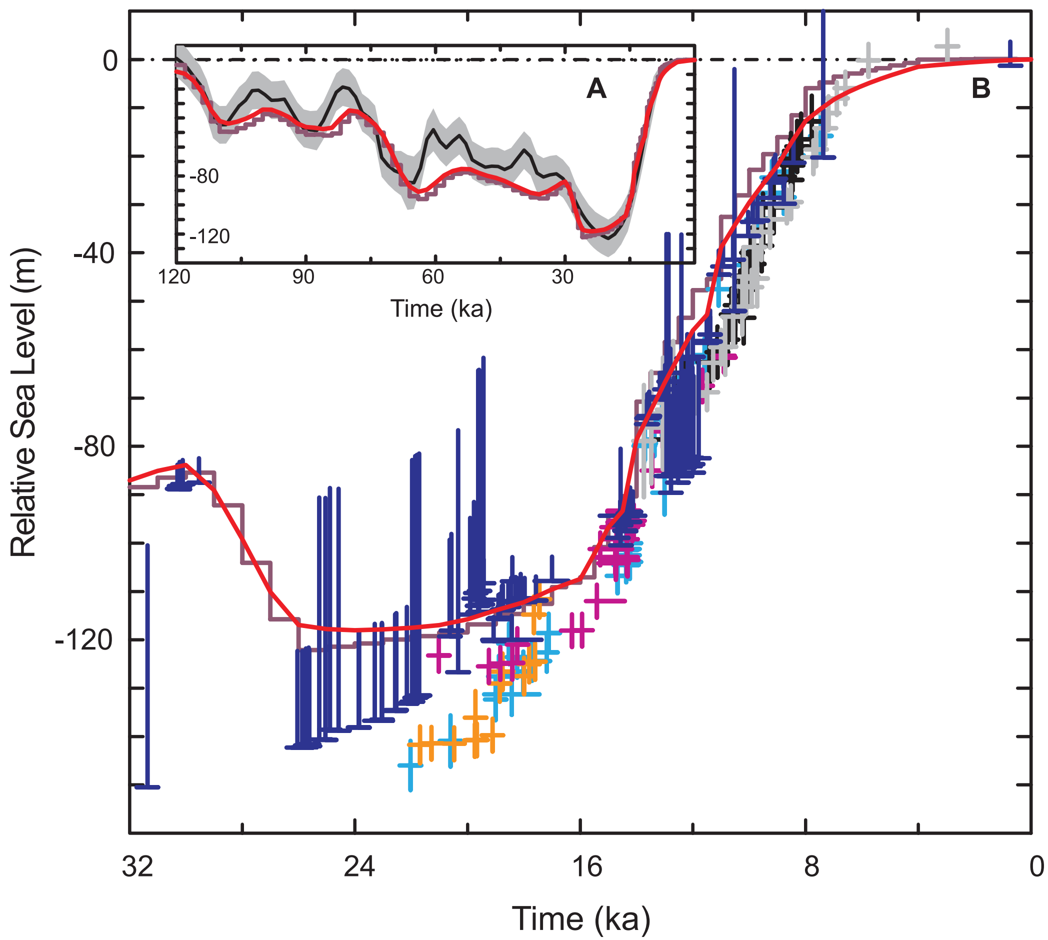


SEA LEVEL CHANGES IN THE PAST

Relative Sea Level (past 420kyr)

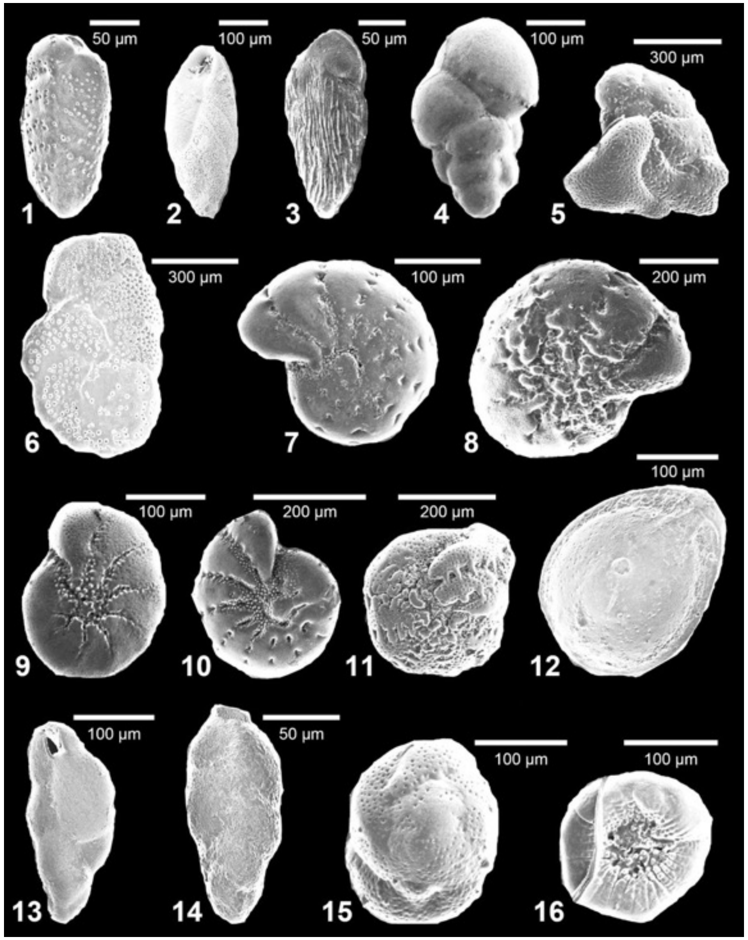


Relative Sea Level (past 32kyr and 120kyr)

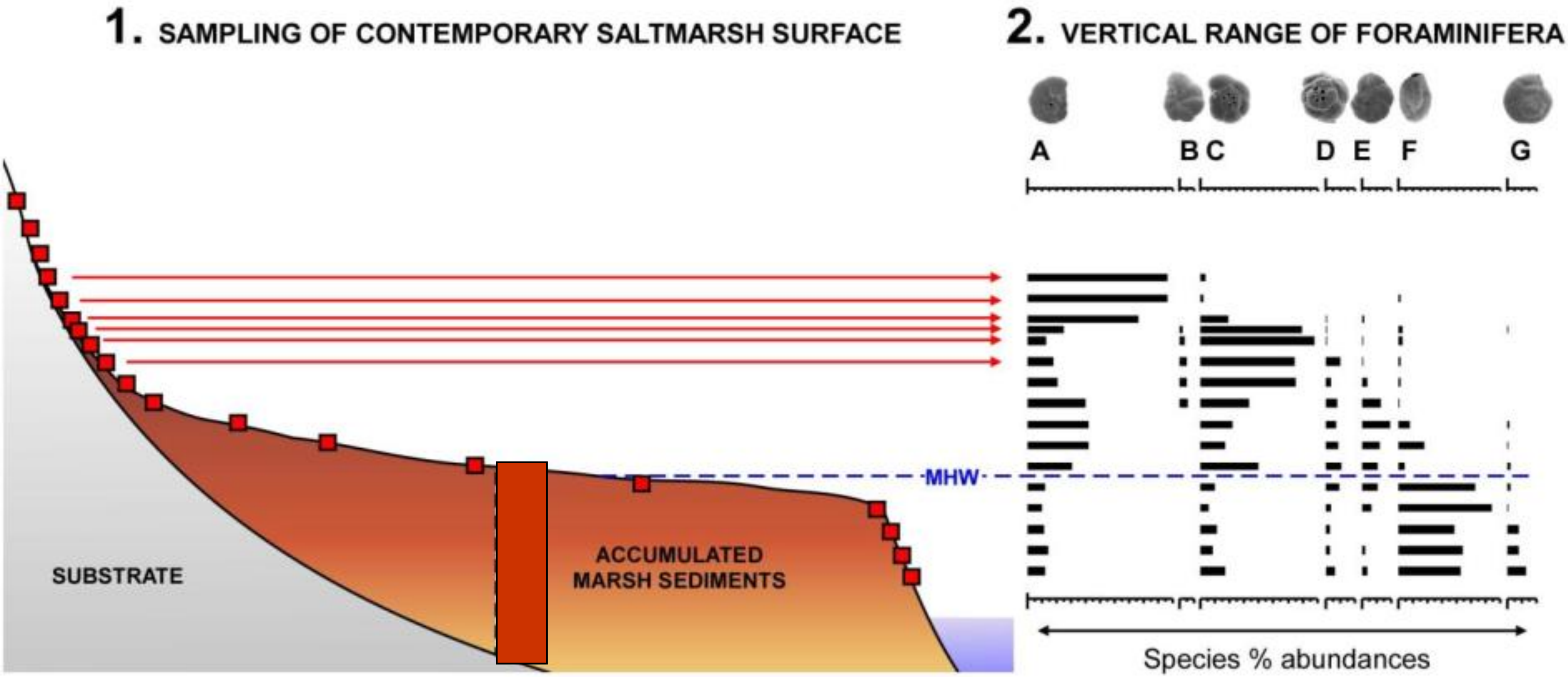


What are Foraminifera?

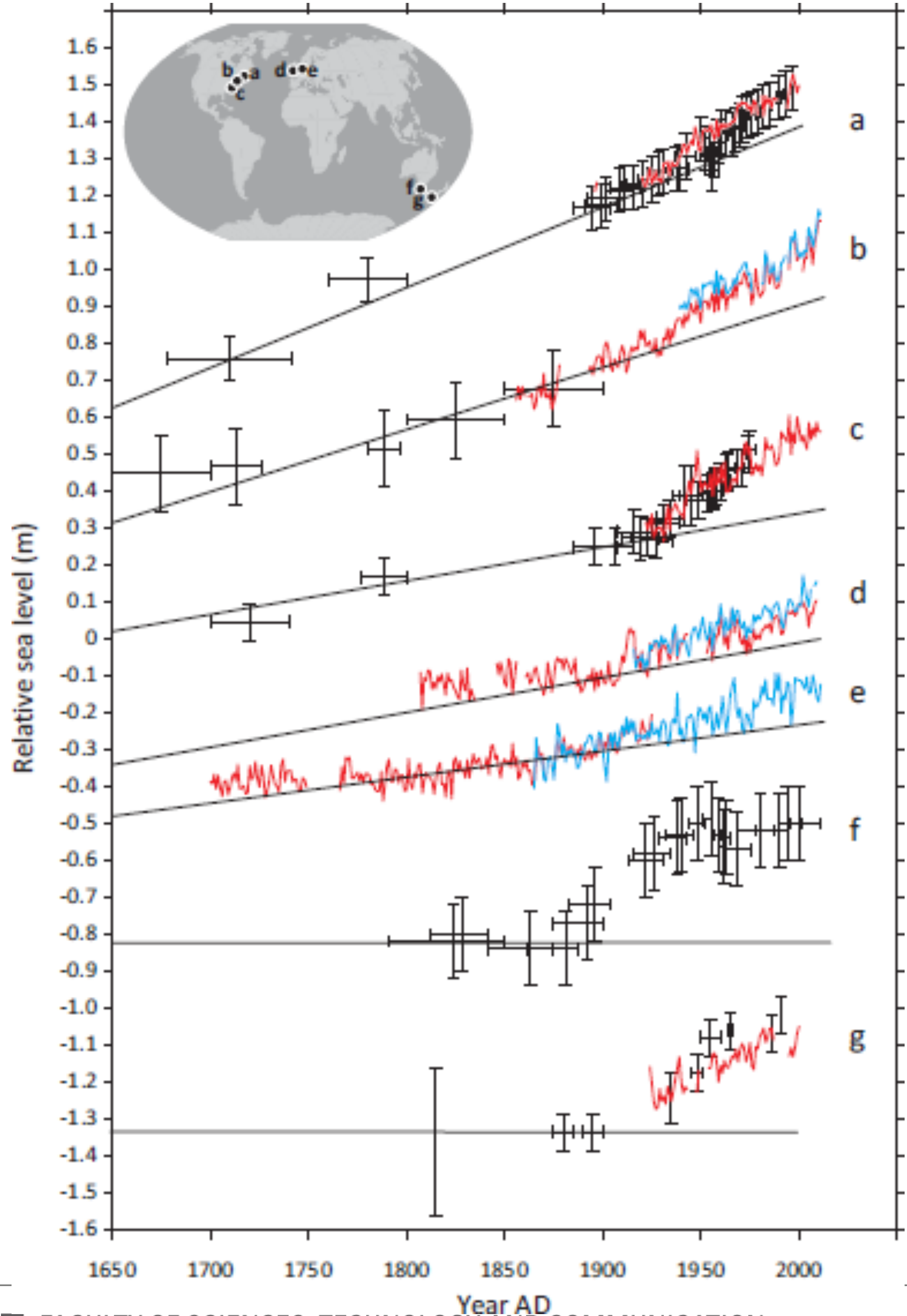
- Foraminifera are microscopic animals (Protozoa) that live in the sea
- They have shells made of calcite (a type of calcium carbonate)
- Forams have many species and come in a huge variety of shapes and sizes
- Also there are diatoms, phytoplankton made of silica (hydrated silicon dioxide)



From Roland Gehrels



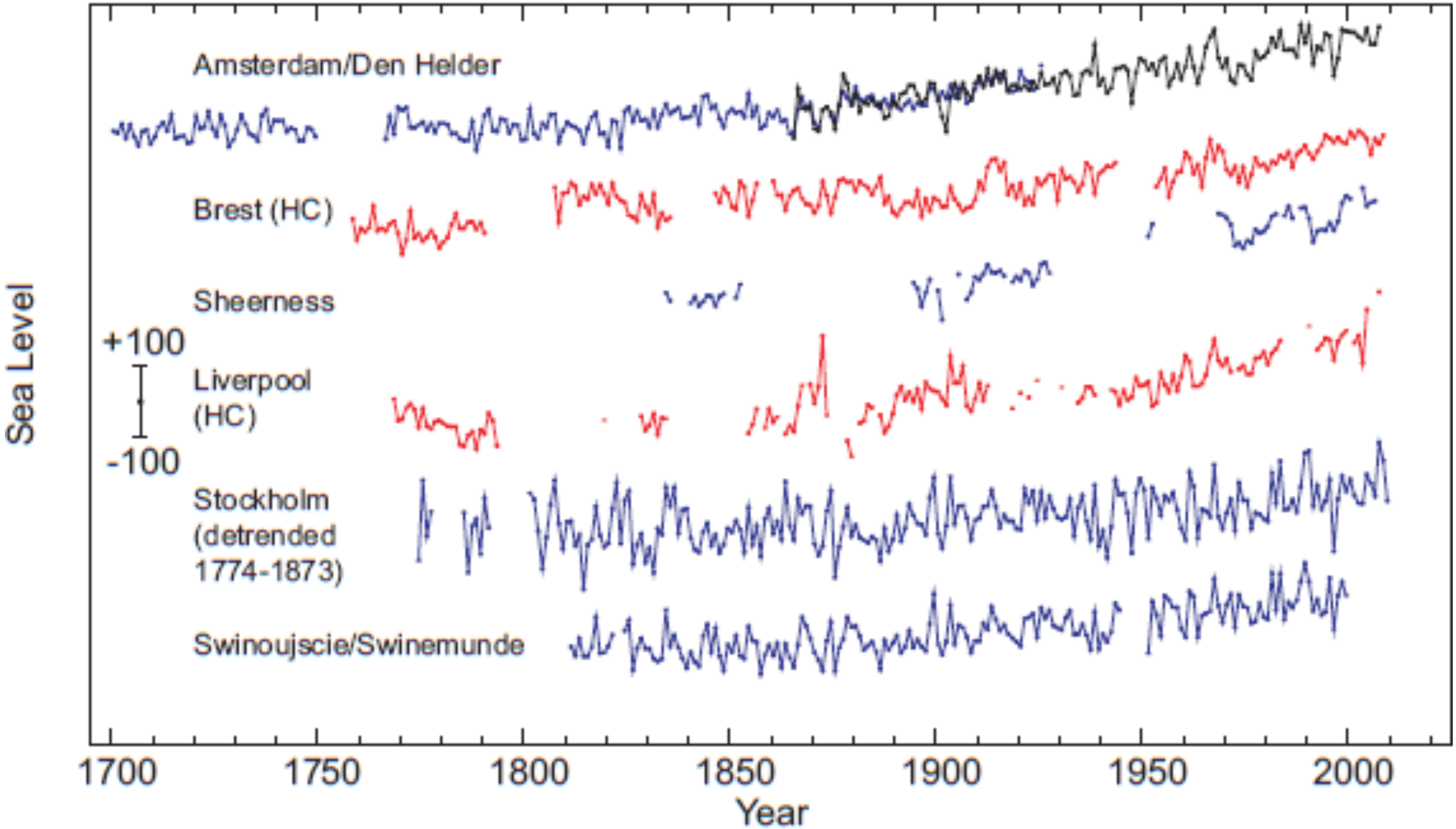
A ‘***transfer function***’ quantifies the relationship between foram assemblages and elevation to reconstruct in cores the elevation at which fossil forams lived



Salt marsh data (black crosses) and corresponding tide gauge information (coloured lines)

Gehrels and Woodworth, GPC, 2013

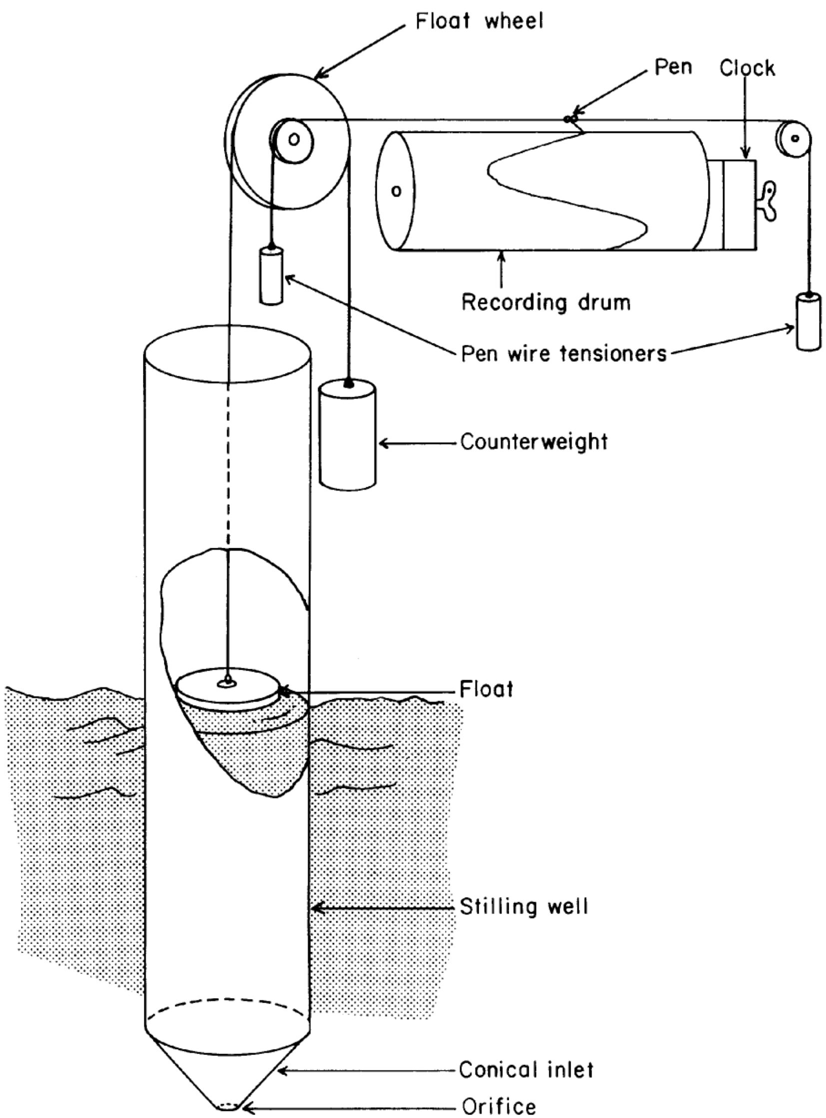
SEA LEVEL CHANGES DURING THE INSTRUMENTAL RECORD



Long tide gauge records from northern Europe

Classical Float Gauge

Introduced in the 1830s and used in many ports around the world by the late 19th century.

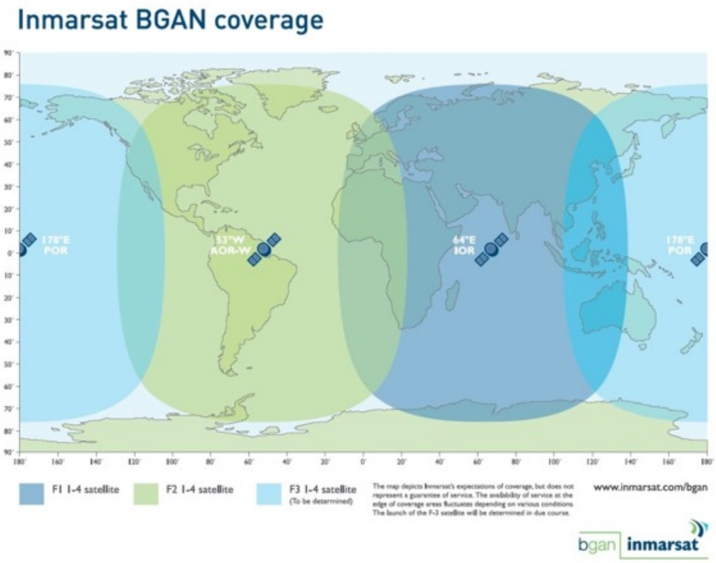


Float Gauge at Holyhead, UK

Float gauges are still important components of GLOSS and can be made into digital gauges with the use of encoders

Radar tide gauge provided by NOC and UNESCO to Alexandria

BGAN-enabled Tide Gauges



PSMSL Permanent Service for Mean Sea Level

About Us | Data | Products | Training & Information | Links

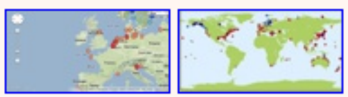
You are here: home >

News

- Updated Trends
- Flag Changes
- MTL and MSL Changes
- New Notes from Hogarth Article
- ICSU World Data System Membership
- More News ...

Explore the Dataset

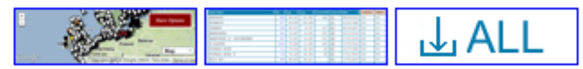

Map-Based Data Page

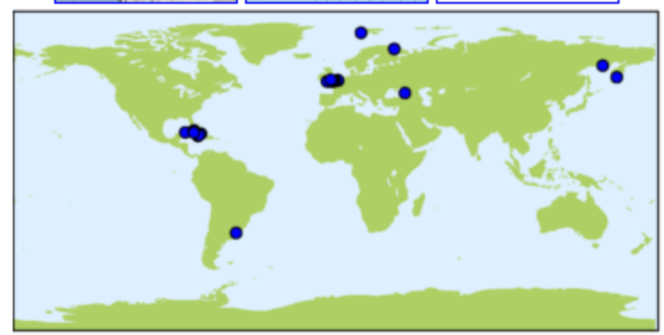

Trends and Anomalies

Welcome to the Permanent Service for Mean Sea Level (PSMSL)

Please read news items on changes to combined MTL and MSL records and flags.

PSMSL is the global data bank for long term sea level change information from tide gauges and bottom pressure recorders.




Tide gauge records updated in the 30 days prior to 23 Feb 2016

About Us:

Learn about PSMSL, contact us, read news items and annual reports

Data:

Obtain and submit tide gauge and bottom pressure data

Products:

Browse the data set via GoogleEarth or obtain derived products, view regional commentaries and author archives

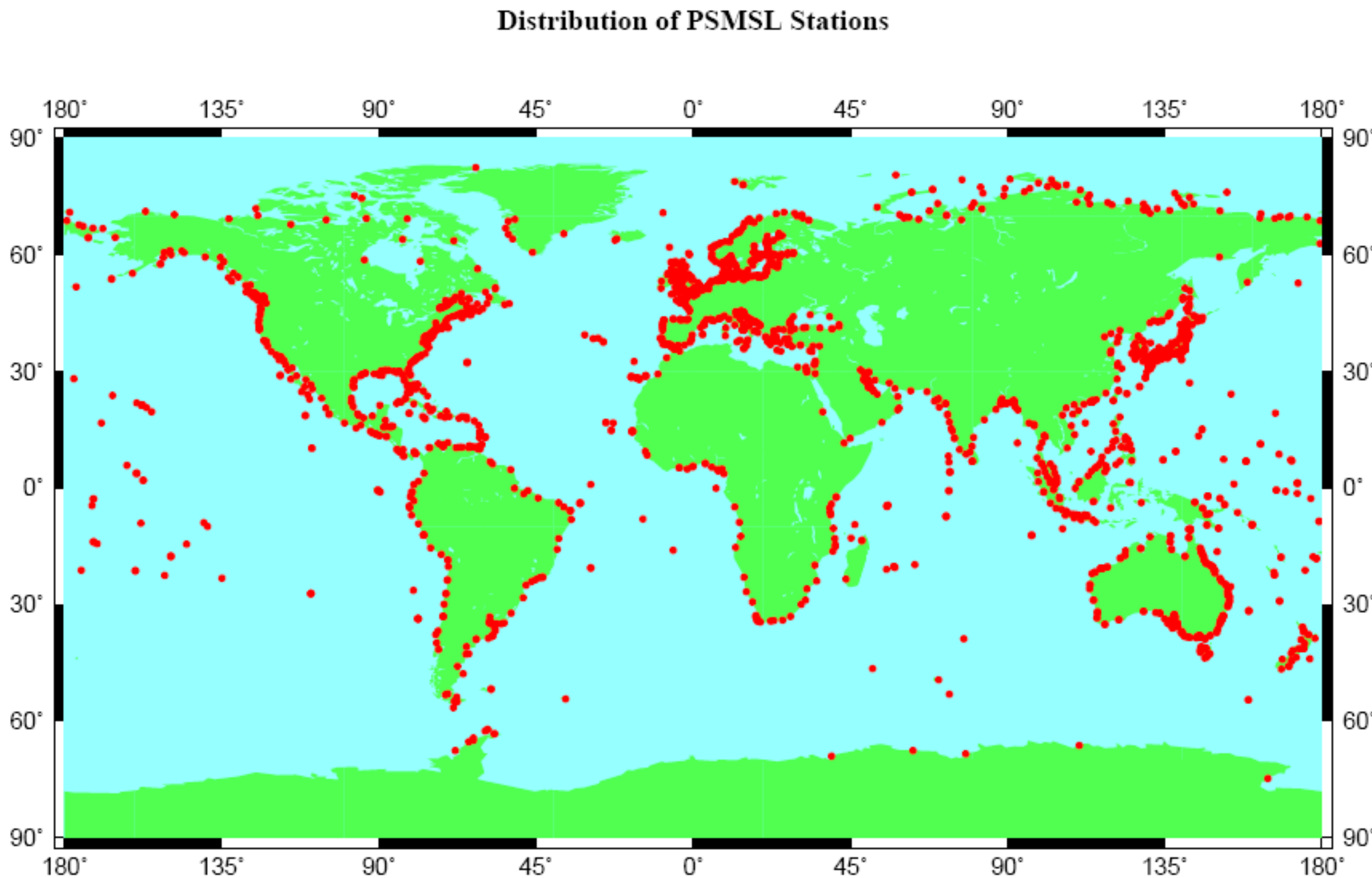
Training & Information:

A wide variety of FAQs, training and software documentation, information on non-oceanographic signals in tide gauge records (e.g., glacial isostatic adjustment, atmospheric pressure, etc.)

Links:

Links to other networks and programs, as well as international sea level contacts

www.psmsl.org



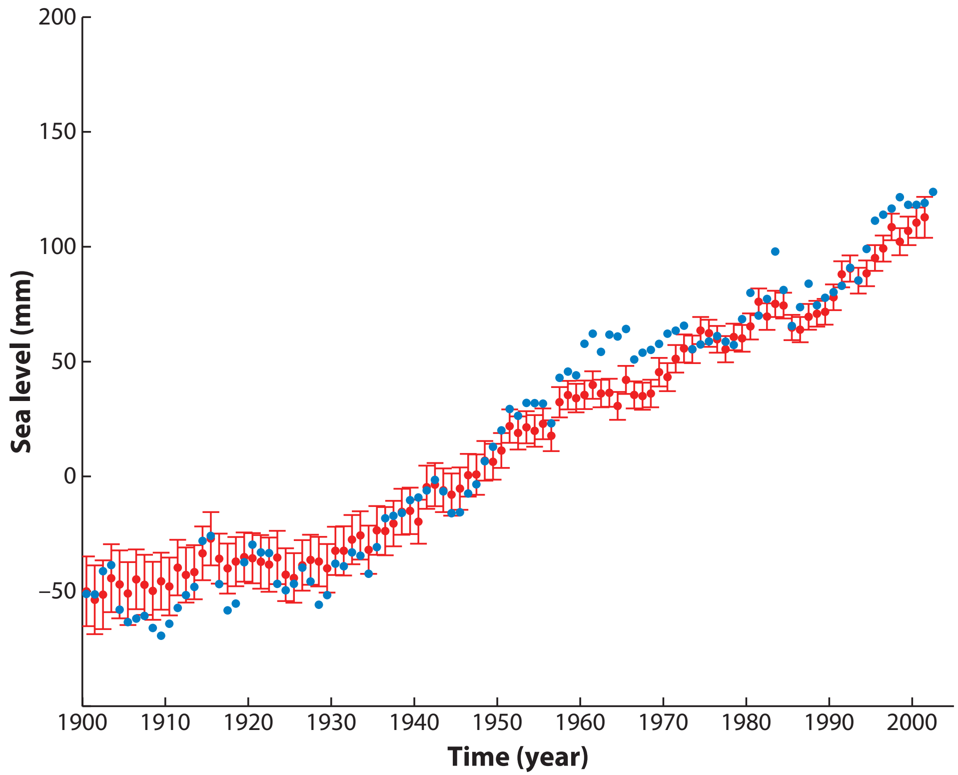
1987: 27000 station-years of data
2014: 61000 station-years of data

www.psmsl.org

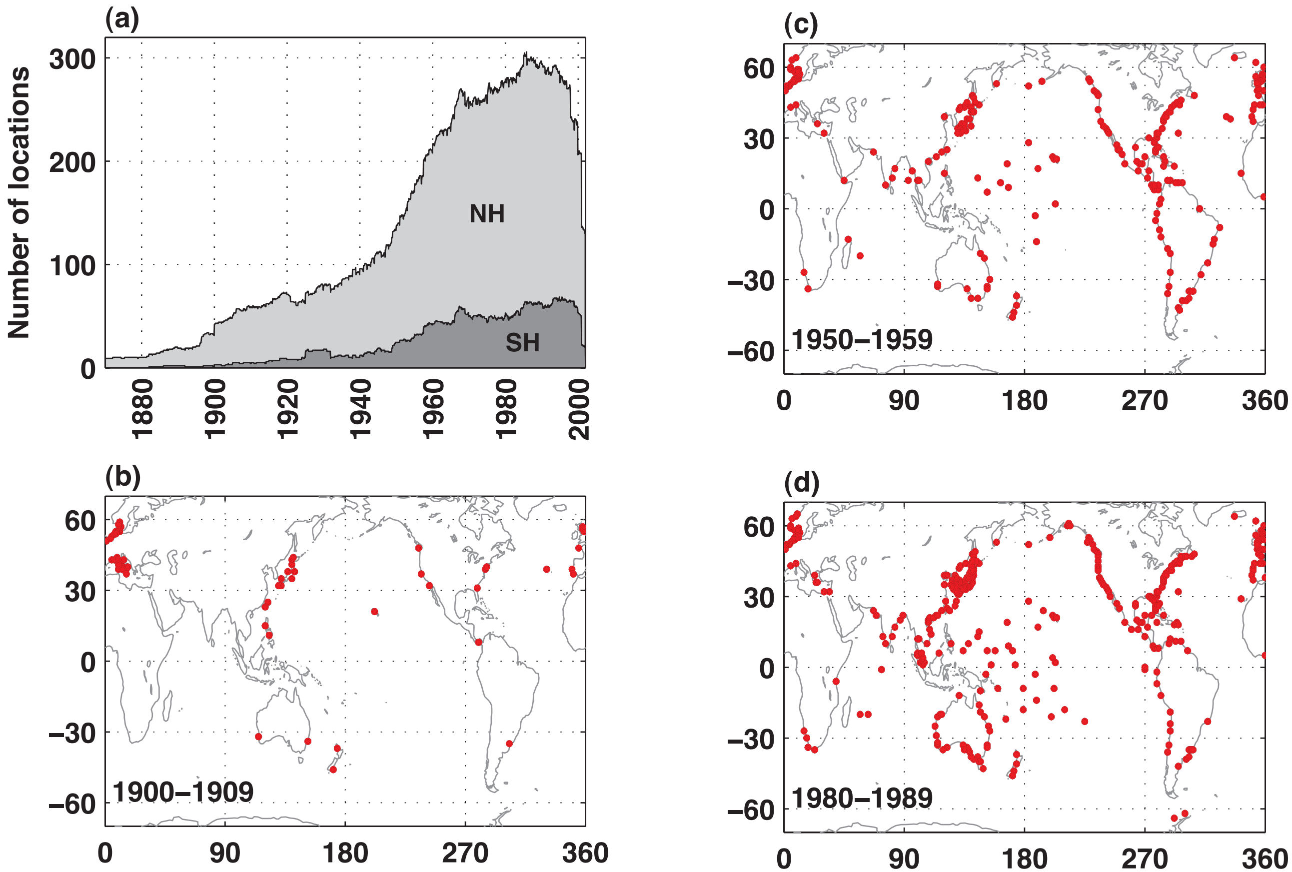
PSMSL
1933 75th Anniversary 2008

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).

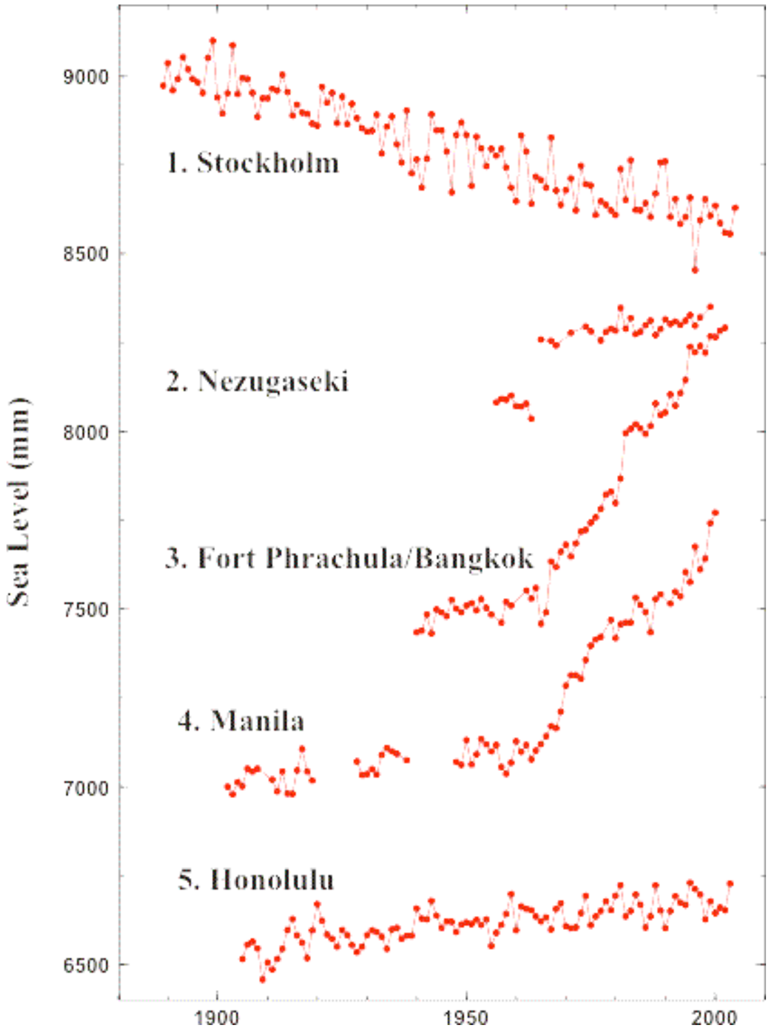


But…
The Tide Gauge Network 1900-1989



UNIVERSITÉ DU LUXEMBOURG

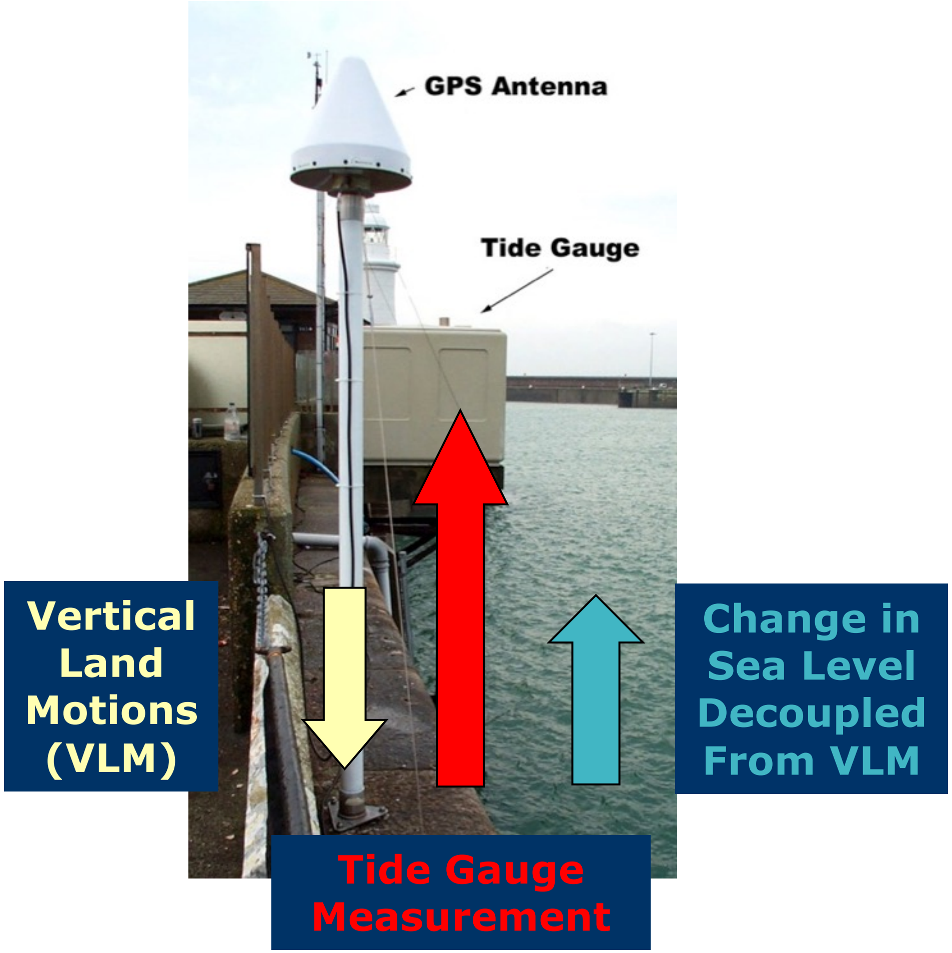
Mean Sea Level (MSL) Records from PSMSL



- **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)

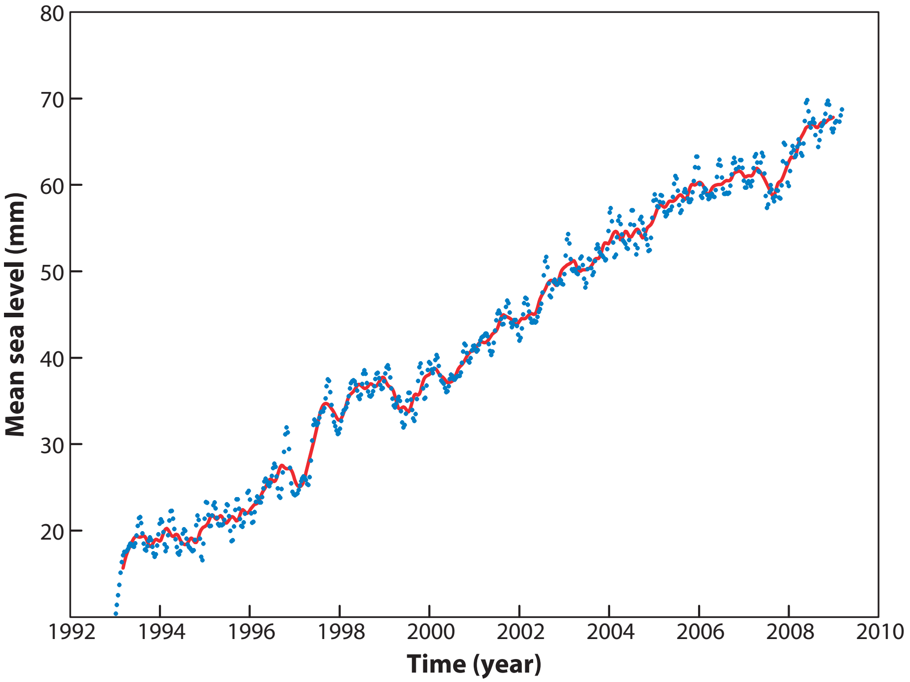
Monitoring Vertical Land Motions at Tide Gauges

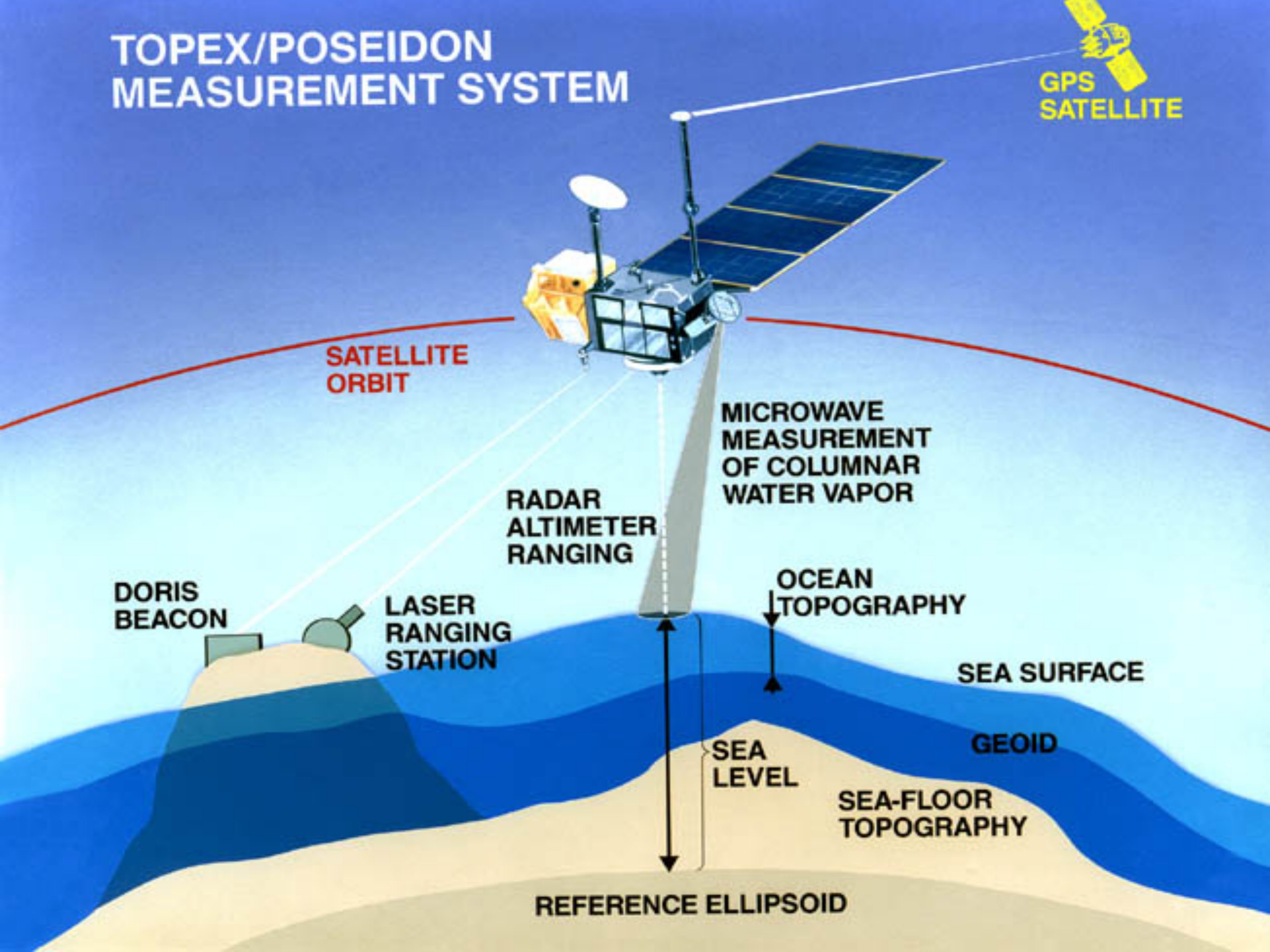


- Tide gauges (TG) measure local sea level
- Vertical land motions (VLM) are determined from CGPS and AG at or close to the tide gauge
- The change in sea level de-coupled from VLM can be inferred

Sea Level Change from Satellite Altimetry

- Global mean sea level from satellite altimetry between January 1993 and December 2008.
- Annual cycle has been removed.
- Blue dots are raw 10-day data.
- Red line corresponds to a 90-day smoothing of the raw data.
- The −0.3 mm/yr GIA correction has been removed.




TOPEX/POSEIDON
MEASUREMENT SYSTEM
GPS
SATELLITE
SATELLITE
ORBIT
MICROWAVE
MEASUREMENT
OF COLUMNAR
WATER VAPOR
RADAR
ALTIMETER
RANGING
DORIS
BEACON
LASER
RANGING
STATION
OCEAN
TOPOGRAPHY
SEA SURFACE
GEOID
SEA
LEVEL
SEA-FLOOR
TOPOGRAPHY
REFERENCE ELLIPSOID

Jason-2 (or Ocean Surface Topography Mission, OSTM)

Envisat

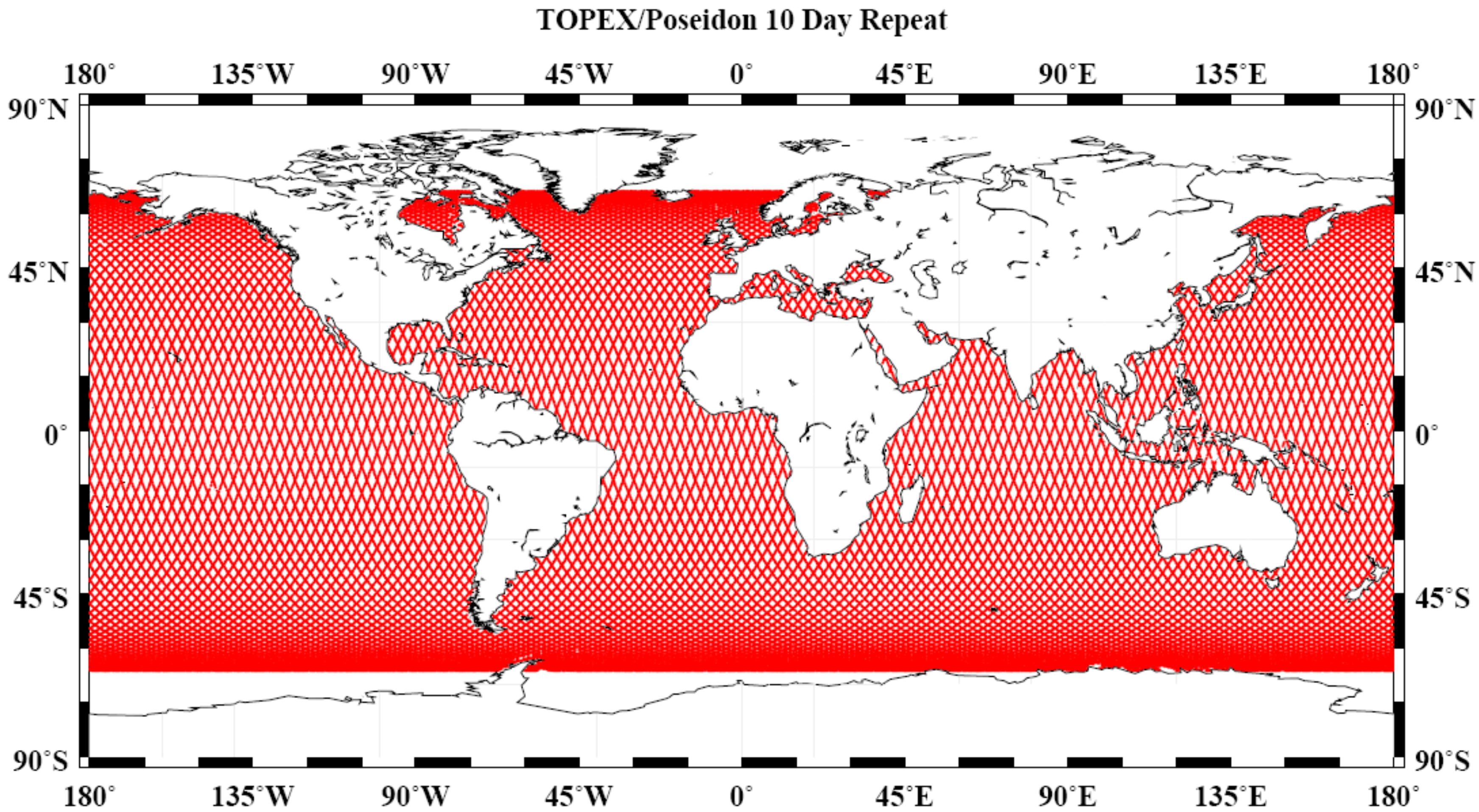
The various missions (past and present)

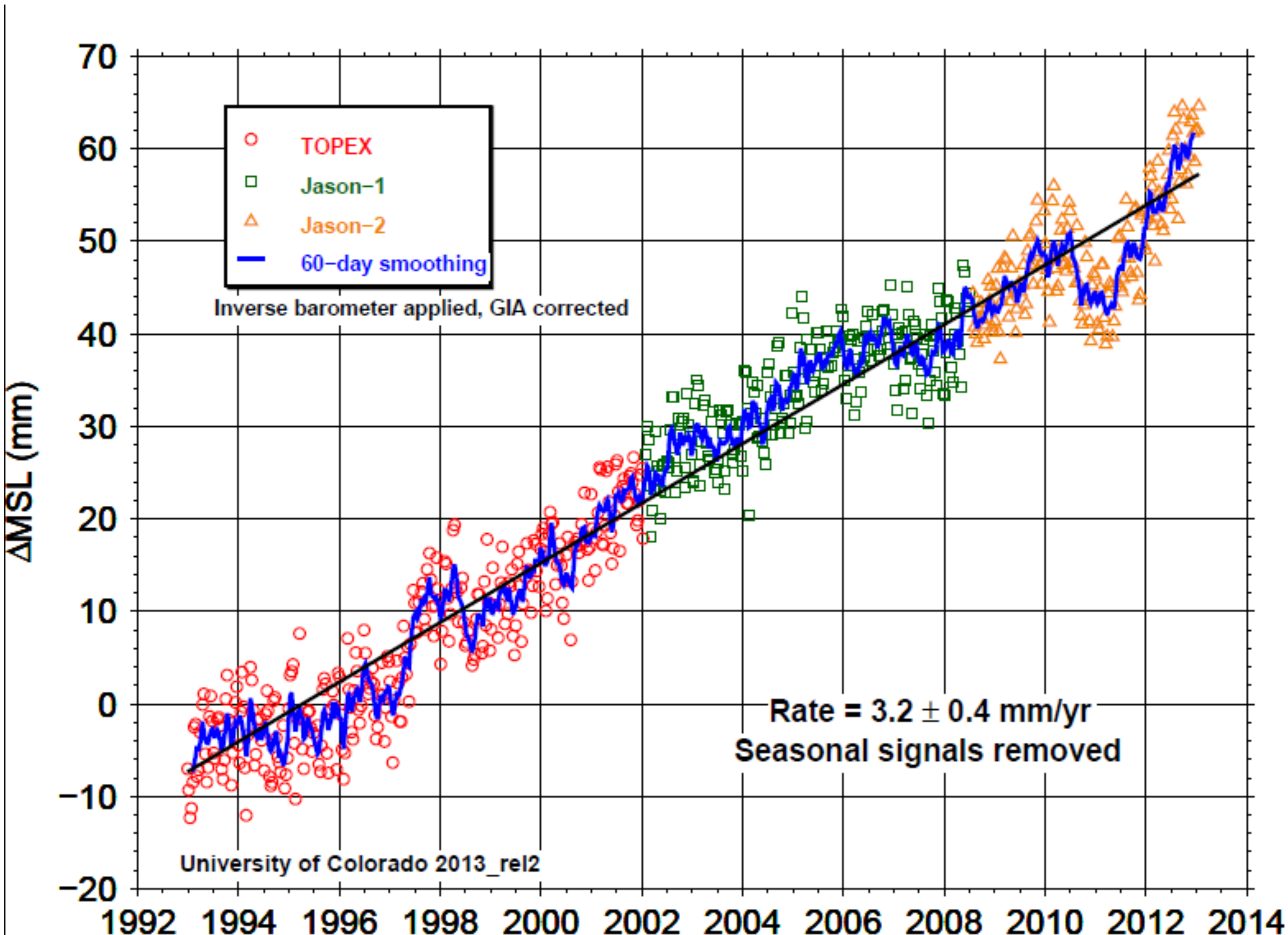
- Skylab (1973-74)
- GEOS-3 (1975-78)
- SEASAT (1978)
- Geosat (1985-90)
- Geosat Follow-On (GFO) (1998-2008)
- ERS-1 (1991-96)
- ERS-2 (1995-2011)
- Envisat (2002-12)
- TOPEX/Poseidon (1992-2005)
- Jason-1 (2001-13)
- Ocean Surface Topgraphy Mission (OSTM)/Jason-2 (2008-)
- Cryosat-2 (2010-)
- HY-2A (Hai Yáng meaning Ocean) (2011-)
- SARAL (Satellite with ARgos and ALtika) means ‘Simple’ in Hindi (2013-)

The various missions (cont)

- Jason-3 – 17 Jan 2016
- Sentinel-3A – 16 Feb 2016
- Sentinel-3B – 2017
- Sentinel-3C – 2020?
- Geosat Follow-On 2 (GFO-2) (?)
- Jason-CS (Jason Continuity of Service) (2018?)
- SWOT (Surface Water and Ocean Topography) (after 2020?)

Altimeter satellites trace out a 'ground track' every 'repeat period'

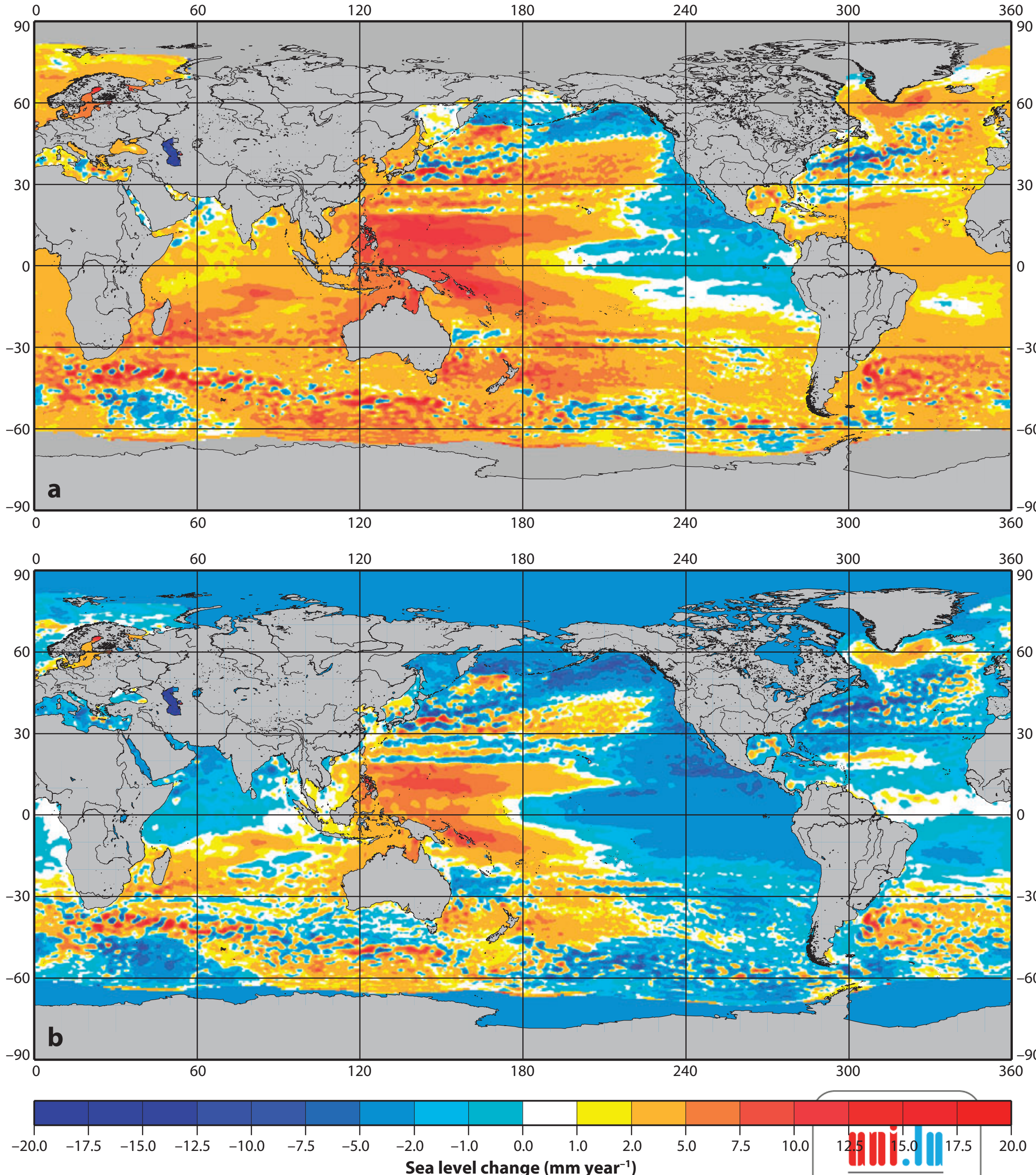




ΔMSL (mm)
TOPEX
Jason−1
Jason−2
60−day smoothing
Inverse barometer applied, GIA corrected
Rate = 3.2 ± 0.4 mm/yr
Seasonal signals removed
University of Colorado 2013_rel2
70
60
50
40
30
20
10
0
−10
−20
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014

Geographic Pattern of Sea Level Change

- Map of spatial trend patterns of observed sea level between January 1993 and December 2008.
- (b) Same as (a) but a uniform global mean trend of 3.4 mm/year has been removed.

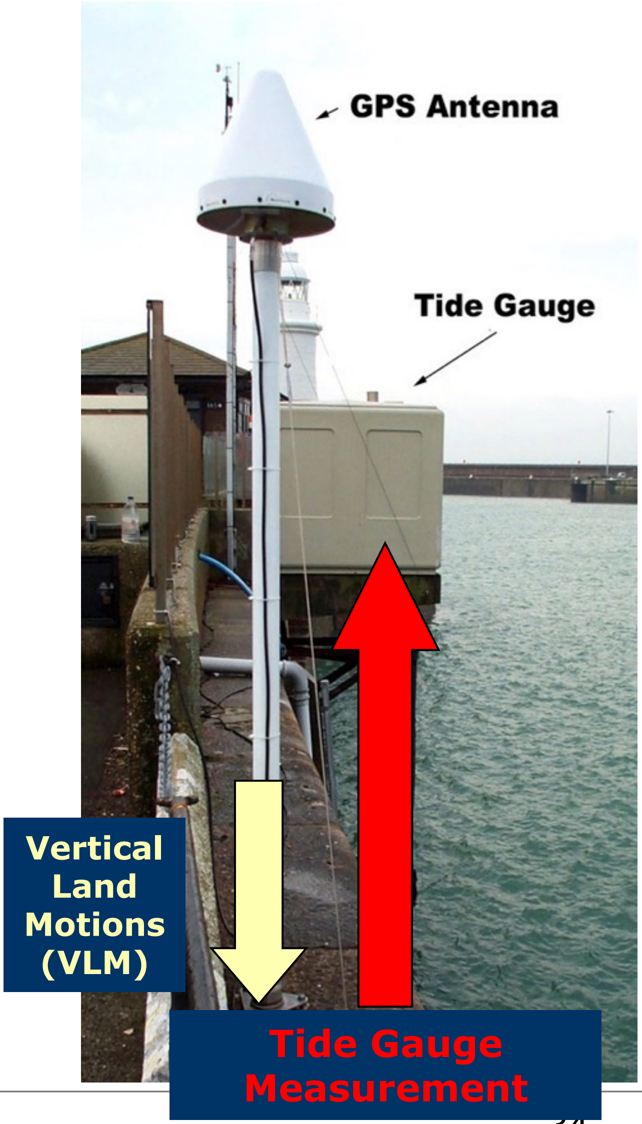


UNIVERSITÉ DU LUXEMBOURG

MONITORING OF VERTICAL LAND MOVEMENTS AND TIGA ACTIVITIES

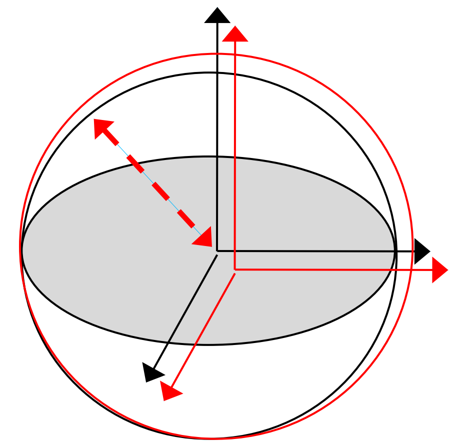
A Brief History of GNSS Tide Gauge Monitoring

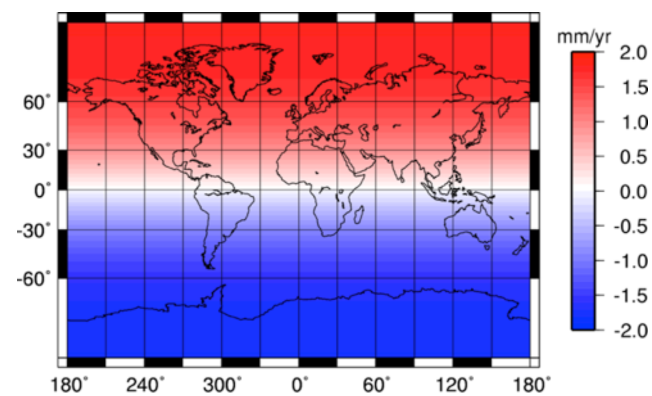
- IAPSO committee recommends GPS to monitor tide gauge benchmarks [Carter et al, 1989]
  - To determine vertical land movements (VLM)
- First attempts using episodic GPS in UK [Ashkenazi et al., 1993]
- IAPSO committee and IGS/PSMSL recommend continuous GPS [Carter, 1994; Neilan et al, 1997]
- IGS establishes TIGA PP (2001) which becomes TIGA WG after 2010
- Many projects to measure geocentric sea level [Sanli and Blewitt, 2001; Teferle et al., 2002, Snay et al., 2007; Wöppelmann et al., 2007; …]
- …but, it was not so straight forward as initially thought…



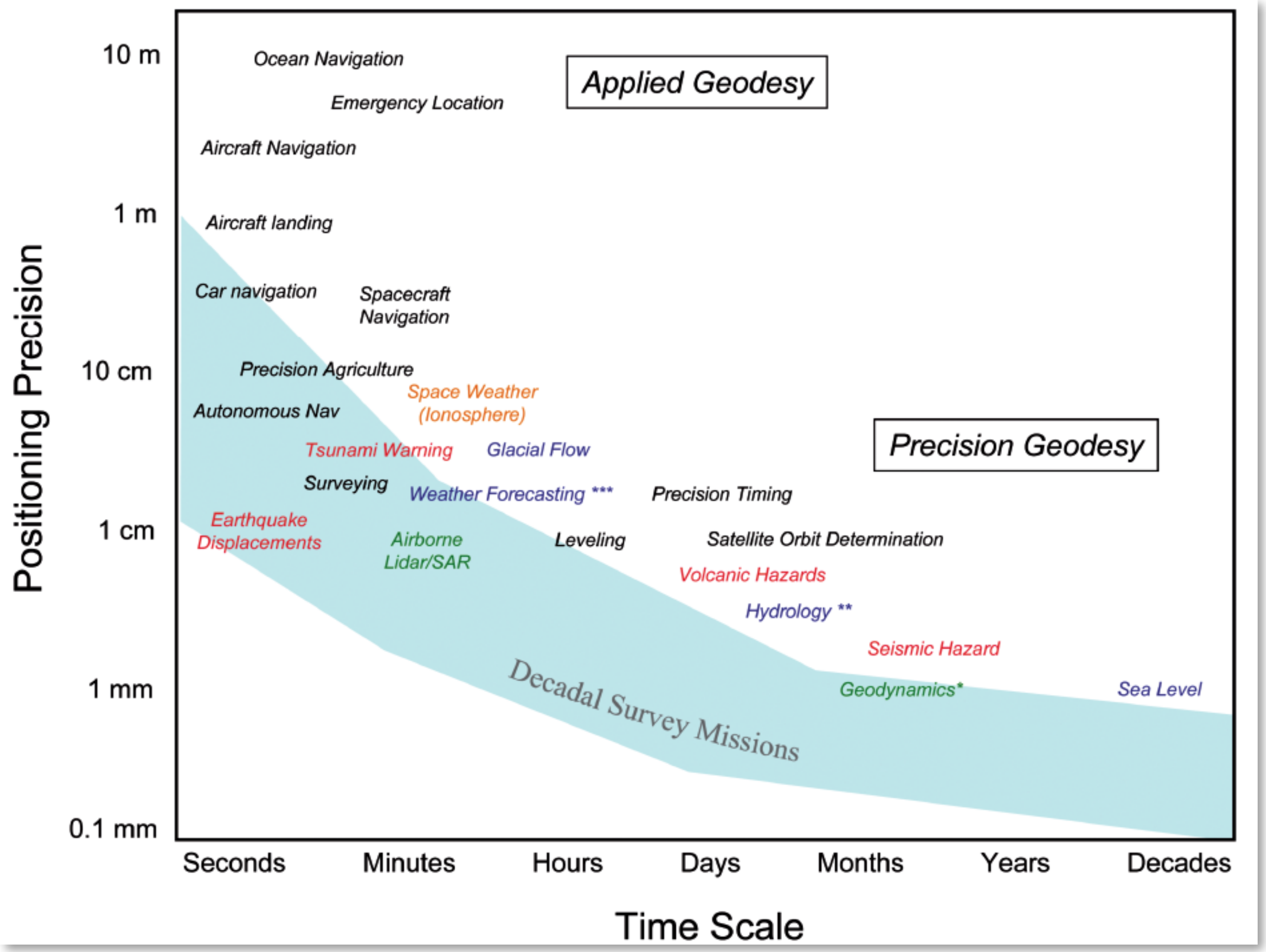
Reference Frames Requirements

- For sea level studies (e.g. tide gauge monitoring, satellite altimetry) the vertical component is of primary concern
- Vertical velocities are measured conceptually relative to the geocentre, but in reality are relative to a practical realization – a reference frame
- Accuracy of the vertical velocities depends on the **stability of the origin** and **scale** of this frame
- Sea level studies require a **frame stability of 0.1 mm/yr** and a **scale stability of 0.01 ppb/yr** (e.g. Blewitt et al., 2006; 2010)
- Then (2010) an improvement of an order of magnitude was required!





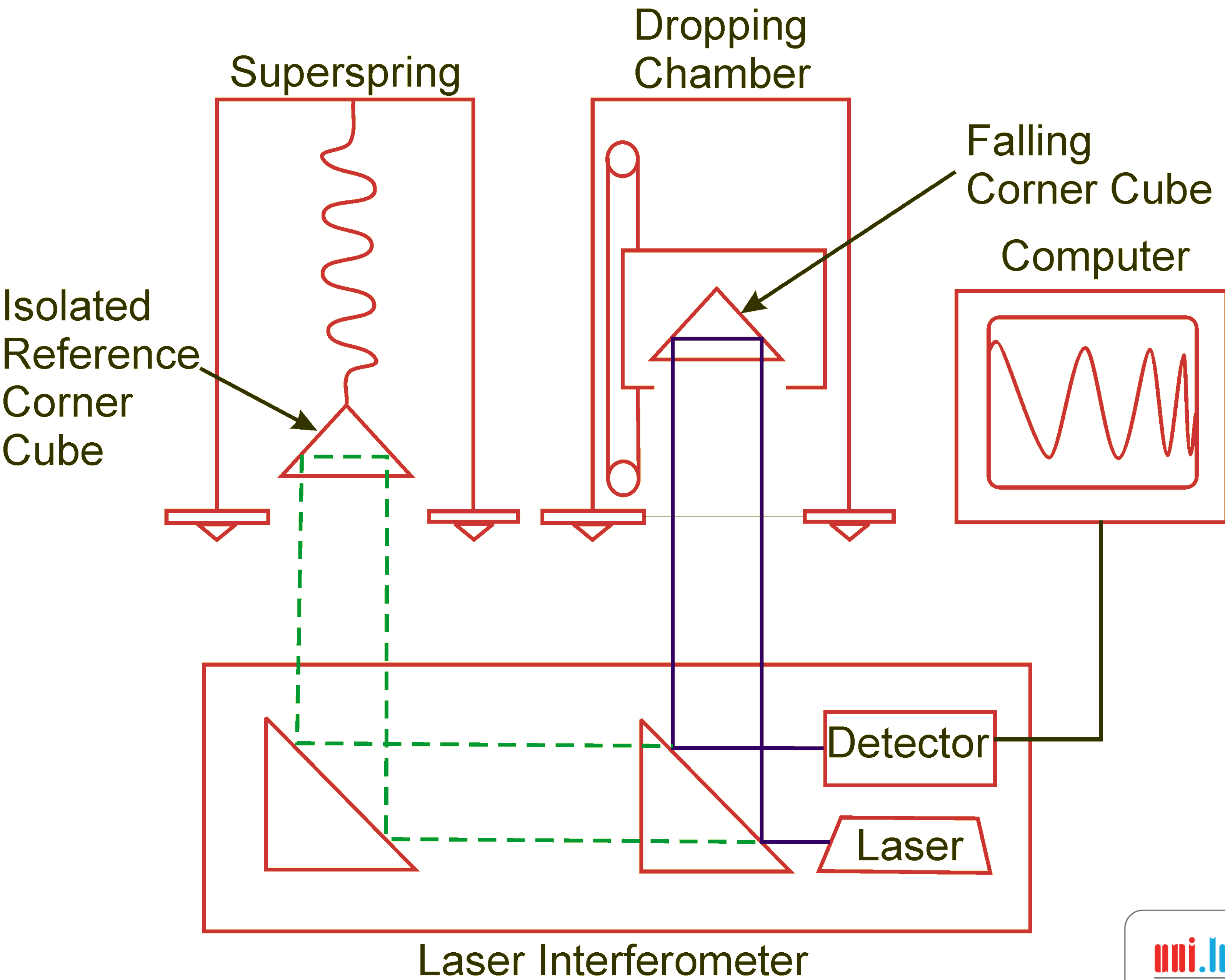
Geodesy Requirements for Earth Science



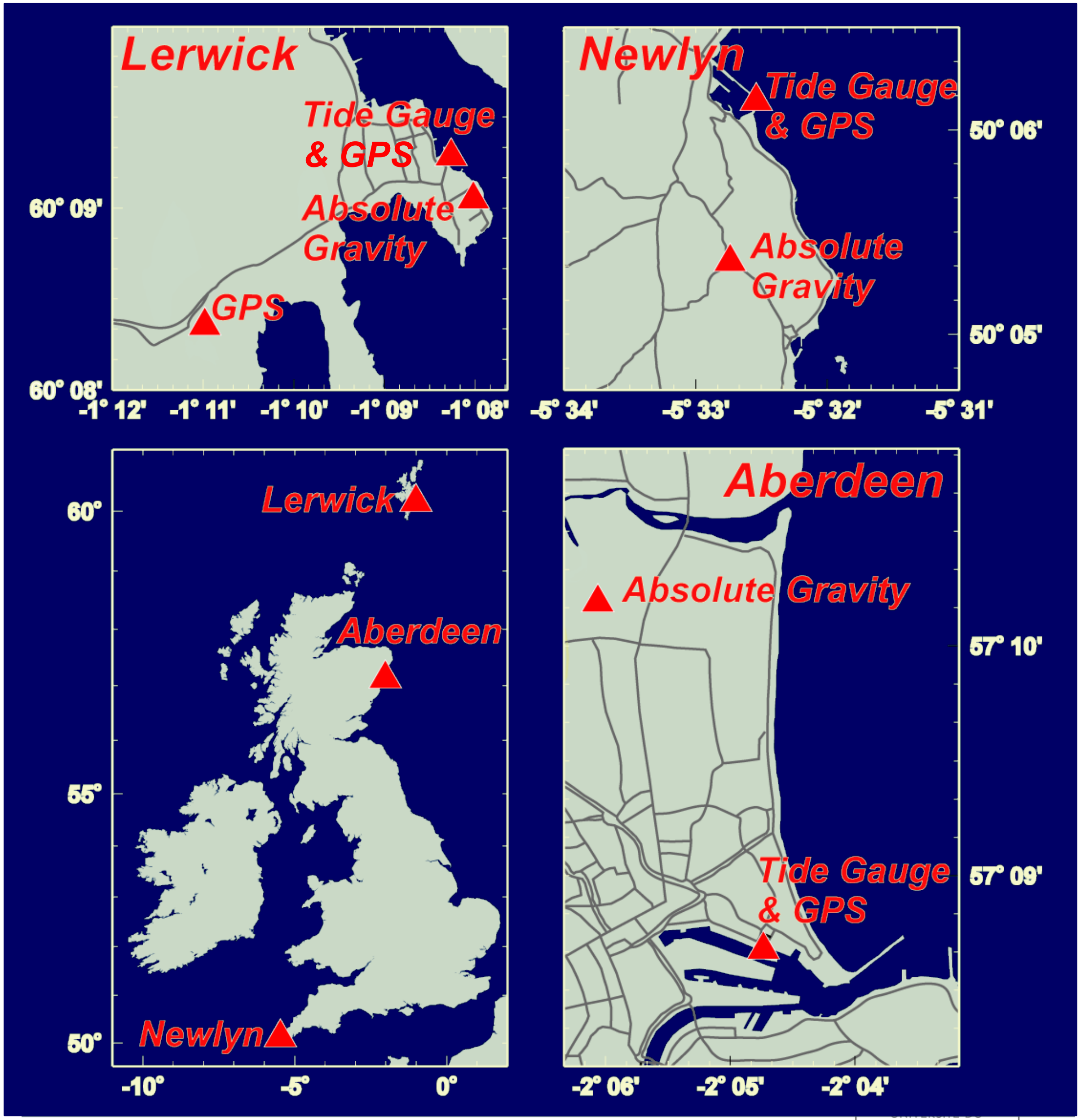
NRC Report [2010]

Absolute Gravimetry: The FG5 Instrument

- The free fall principle
- Drag free chamber
- Interferometer (distance measurement)
- Superspring (inertial reference frame)
- Data acquisition and analysis


Dropping
Chamber
Superspring
Falling
Corner Cube
Computer
Isolated
Reference
Corner
Cube
Detector
Laser
Laser Interferometer

Overview of the Co-located Sites Occupied Since 1995



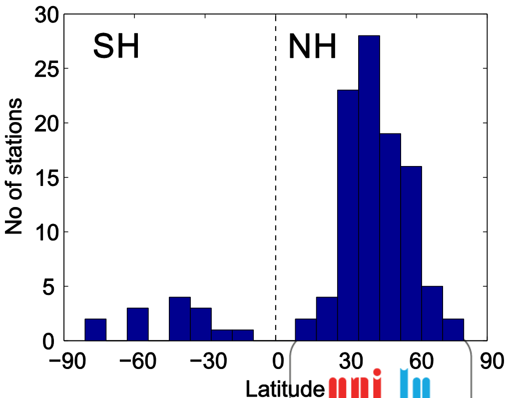
Methodology of AG Measurements

- Measure for at least 3 days at each site, at least once per year
- Data from each day are processed separately and correction made for solid-earth tides, ocean-loading effects, atmospheric pressure, polar motion and comparator response
- Single admittance factor and local pressure data are used to correct for atmospheric pressure
- Gravity gradients for Newlyn and Aberdeen determined using a relative spring gravimeter
- Error model accounts for set up errors and stochastic noise (Van Camp et al., 2005)

The IGS Tide Gauge Benchmark Monitoring (TIGA) Working Group

Goals and Objectives:

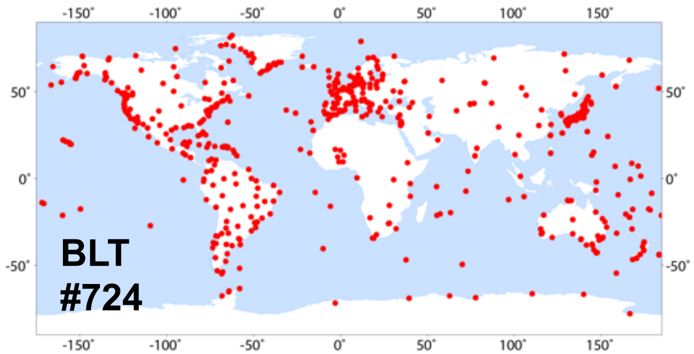
- To provide homogeneous sets of coordinates. velocities. robust uncertainties of continuous GNSS stations at or close to tide gauges (GNSS@TG)
- To establish and expand a global GNSS@TG network for satellite altimeter calibration studies and other climate applications
- To contribute to the IGS realization & densification of a global terrestrial reference frame
  - 2 TACs contributed to ITRF2014
- Promote the establishment of more continuous GNSS@TG. in particular in the southern hemisphere
- Promote the establishment of local ties between GNSS antenna and tide gauge benchmarks (TGBMs)

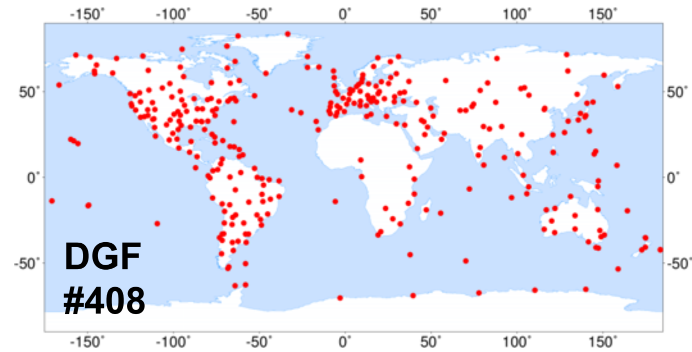


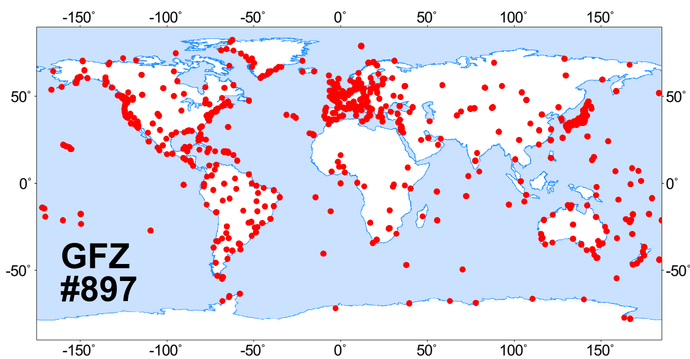
Current TIGA Analysis Centres (TAC)

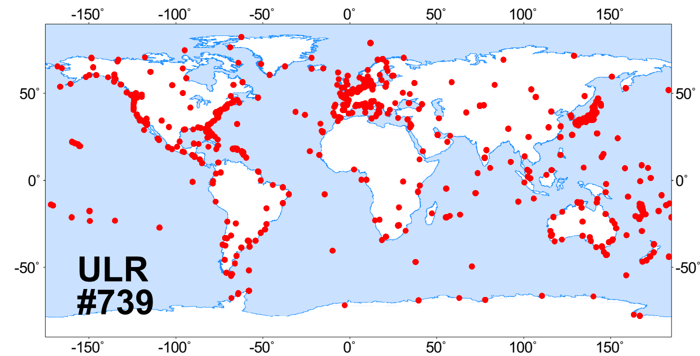
TAC	Host Institutions	Software package	Contributors
AUT	GeoScience Australia, Canberra, Australia	Bernese GNSS Software V5.2	M. Moore, M. Jia
BLT	British Isles continuous GNSS Facility and University of Luxembourg TAC (BLT), UK and Luxembourg	Bernese GNSS Software V5.2	F. N. Teferle A. Huneganw R. M. Bingley D. N. Hansen
DGF	The Deutsches Geodätisches, Forschungsinstitut, Germany	Bernese GNSS Software V5.2	L. Sanchez
GFZ	GeoForschungsZentrum (GFZ), Potsdam, Germany	EPOS P8	T. Schöne Z. Deng
ULR	Centre Littoral de Geophysique, University of La Rochelle (ULR), France	GAMIT V10.5	G. Wöppelmann A. Gómez-A. Santamaría M. Gravelle

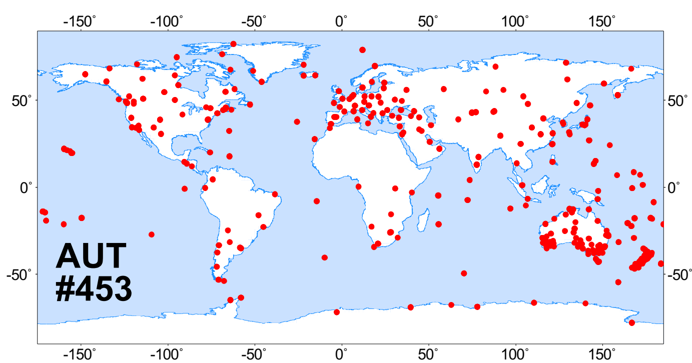
TAC Global Networks









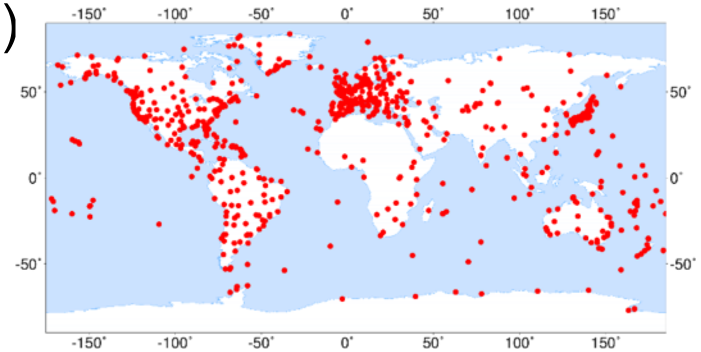


TIGA Data Centre:
University of La Rochelle (ULR):
www.sonel.org

TIGA Combination (Release 0.99)

- Produced by TIGA combination center (TCC) at the University of Luxembourg

- The main TIGA product is an IGS-style combination of individual TAC solutions



All tracking stations in the combined solution

- Daily TIGA repro2 SINEX combination
- Modelling of station position time series. Specifically:

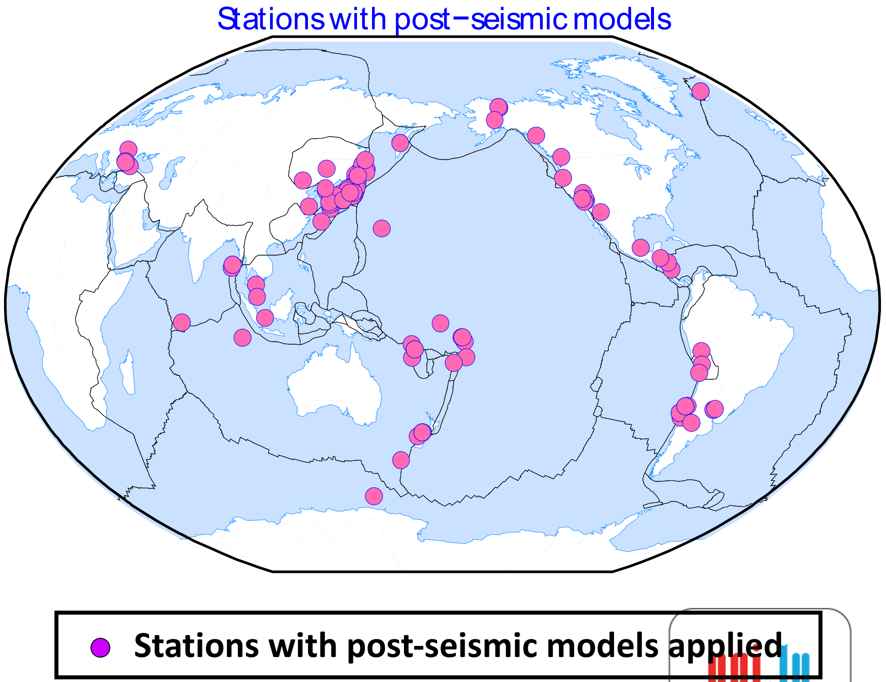
  - Offsets, depending on TAC solutions
  - Computationally intensive, depends on the use of UL HPC infrastructure

- Long-term stacking
- Software packages for combination: CATREF and Globk (during preliminary solutions)

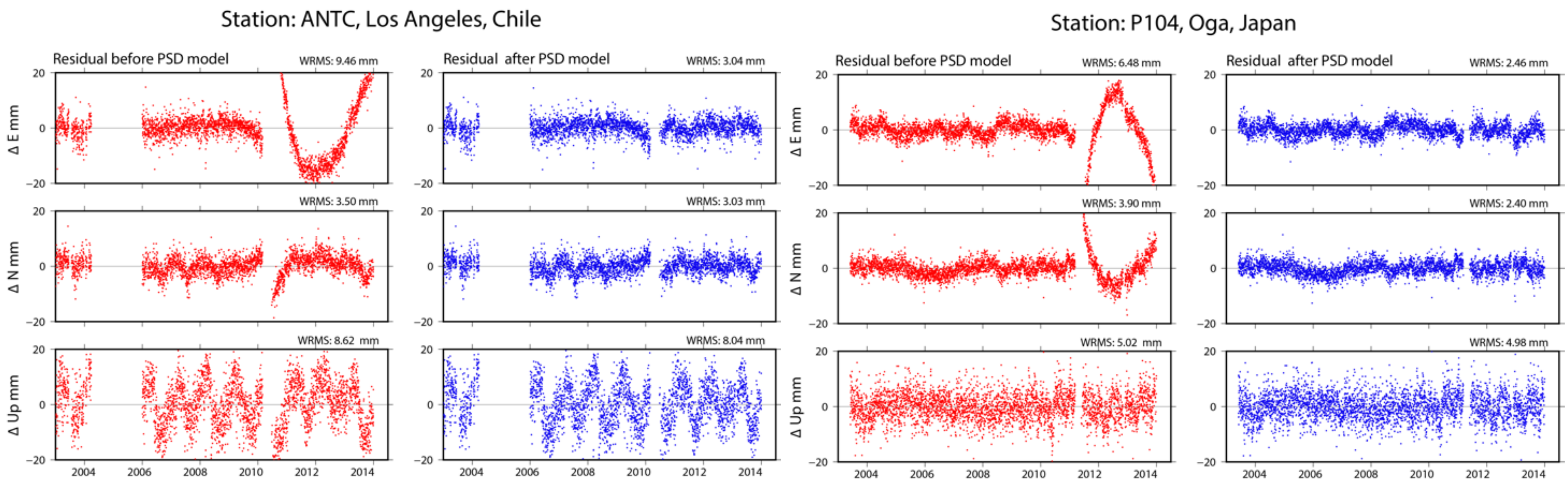
Post-seismic deformation modeling

- We correct post-seismic deformations before stacking
- For each E, N and U time series:
  - Used models: Exp, Log, Exp+Exp, Exp+Log

- **119 stations are affected**
- **11% of all stations**



Post-seismic Deformation Modelling (following ITRF2014)



- RMS reduction in E and N components are substantial
- Significant improvements also in the Up component

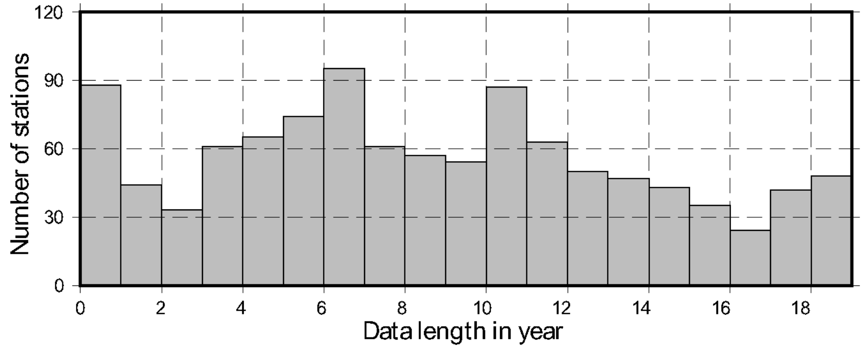
UNIVERSITÉ DU LUXEMBOURG

TIGA Combination Solution Information

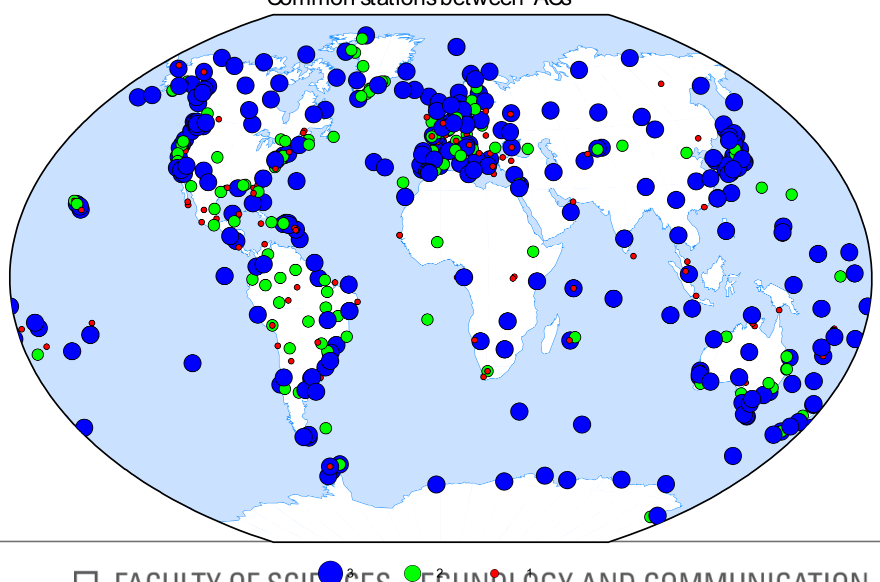
- 6936 SINEX solutions

- Daily station positions
- January 1, 1995 → January 1, 2014
- 1087 stations

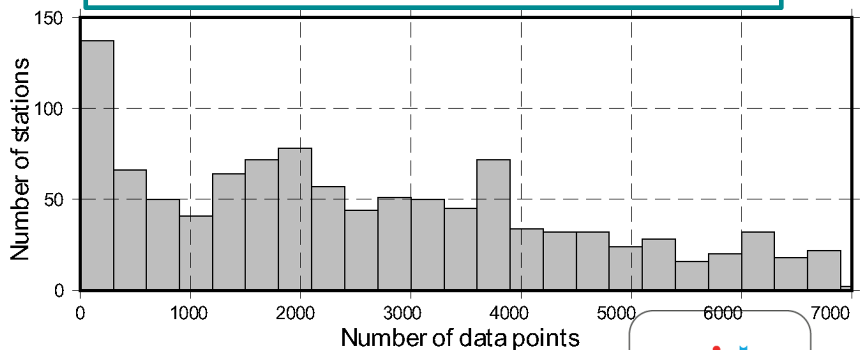
Histogram of data length of TIGA combination time series



Common stations between ACs



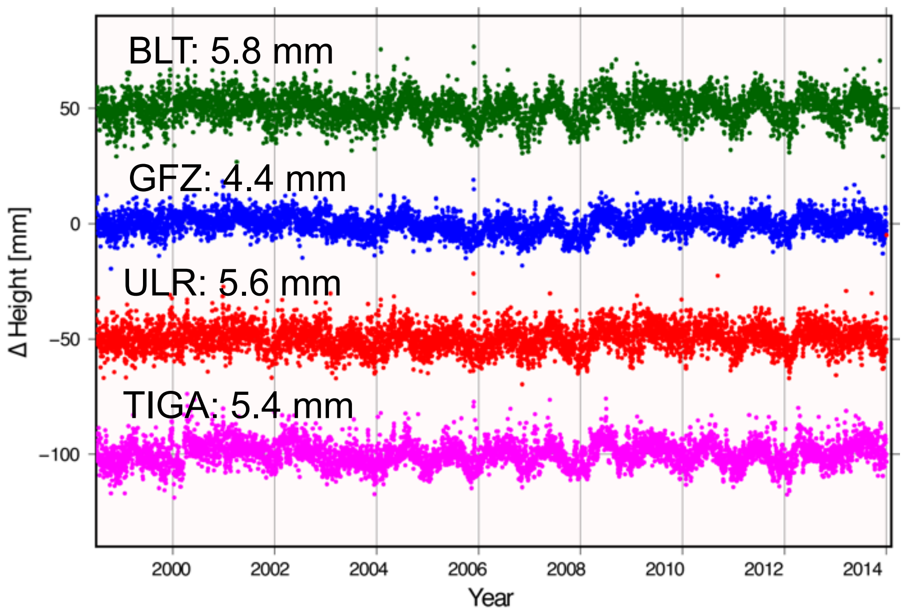
Histogram of data points in TIGA combination time series



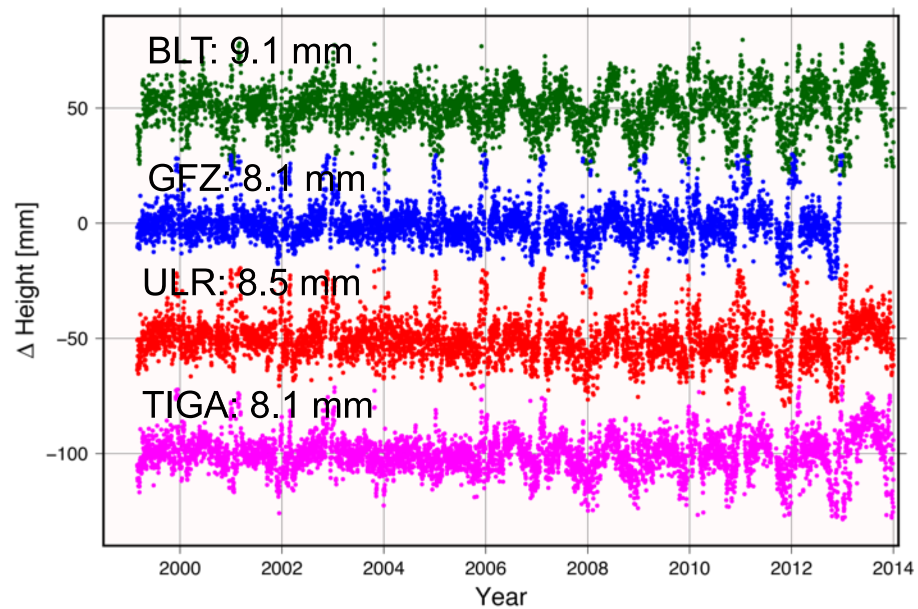
UNIVERSITÉ DU LUXEMBOURG

Residual Coordinate Time Series from TAC and Combined Solutions

GPS station, WSRT



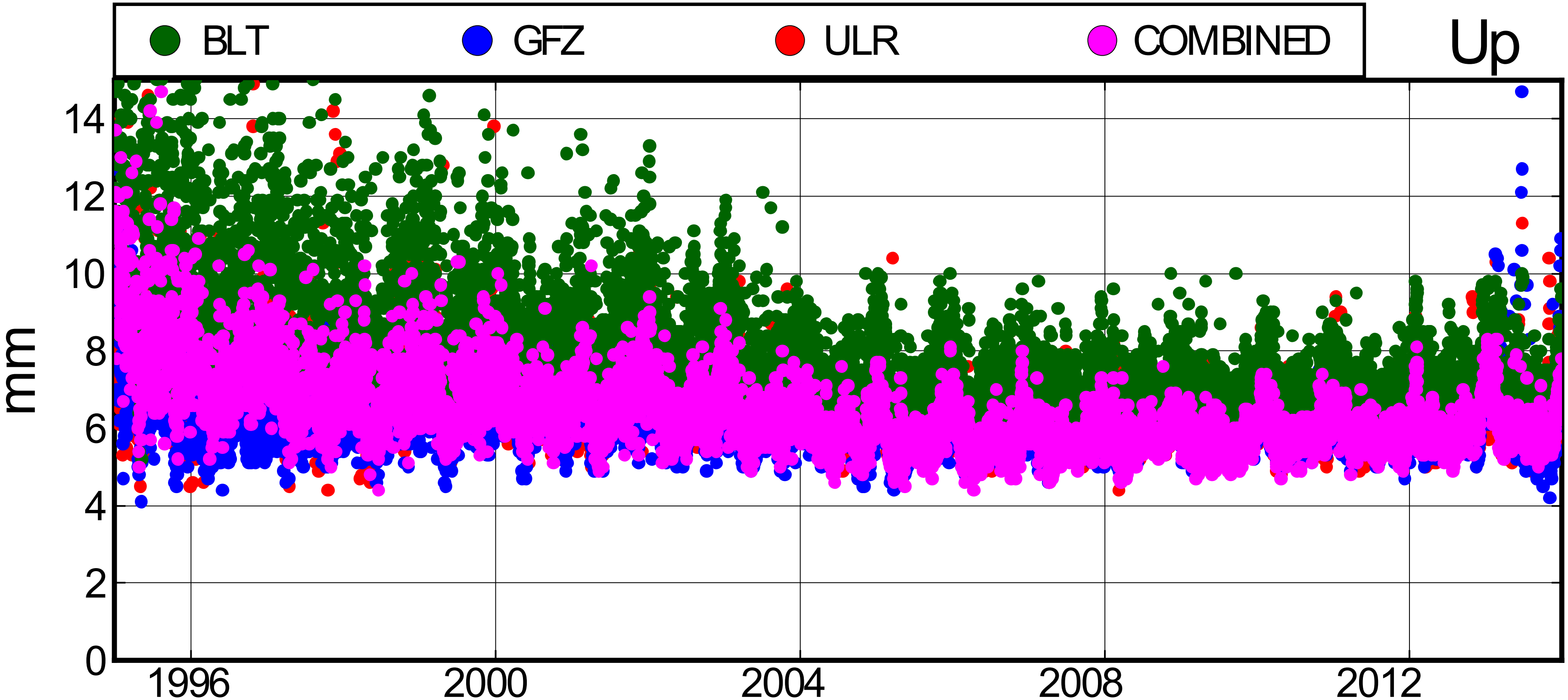
GPS station, VAAS



BLT GFZ ULR COMBINED

UNIVERSITÉ DU LUXEMBOURG

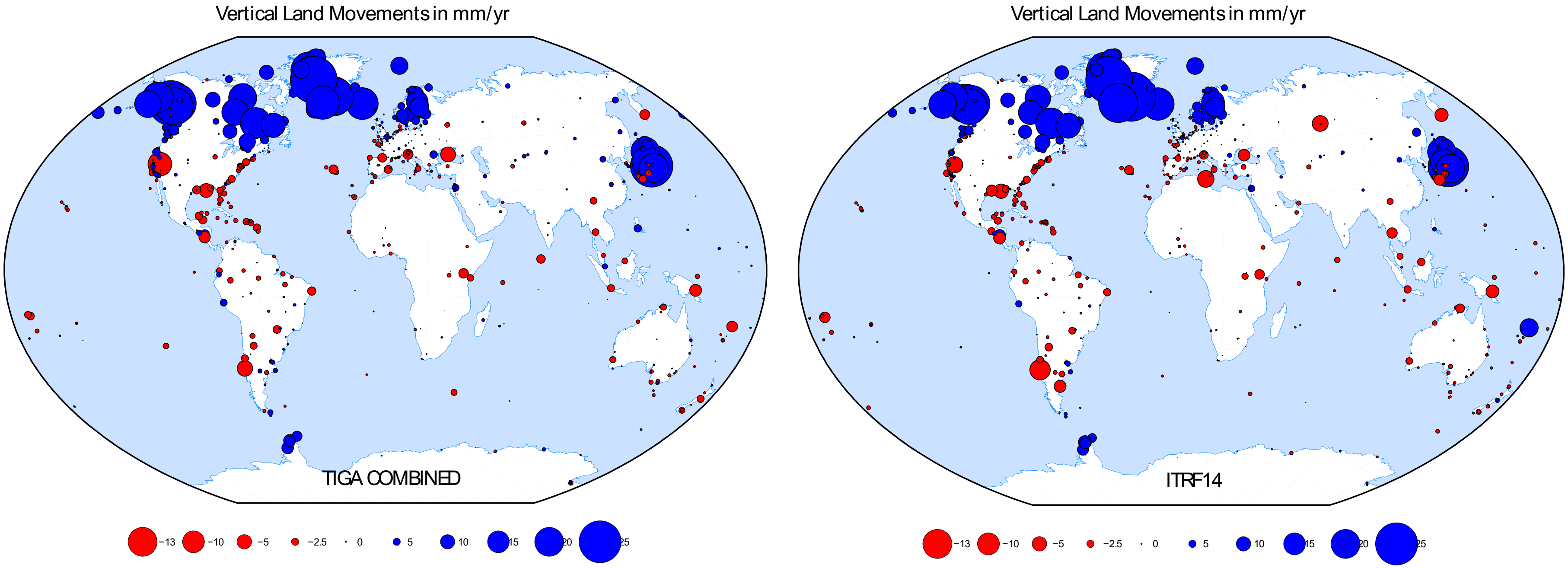
Daily WRMS for TAC and Combined Solutions



Daily WRMS of TAC and combined station position residuals

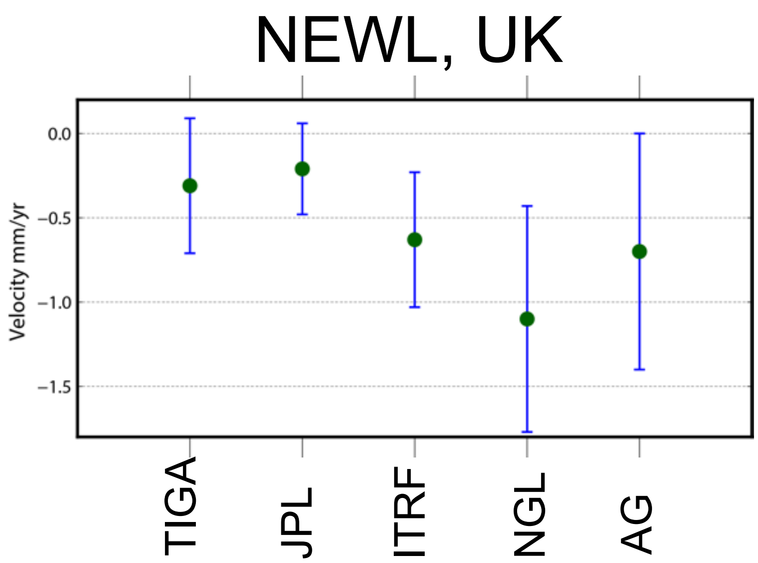
- **Inter-agreement from 2004 …**

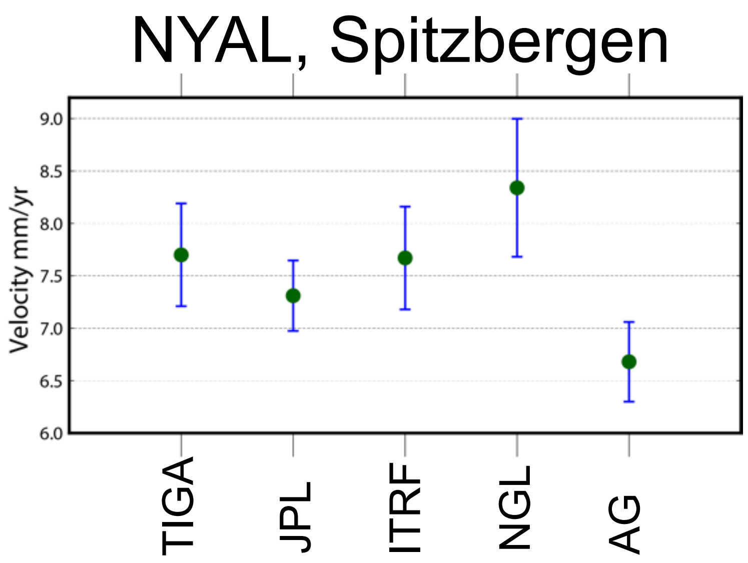
VLM from TIGA Combination and ITRF2014 Solutions



Overall the picture of VLM agrees with some larger differences at individual stations.

VLM Comparison with Absolute Gravity





VLM-Corrected MSL Trends

TG names	Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend	GIA Trend	TIGA Trend	TG+GIA Trend	TG+TIGA Trend
North Europe								
STAVANGER	63	16000	47	0.35 ±0.18	0.59	**1.91 ±0.40**	0.94	2.26
KOBENHAVN	101	7300	82	0.56 ±0.12	0.06	**1.30 ±0.85**	0.62	2.09
NEDRE GAVLE	90	11000	99	-6.04 ±0.22	6.87	**7.92 ±0.88**	0.83	1.88
North Sea and English Channel								
ABERDEEN	103	2	361	0.97 ±0.25	1.01	**0.75 ±0.21**	1.98	1.72
NEWLYN	87	10	202	1.81 ±0.12	-0.72	**-0.31±0.17**	1.09	1.50
BREST	83	350	1	0.97 ±0.12	-0.61	**-0.10±0.28**	0.36	0.87
East Atlantic								
CASCAIS	97	84	52	1.29 ±0.18	-0.34	**-0.07±0.24**	0.95	1.22
LAGOS	61	138	162	1.56 ±0.25	-0.41	**-0.34±0.22**	1.15	1.22
Mediterranean								
MARSEILLE	105	5	61	1.33 ±0.12	-0.32	**0.93 ±0.30**	1.01	2.26
GENOVA	78	1000	59	1.17 ±0.08	-0.16	**-0.34±0.18**	1.01	0.83

TG stations are selected and grouped according to Douglas (2001)

VLM-Corrected MSL Trends (2)

TG names	Span [yr]	GPS/TG Dist. [m]	PSMSL TG ID	TG Trend	GIA Trend	TIGA Trend	TG+GIA Trend	TG+TIGA Trend
NE North America								
EASTPORT	63	800	332	2.21 ±0.3	-1.34	-0.38±0.37	0.87	1.83
NEWPORT	70	500	351	2.48 ±0.14	-1.42	-0.27±0.21	1.06	2.21
HALIFAX	77	3100	96	3.06 ±0.19	-1.54	-0.91±0.15	1.52	2.15
ANNAPOLIS	70	11577	311	3.5 ±0.14	-1.84	-2.09±0.11	1.66	1.41
SOLOMON ISL	62	200	412	3.69 ±0.18	-1.71	-1.54± 0.33	1.98	2.15
NW North America								
VICTORIA	86	12000	166	0.74 ± 0.05	-0.53	1.01 ±0.20	0.21	1.75
NEAH BAY	65	7800	385	-1.80 ±0.09	-1.16	3.58 ±0.28	-2.96	1.78
SEATTLE	104	5900	127	1.99 ± .14	-0.84	-1.00±0.22	1.15	0.99
SE North America								
CHARLESTON I	82	8200	234	3.31 ±0.28	-1.13	-1.65±0.73	2.18	1.66
GALVESTON II	94	4200	161	6.33 ±0.31	-1.06	-3.65± 0.55	5.27	2.68
MIAMI BEACH	45	4800	363	2.29 ±0.26	-0.83	0.25±0.72	1.46	2.54
KEY WEST	90	16000	188	2.40 ±0.16	-0.82	-0.29±0.37	1.58	2.11
SW North America								
LA JOLLA	72	700	256	2.21 ±0.12	-0.72	-0.72±0.58	1.49	1.49
LOS ANGELES	78	2200	245	0.94 ±0.14	-0.74	-0.19±0.28	0.20	0.75
New Zealand								
AUCKLAND II	85	5	150	1.32 ±0.11	0.08	-0.43±0.25	1.40	0.89
PORT LYTTELTON	101	2	247	2.18 ±0.27	0.14	-0.69±0.25	2.32	1.49
Pacific								
HONOLULU	99	5	155	1.43 ±0.3	-0.23	-0.68±0.19	1.20	0.75

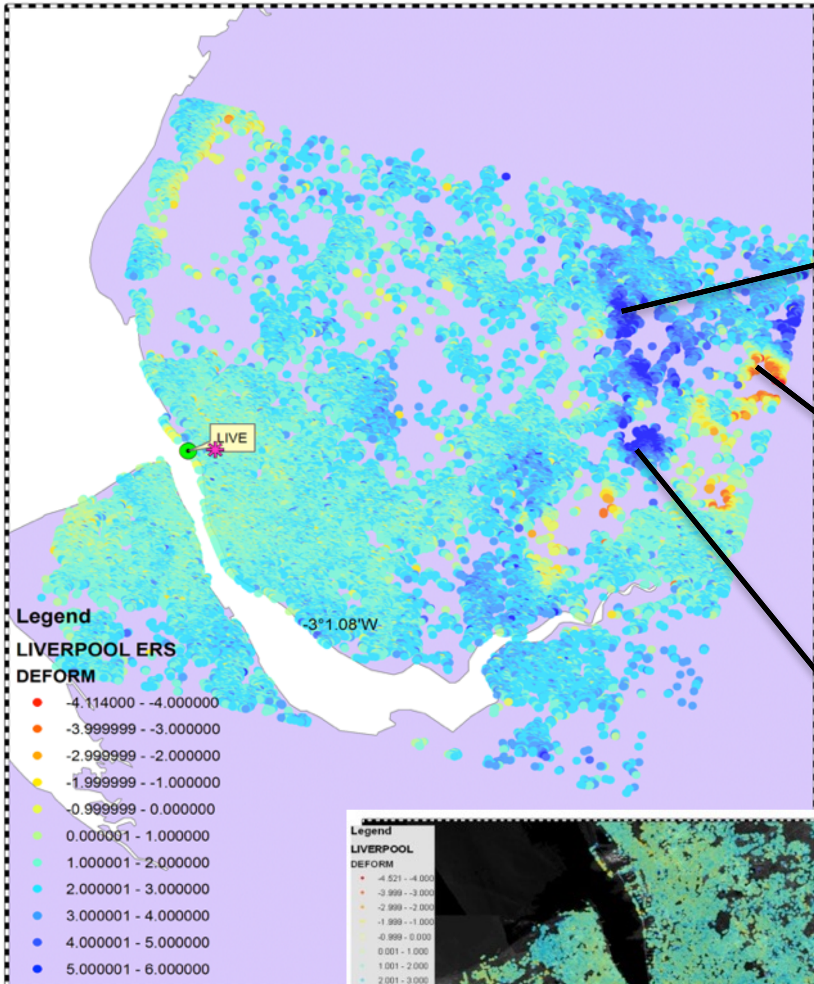
WHY USE PERSISTENT SCATTERER INTERFEROMETRY AS COMPLEMENTARY TECHNIQUE TO CGPS AND ABSOLUTE GRAVITY?

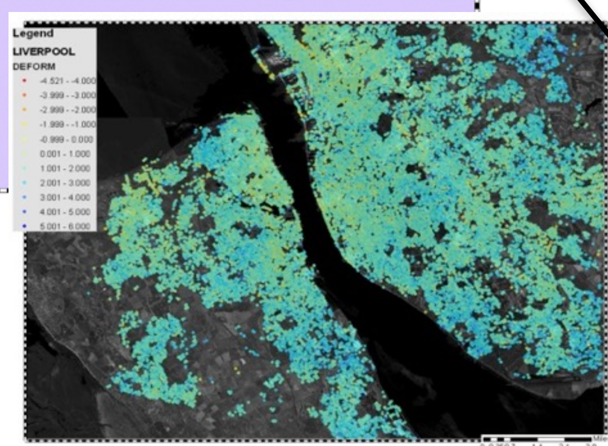
Why PSI for Sea Level Studies?

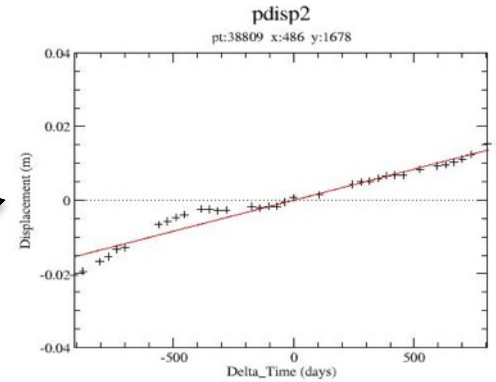
- **PSI for sea level studies** has **two main applications**: **regional** and **local**
- For the regional, PSI can provide **maps of relative changes in land level over a large (10s of km) coastal area**
  - These are useful as most planning for Flood and Coastal Risk Management assumes a single value for the change in land level along a stretch of coast and combines this with future predictions of changes in sea level
  - In this case, PSI could provide information to confirm or contradict any assumption of uniform changes in land level, e.g. highlighting coastal and estuarine areas that are undergoing more subsidence.
- For the local, PSI can **complement the levelling of benchmark networks**
  - This would be useful as it could provide information on changes in land level going back in time to 1992 and could remove the need to go into the field
  - In this case, PSI could provide information on the stability of a structure that supports a tide gauge and could help to de-correlate any local movements of that structure from the total movements observed using continuous GPS

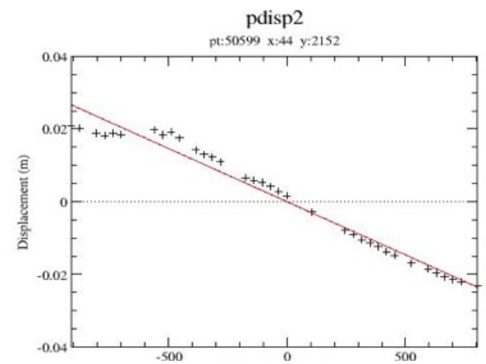
PSI at GPS@TG Sites in the UK

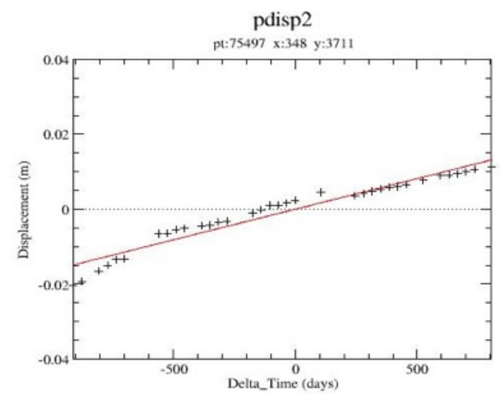
- All 10 CGPS@TG sites considered
- Sites checked against radar data availability (ERS1/2 and ENVISAT ASAR)
- Investigation of different methods for PS candidates selection
- Determine the number and pattern of the potential PS candidates
- Four sites selected with various levels of vegetation/urbanization and PS pattern





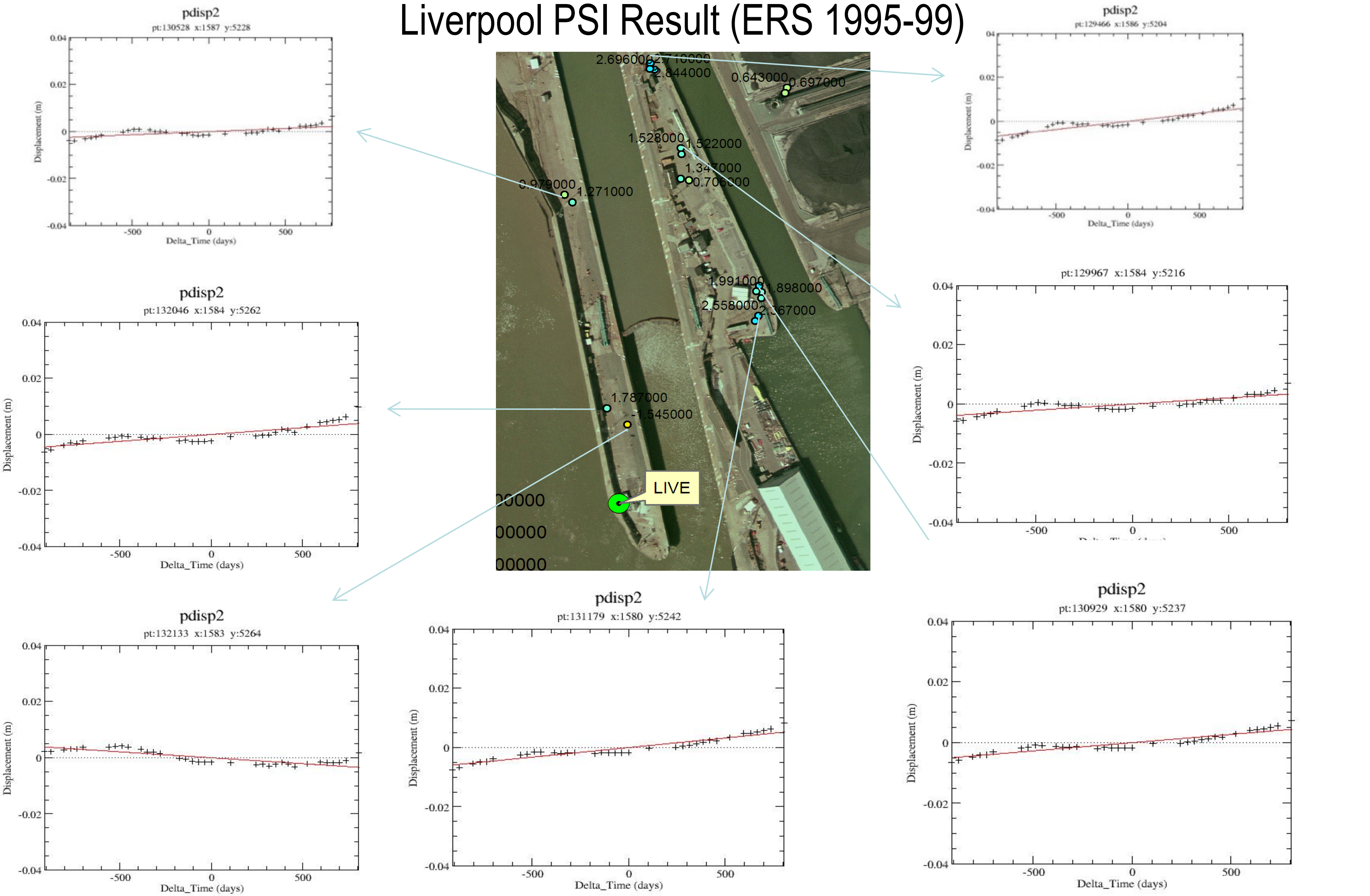




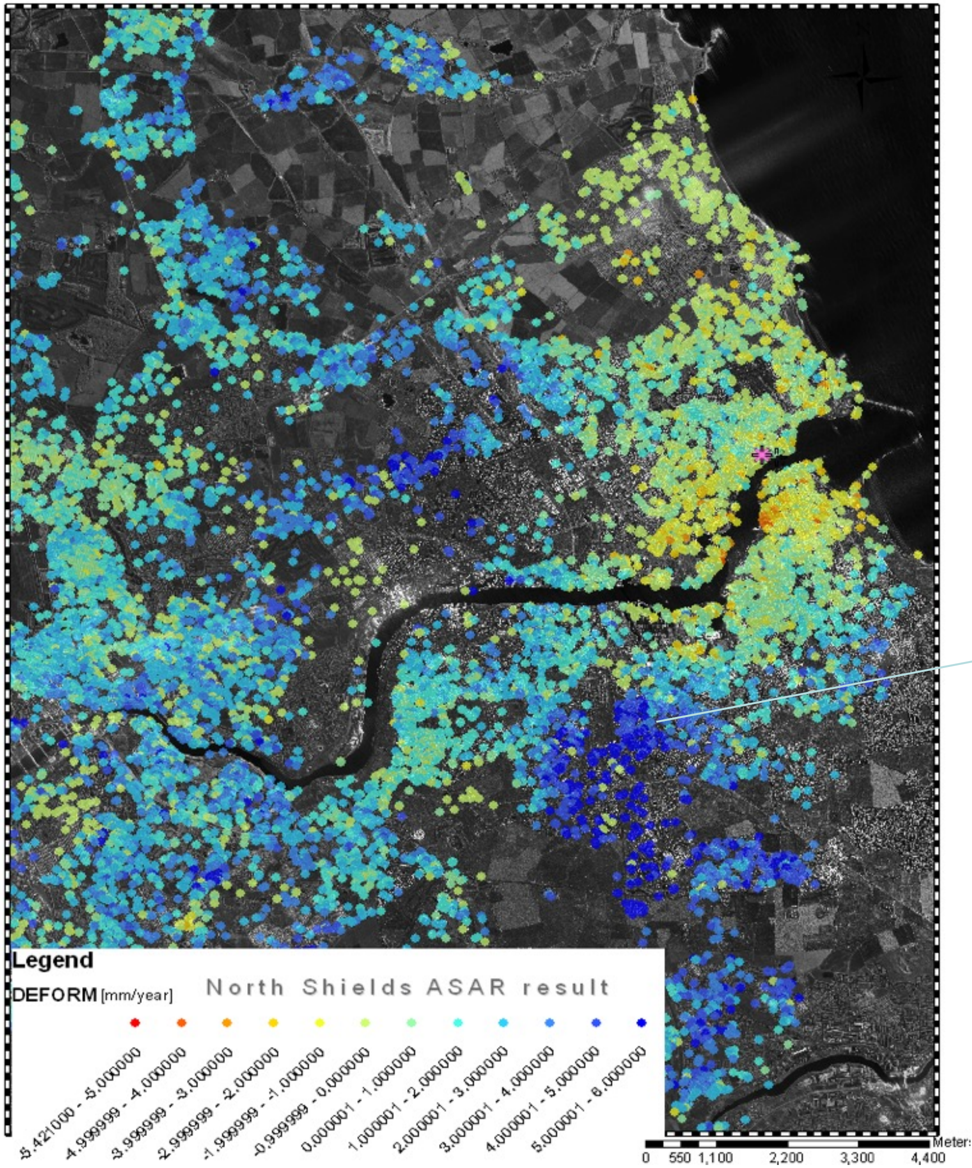


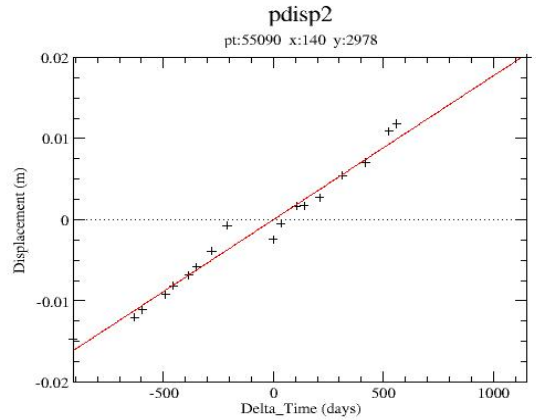
Liverpool PSI Result (ERS 1995-99)

Liverpool PSI Result (ERS 1995-99)



North Shields PSI Results (ASAR 2003-2008)





North Shields PSI Results (ASAR 2003-2008)

NOC Sea Level Stations in the South Atlantic, Antarctica and Gibraltar

9 Sea Level Stations

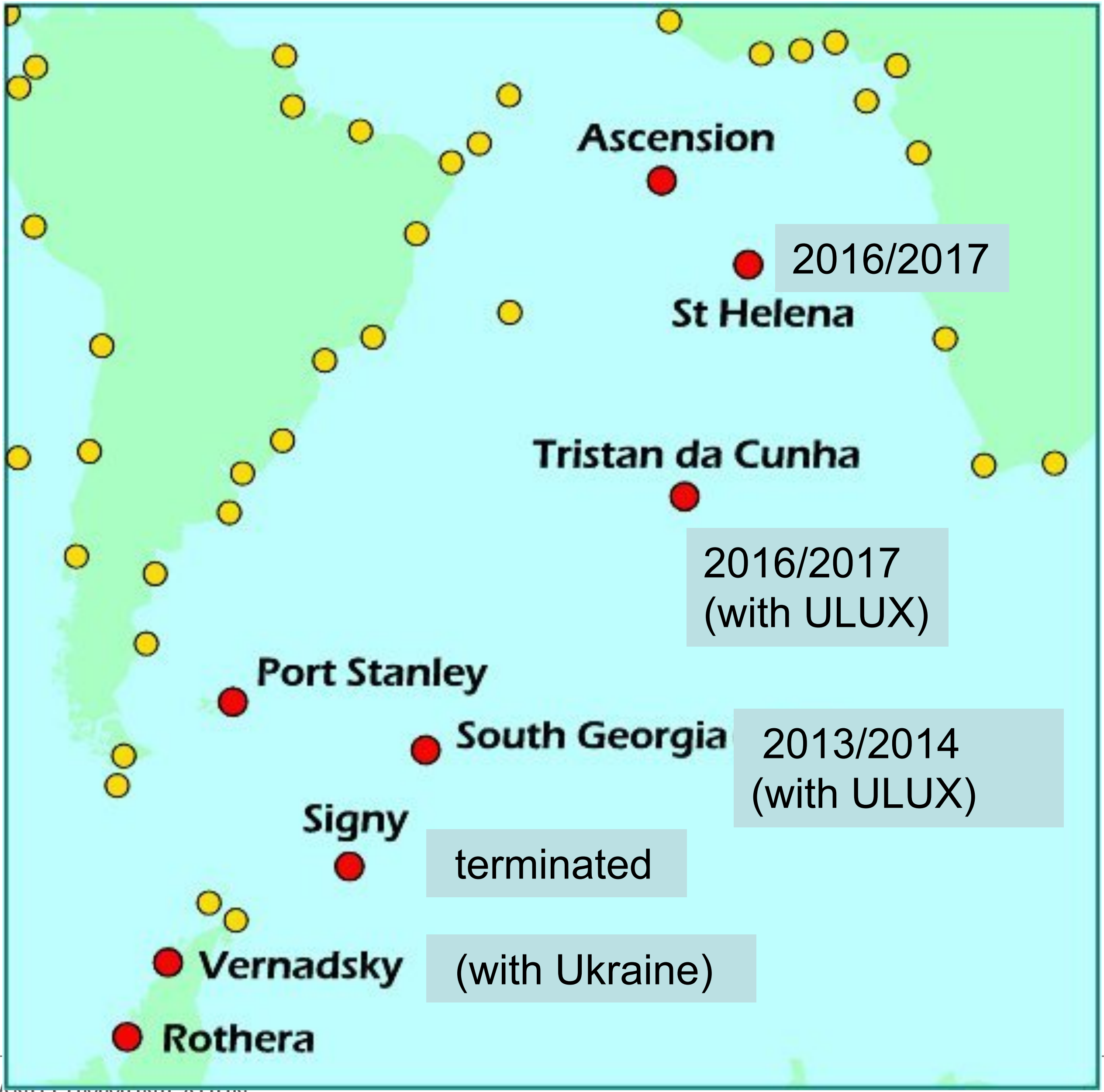
Real time telemetry:

Ascension Island
Saint Helena
Port Stanley
Tristan
Vernadsky (Faraday)
Rothera
Gibraltar

Delayed mode data:

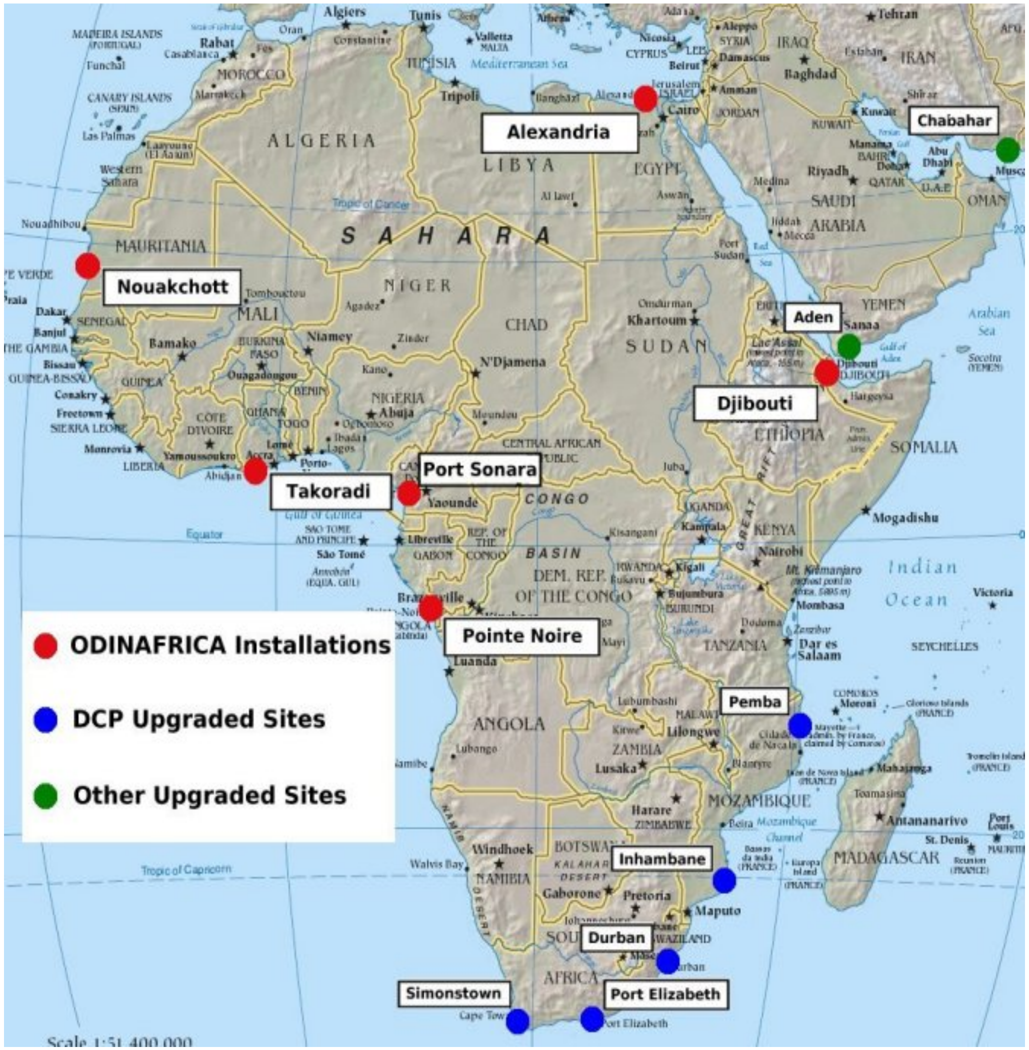
Signy

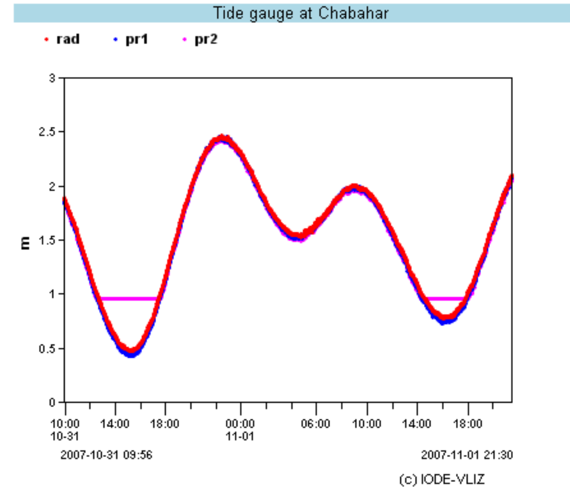
St.Helena and Tristan recently re-built after storm damage



ODINAFRICA
Ocean Data and Information Network for Africa

GLOSS and ODINAFRICA - III





View of the radar sensor arm (viewed from the top of the observatory)

Nouakchott, Mauritania

Thank you for your attention!

Acknowledgments

The TCC would like to acknowledge the IGN/ITRF for the provision of the CATREF combination software.

The TIGA WG also promotes the installation of GNSS @ TG stations, especially in the Southern Hemisphere: Lüderitz, Namibia

HartRAO/Univ. Luxembourg

UNIVERSITÉ DU LUXEMBOURG

Acknowledgements

- My special thanks go to Phil Woodworth who shared a number of slides with me for this presentation.
- Other thanks go to colleagues at
  - National Oceanography Centre, Liverpool, UK
    - Simon Williams, Jeffrey Pugh, Angela Hibbert, Phil Woodworth
  - University of Luxembourg
    - Kibrum Ebuy Abraha, Addisu Hunegnaw
  - University of Nottingham, Nottingham, UK
    - Richard Bingley, Andrew Sowter