

# Measuring vertical land movement at global tide gauges using GPS

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# Geocentric Sea Level

TGs measure **relative** sea level

- Of primary interest to local residents
- To study, e.g., volume/mass change in the oceans, we need a correction for vertical land movement (**VLM**)
- VLM induced by
  - Glacial Isostatic Adjustment (**GIA**)
  - Subsidence (ground water, sedimentation etc)
  - Tectonics
  - Pier motion (highly localised)

Correction for VLM allows an estimate of sea level change relative to the geocentre -> geocentric (“absolute”) sea level; **GSL**

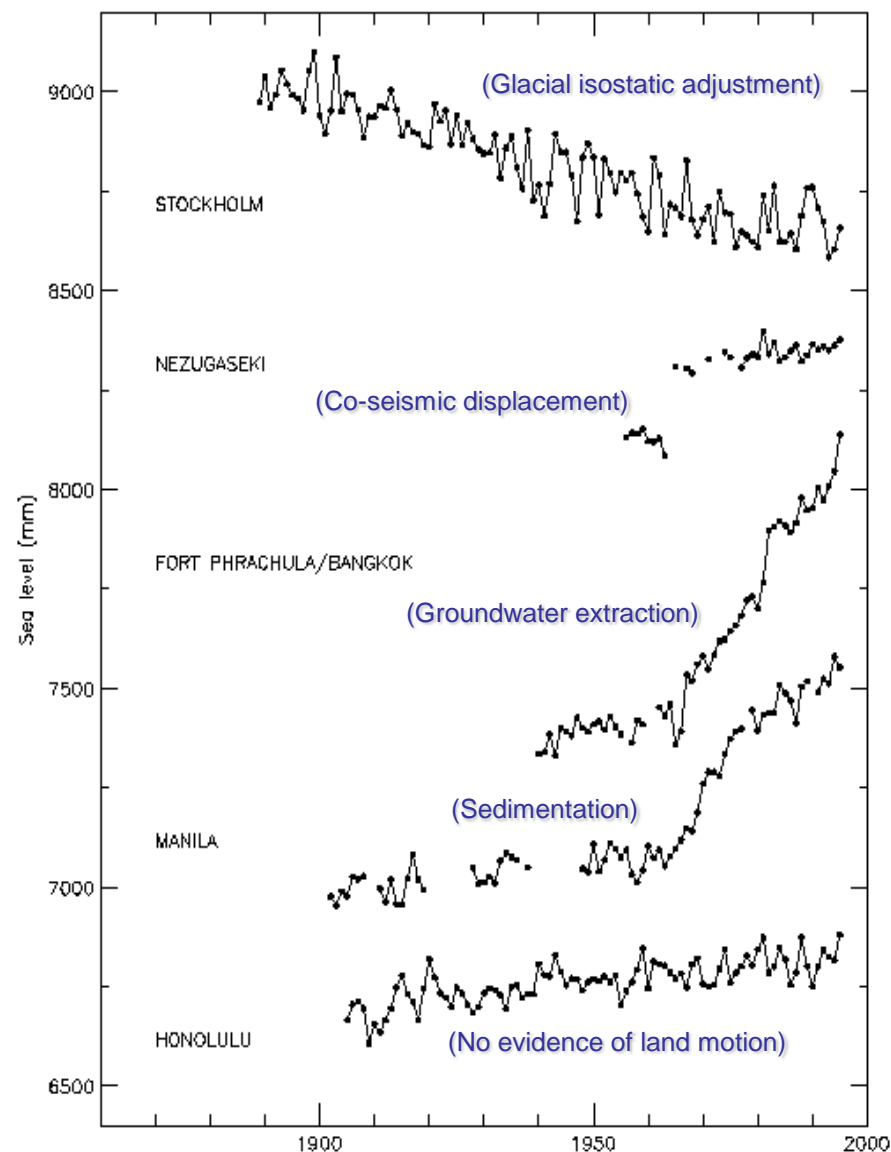


<http://sealevel.jpl.nasa.gov/science/invest-merrifield-fig2.html>

# Correcting for Vertical Land Movement

Until recently done using a GIA model alone

- Primary weakness is that GIA is not the only process
- GIA models are also not perfect due to poorly constrained ice history and Earth response to unloading
- In practice, the number of stations used to compute **GSL** change are often limited to regions where GIA is expected to be well known and the dominant process [e.g., Douglas et al., 2001]



# Measuring VLM

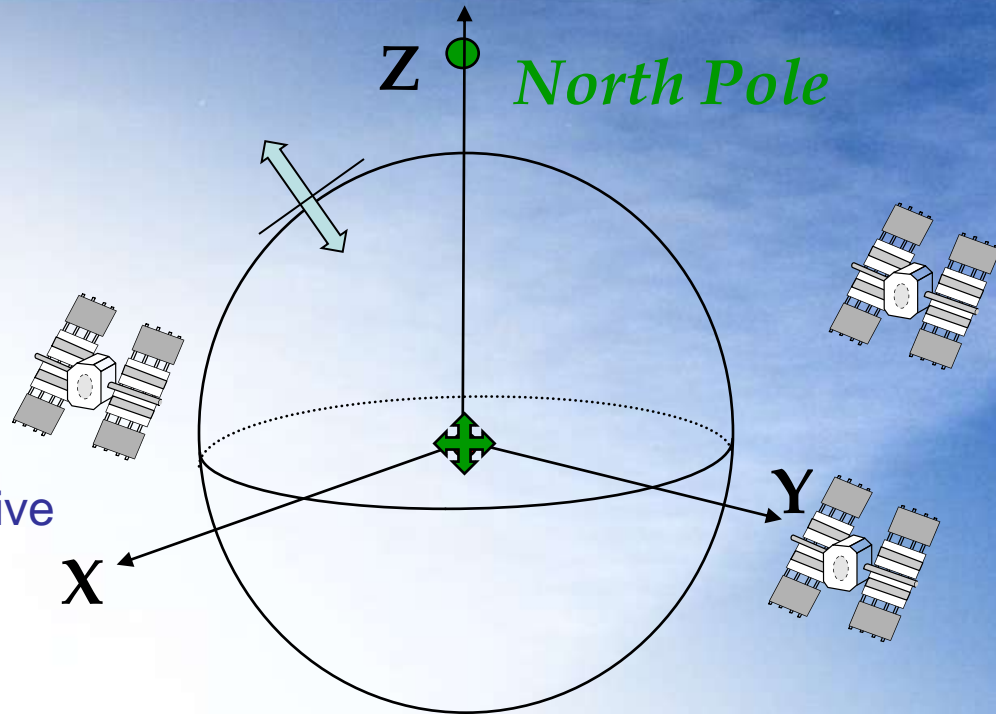
Measuring the actual TG motion is clearly preferred

- Global Positioning System (GPS) coordinate time series identified as a potential way forward since at least Carter et al. [1989]
- From 1989->2007 no reliable GPS-based rates published
- Two outstanding issues relating to geodesy
  - **GPS velocity accuracy and precision** and
  - **Reference frame accuracy**
- One point of debate
  - **What is the GPS to TG distance threshold for each TG? 0km? 15km? 200km?**

# GPS Outstanding Issues (i)

## Reference frame accuracy

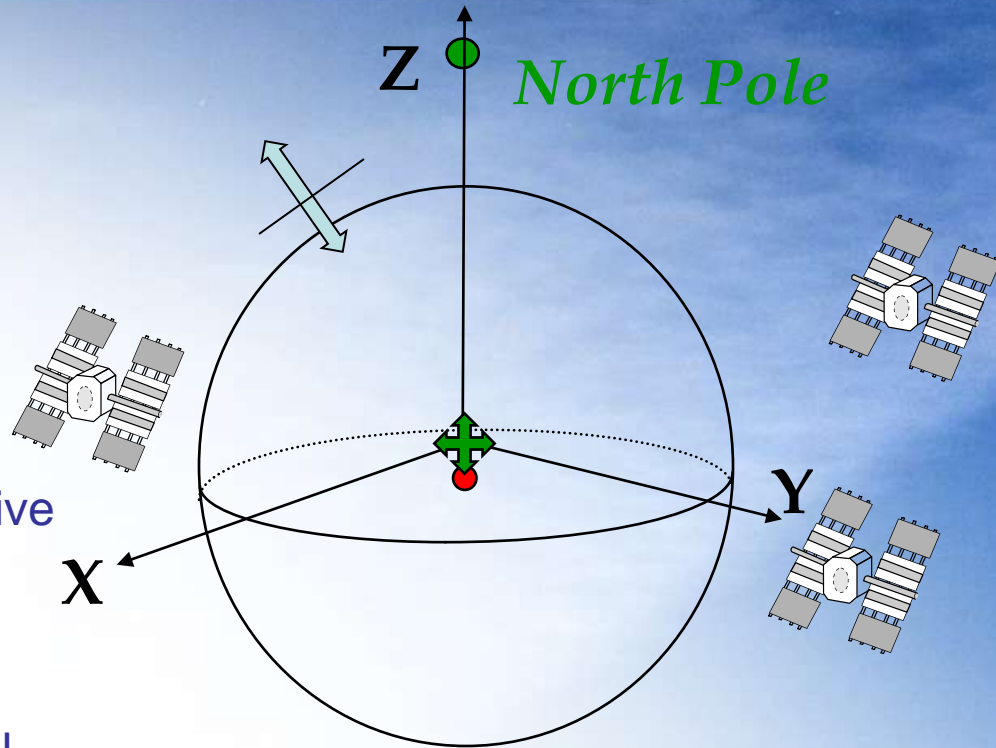
- All velocities measured are conceptually relative to the geocentre, but in reality are relative to a practical realisation – a reference frame
- Errors exist: difference between ITRF2000 and ITRF2005 =  $1.8 \cdot \sin(\text{Lat})$  mm/yr [Altamimi et al., 2007]; 1.8 mm/yr at Poles; 0.0 mm/yr at Equator
- Driven by systematic errors
- Also impacts altimetry



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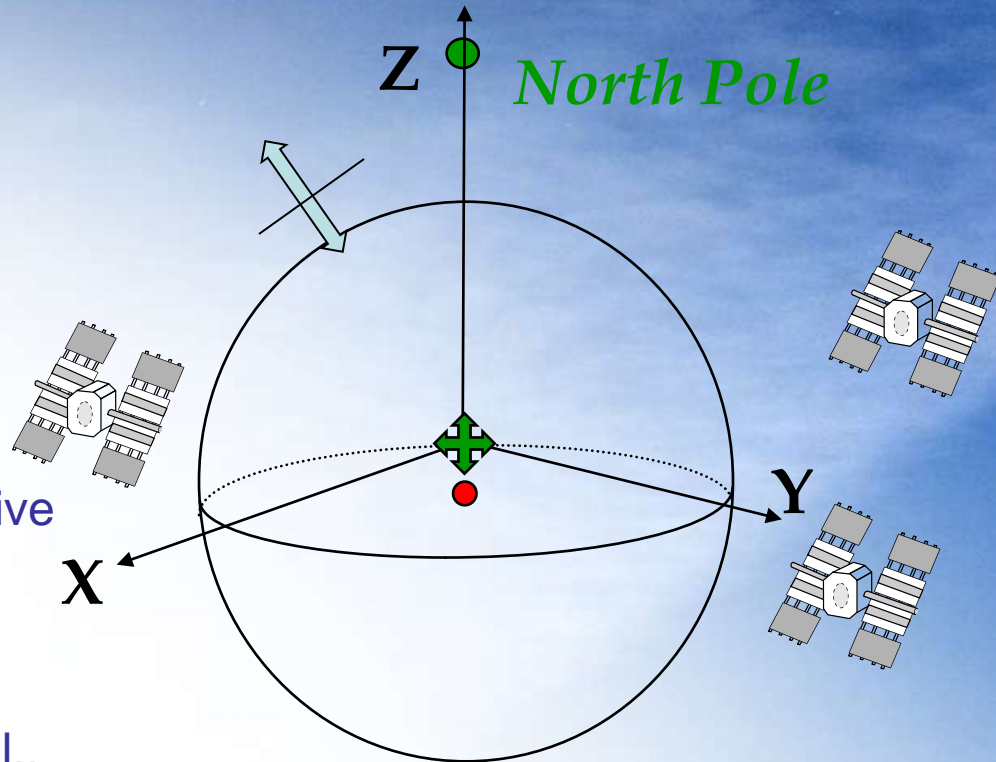
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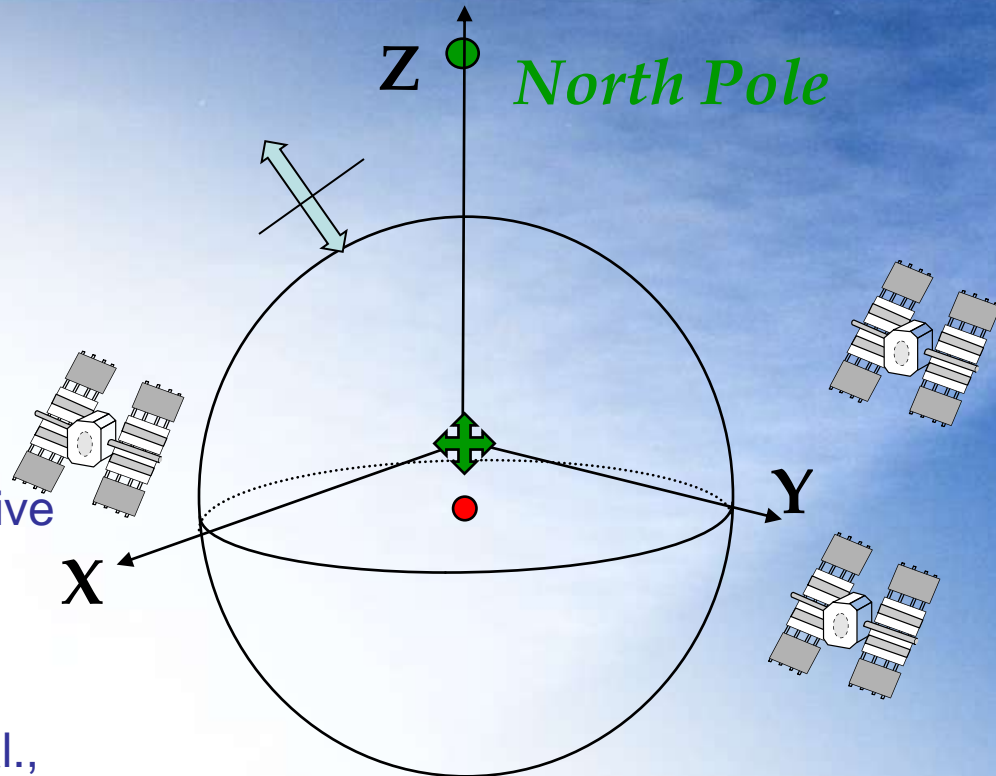
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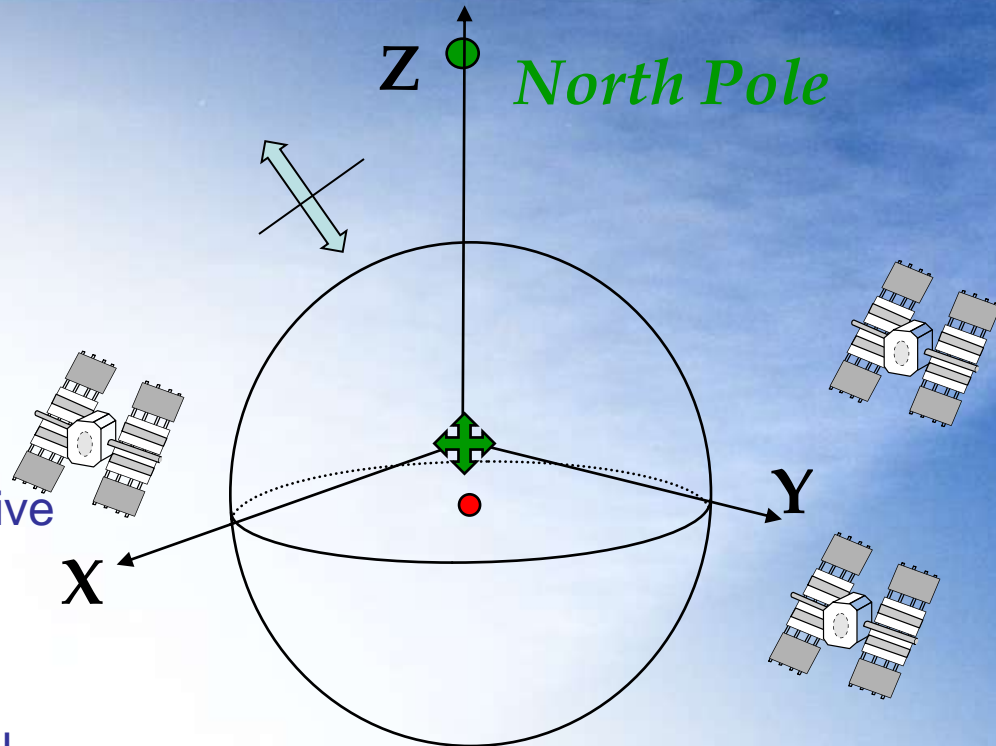
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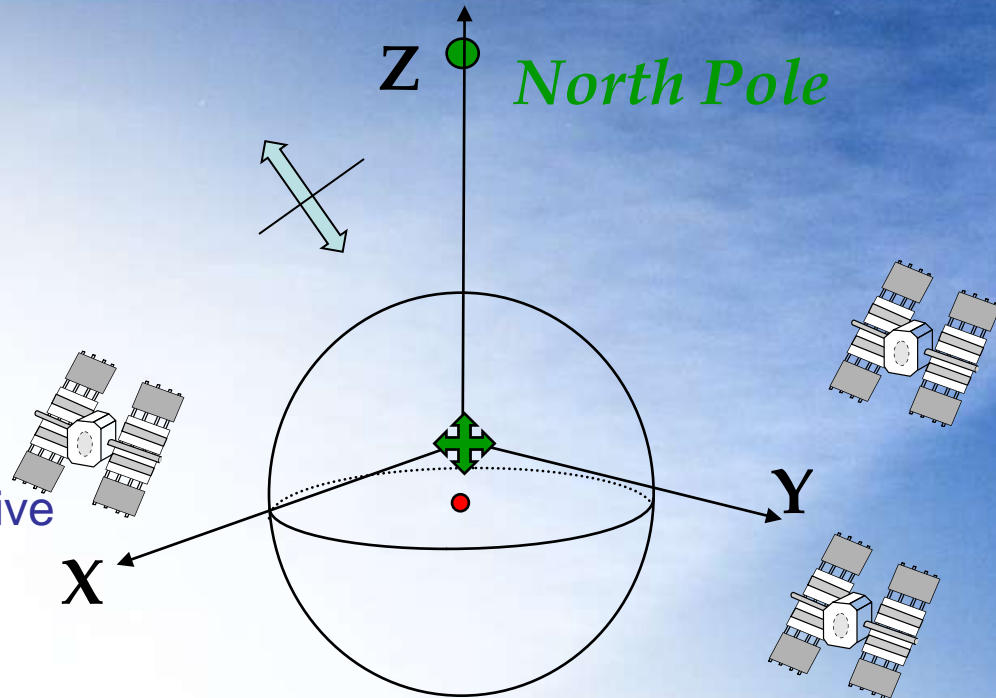
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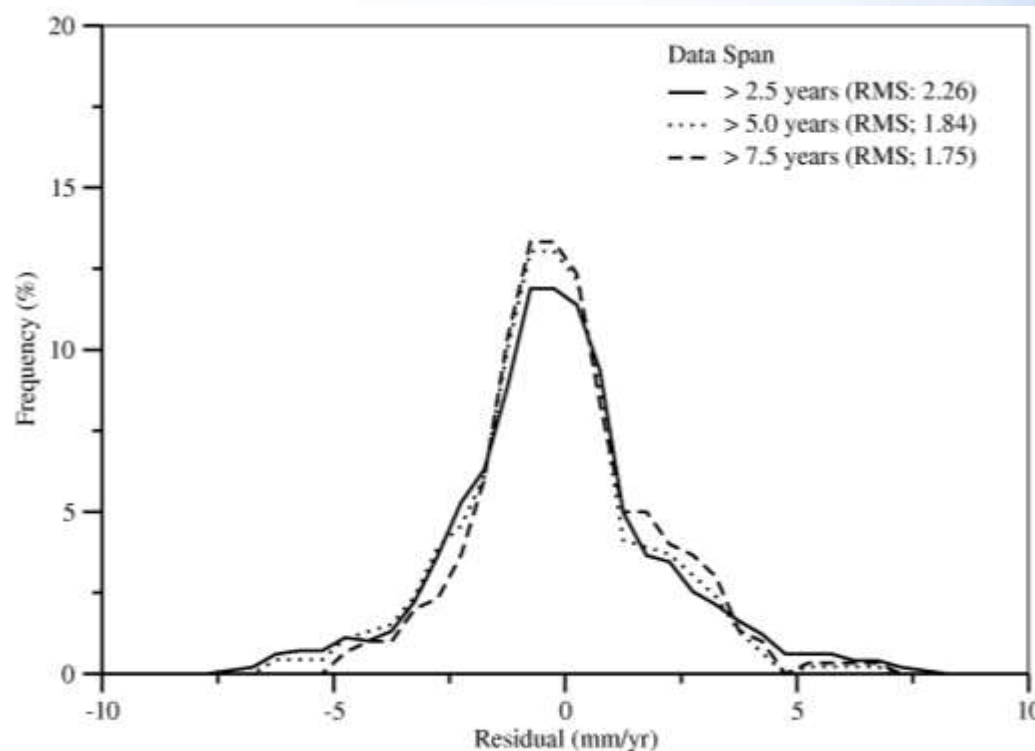
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# GPS Outstanding issues (ii)

## Systematic errors in GPS-derived velocities from historic solutions

- Solutions from different analysis centres produce velocities with scatter 1-2+ mm/yr in vertical
- Biased against “truth” values by equivalent of up to 1-2mm/yr
- Together they suggest historic (cumulative) GPS solutions are not reliable
- Recent advances offer an accuracy step-change



# Recent progress

Major progress now possible- e.g., Wöppelmann et al. [2009] computed GPS corrections for 28 long running gauges and showed important improvements in inter-station and inter-region agreements compared to GIA corrections

Land Motion Correction at the Tide Gauges	No Correction	GIA-Corrected ICE5G (VM2)	GPS-Corrected ULR 3
Scatter of the individual rates of sea-level change	2.05 mm/yr	1.49 mm/yr	1.15 mm/yr (0.98)
Scatter of the regional rates of sea-level change	1.37 mm/yr	0.98 mm/yr	0.62 mm/yr (0.60)

Wöppelmann et al, GRL, 2009

Main result: **Mean GSL of  $1.55 \pm 0.19$  mm/yr**, at the lower end of other recent work giving  $\sim 1.7$  mm/yr [Church and White, 2006; Holgate, 2007]

But, new and/or improved GPS observation models have been made since then -> different GSL estimate

## Newcastle group leading 2 sets of GPS analysis for TG

1. Smaller prototype study (presented here) & analogous to Wöppelmann
2. The large NERC-funded COAST project (initial results very soon)

# GPS Data Analysis Strategy

Consistent reprocessing of all data from 1995.0->2008.0 (every 2<sup>nd</sup> day)

- GAMIT/GLOBK 10.34
- Estimate station coordinates on a daily basis, satellite orbits, tropospheric zenith delays
- Multiple global networks, including TG sites
- Cluster of ~130 processors, 1-2 weeks

State-of-the-art GPS observation-level models

- Tropospheric mapping function: VMF1
- Hydrostatic zenith delay: local met or ECMWF
- Higher order ionospheric corrections
- Absolute ground and satellite antenna phase centre offsets (satellite specific) and variations (satellite block specific)
- (first 3 not included by Wöppelmann et al, 2009)

} Major effect on velocity **noise**

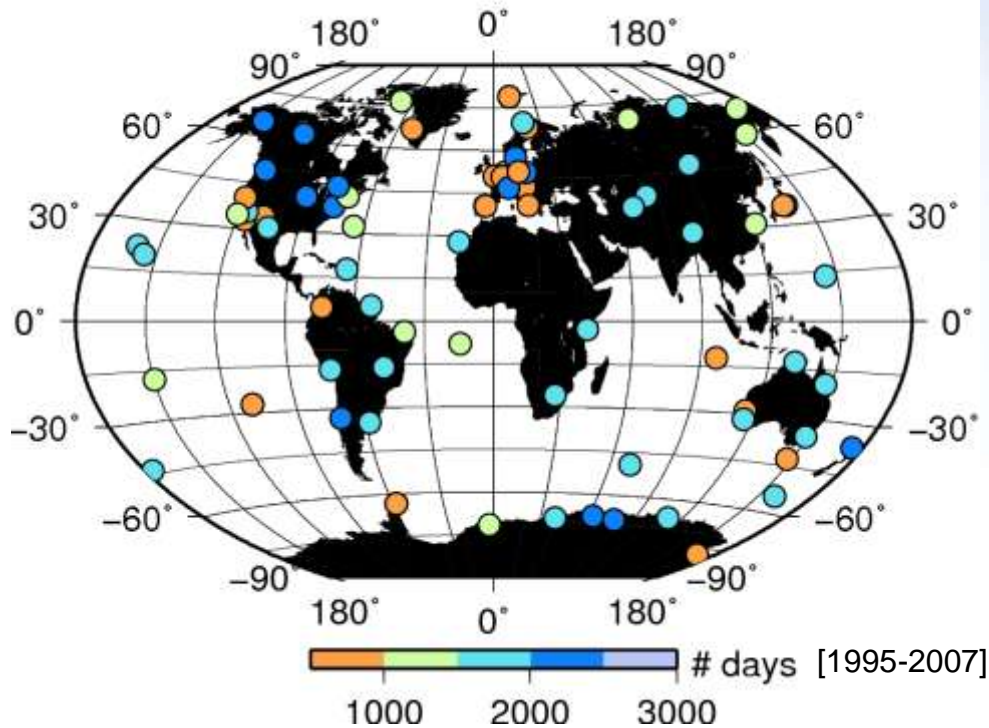
} Major effect on velocity **bias**

# GPS Network

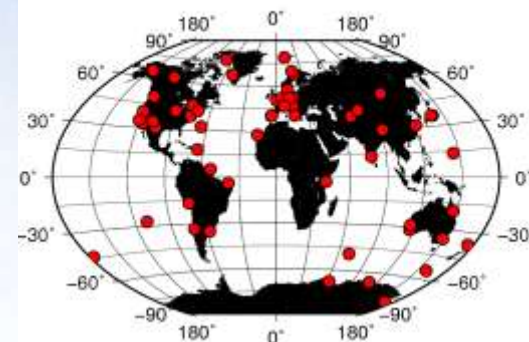
## Stable global network

- Long-running, good hemispheric balance, 86 sites in total, up to 60 on any one day

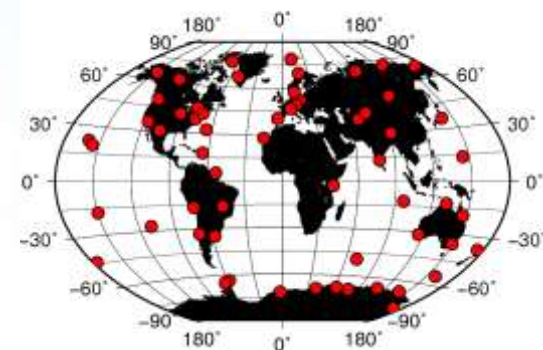
### GPS global network



### GPS global network 1996



### GPS global network 2007

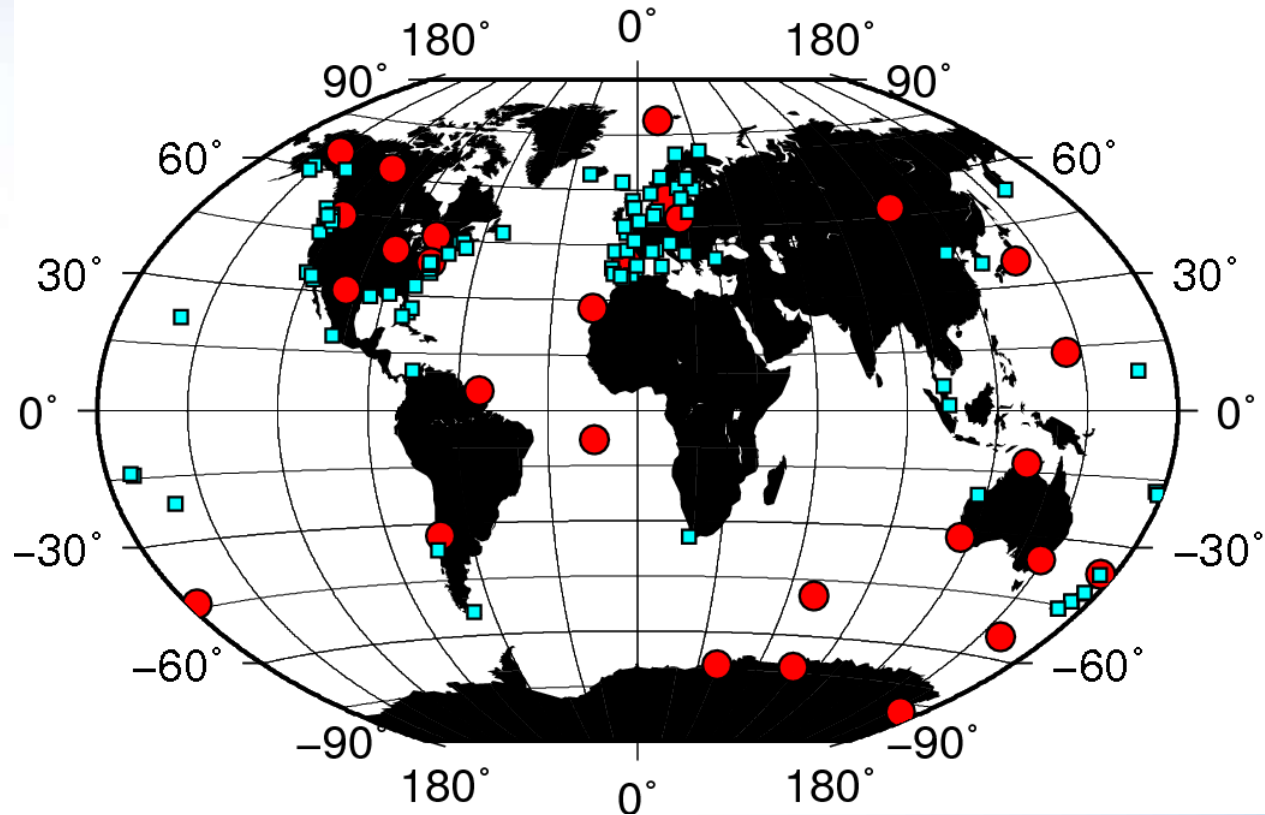


# GPS Network

## Supplementary Network(s)

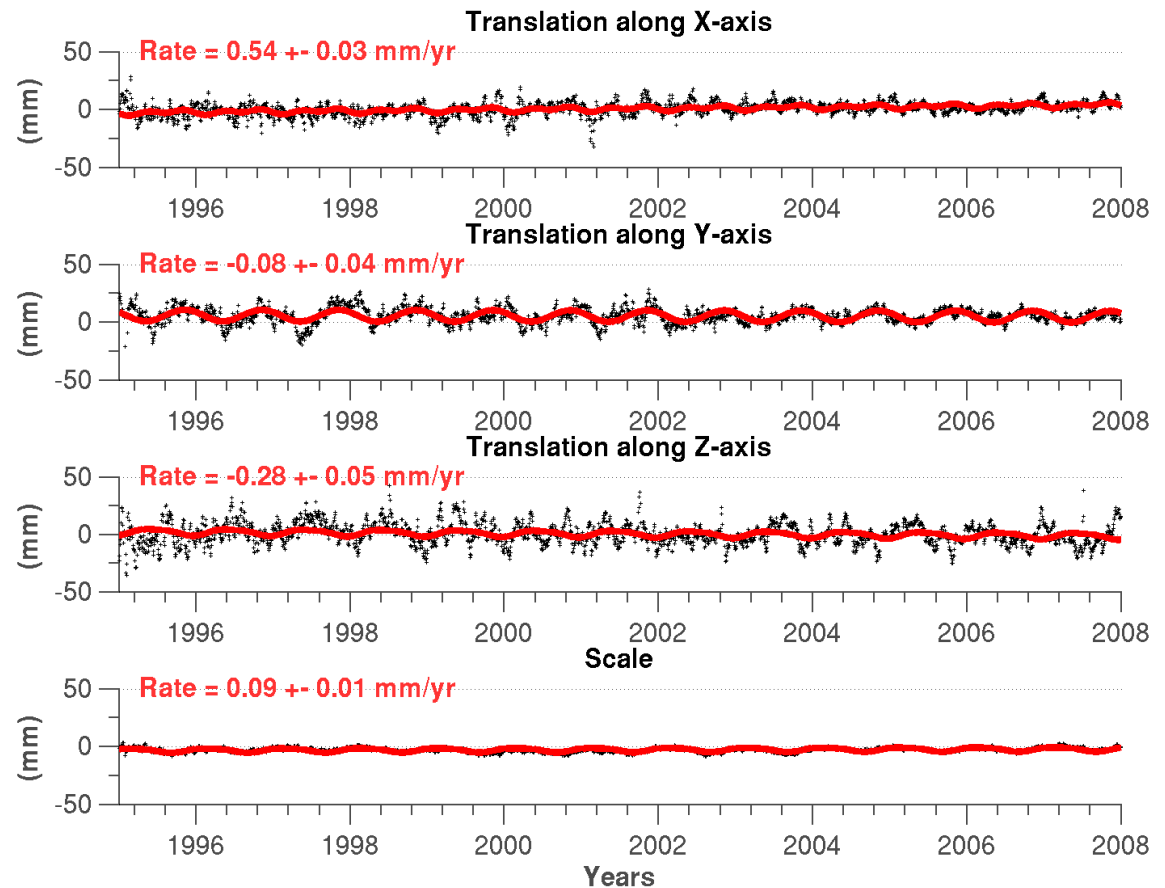
- Fix estimated satellite orbits
- Process remaining sites (96) in 1-4 additional global networks (cyan)
- Sub-networks chosen by maximising network volume
- 28 globally distributed sites added to each network to tie networks together (red)

## Supplementary network



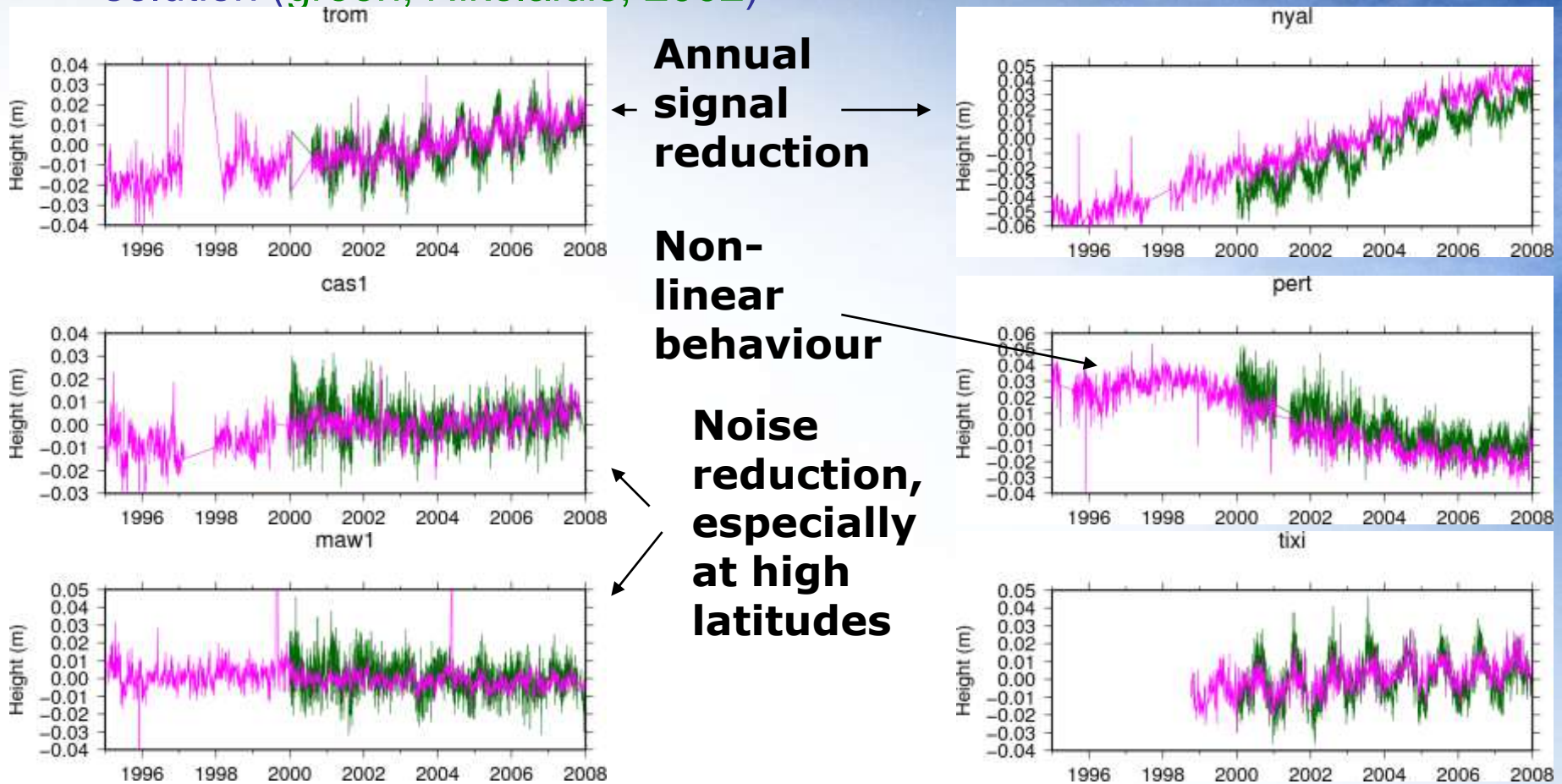
# Reference Frame Stability

Compare our GPS-derived reference frame to ITRF2005 based on independent data (geocentre=SLR; scale=VLBI)



# GPS Height Time Series

Comparison of our reprocessed (magenta) vs early SIO reprocessing solution (green, Nikolaidis, 2002)



# Results

Solutions presented here from same 28 gauges reported on by Woppelmann et al.

TG criteria: generally 60+ years (Miami Beach one exception), 85% of data available [effectively the, e.g., Douglas, 2001 criteria]

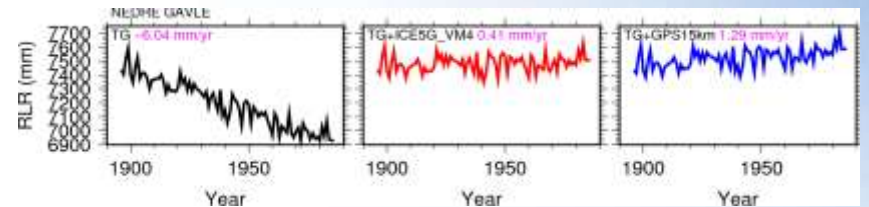
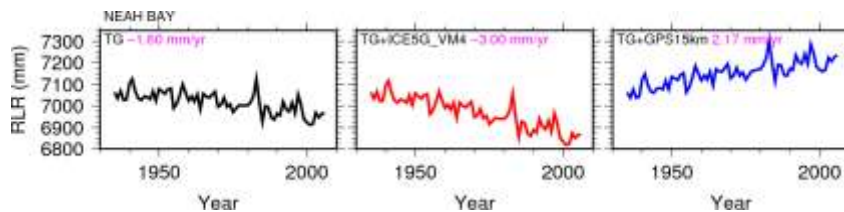
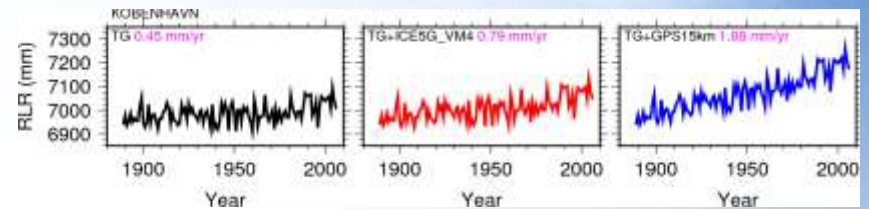
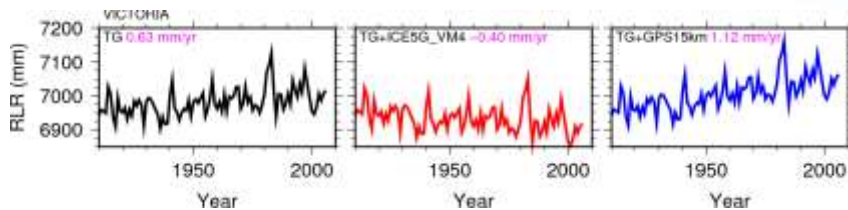
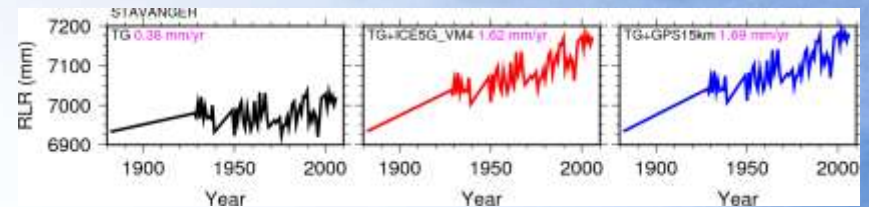
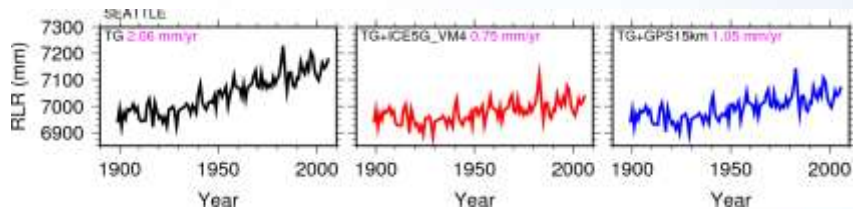
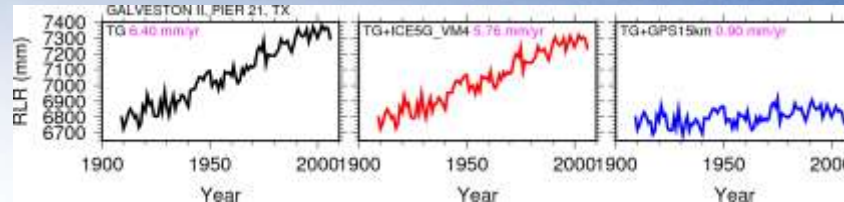
Solutions using VLM correction

1. GPS < 15km from TG
2. GPS < 200km from TG, weighted mean [available for ~50% of TGs]

Groups of Stations	Region	TG mm/yr	TG+GPS15km mm/yr	TG+GPS200km mm/yr	TG+ICE5G_VM2 mm/yr
ABERDEEN I	<i>North Sea+English Channel</i>	0.95	1.84	1.76	1.90
ABERDEEN II	<i>North Sea+English Channel</i>	0.58	1.47	1.39	1.53
NEWLYN	<i>North Sea+English Channel</i>	1.74	1.49	1.49	1.42
BREST	<i>North Sea+English Channel</i>	1.02	1.02	1.02	0.74
<b>Mean</b>		<b>1.07</b>	<b>1.46</b>	<b>1.42</b>	<b>1.40</b>
CASCAIS	<i>Atlantic</i>	1.26	1.35	1.06	1.26
LAGOS	<i>Atlantic</i>	1.44	0.99	1.24	1.39
<b>Mean</b>		<b>1.35</b>	<b>1.17</b>	<b>1.15</b>	<b>1.33</b>
MARSEILLE	<i>Mediterranean</i>	1.22	0.61	1.77	1.19
GENOVA	<i>Mediterranean</i>	1.26		1.90	1.33
<b>Mean</b>		<b>1.24</b>	<b>0.61</b>	<b>1.84</b>	<b>1.26</b>
AUCKLAND II	<i>New Zealand</i>	1.26	0.29	0.20	1.55
LYTTELTON II	<i>New Zealand</i>	2.35		1.95	2.69
<b>Mean</b>		<b>1.81</b>	<b>0.29</b>	<b>1.08</b>	<b>2.12</b>
HONOLULU	<i>Pacific</i>	1.50	0.86	0.86	1.66
<b>Mean</b>		<b>1.50</b>	<b>0.86</b>	<b>0.86</b>	<b>1.66</b>
LA JOLLA	<i>SW North America</i>	2.10	2.58	2.25	1.60
LOS ANGELES	<i>SW North America</i>	0.88	0.44	1.03	0.37
<b>Mean</b>		<b>1.49</b>	<b>1.51</b>	<b>1.64</b>	<b>0.99</b>
CHARLESTON I	<i>SE North America</i>	3.17	1.40	1.40	2.34
FERNANDINA	<i>SE North America</i>	2.00			1.34
GALVESTON II	<i>SE North America</i>	6.40	0.90	0.90	5.76
MIAMI BEACH	<i>SE North America</i>	2.29	1.35	1.24	1.89
KEY WEST	<i>SE North America</i>	2.22	1.24	1.24	1.82
<b>Mean</b>		<b>3.22</b>	<b>1.22</b>	<b>1.20</b>	<b>2.63</b>
EASTPORT	<i>NE North America</i>	2.05	4.04	2.23	1.67
NEWPORT	<i>NE North America</i>	2.57	2.57	2.24	0.81
HALIFAX	<i>NE North America</i>	3.21	3.10	3.10	2.04
ANNAPOLIS	<i>NE North America</i>	3.52	1.32	1.92	2.35
SOLOMON'S ISLAND	<i>NE North America</i>	3.48	0.15	1.89	2.39
<b>Mean</b>		<b>2.97</b>	<b>2.24</b>	<b>2.28</b>	<b>1.85</b>
STAVANGER	<i>Northern Europe</i>	0.38	1.69	1.69	1.62
KOBENHAVN	<i>Northern Europe</i>	0.45	1.88	2.58	0.79
NEDRE GAVLE	<i>Northern Europe</i>	-6.04	1.29	1.29	0.41
<b>Mean</b>		<b>-1.74</b>	<b>1.62</b>	<b>1.85</b>	<b>0.94</b>
VICTORIA	<i>NW North America</i>	0.63	1.12	1.32	-0.40
NEAH BAY	<i>NW North America</i>	-1.60	2.17	-0.91	-3.00
SEATTLE	<i>NW North America</i>	2.06	1.05	2.36	0.75
<b>Mean</b>		<b>0.36</b>	<b>1.45</b>	<b>0.92</b>	<b>-0.88</b>
<b>Average of Group Values</b>		<b>1.33</b>	<b>1.24</b>	<b>1.42</b>	<b>1.33</b>
<b>Std Deviation of Group Value</b>		<b>1.37</b>	<b>0.55</b>	<b>0.46</b>	<b>0.94</b>
<b>Average of All Values</b>		<b>1.53</b>	<b>1.47</b>	<b>1.51</b>	<b>1.42</b>
<b>Std Deviation of All Values</b>		<b>2.01</b>	<b>0.87</b>	<b>0.77</b>	<b>1.35</b>

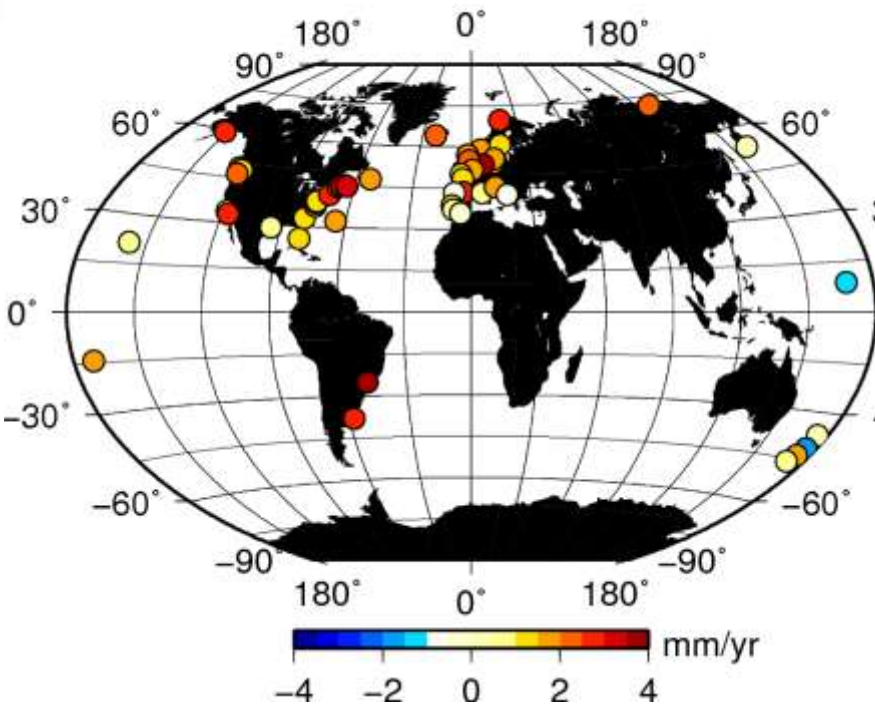
mm/yr

# Corrected TG Time Series

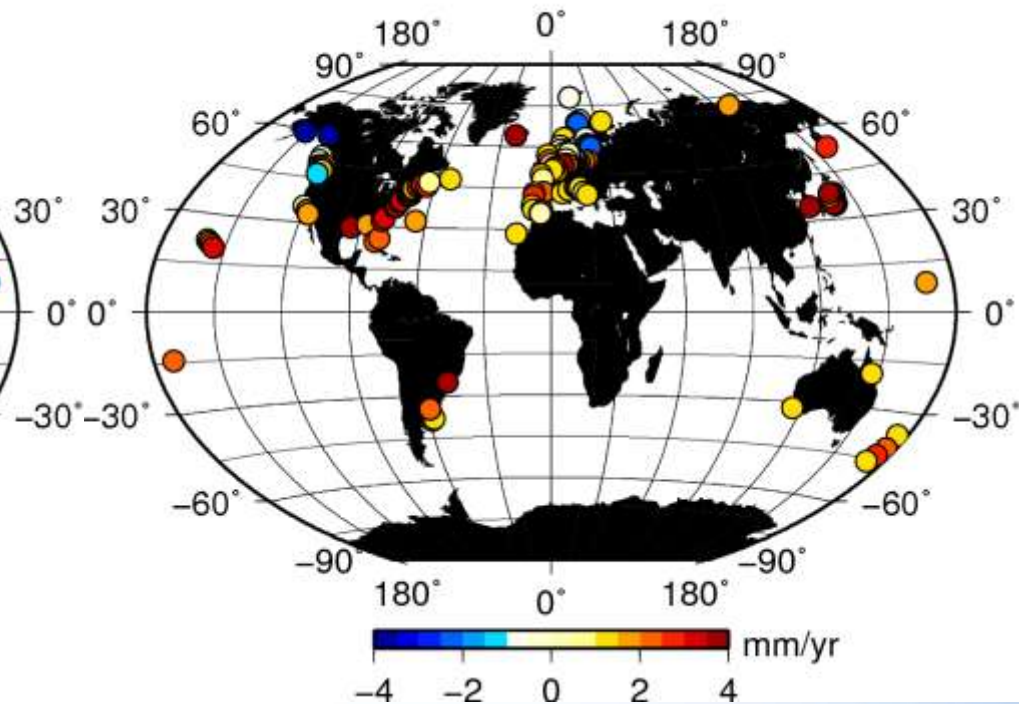


# GSL Trends Spatially

TG+GPS15km

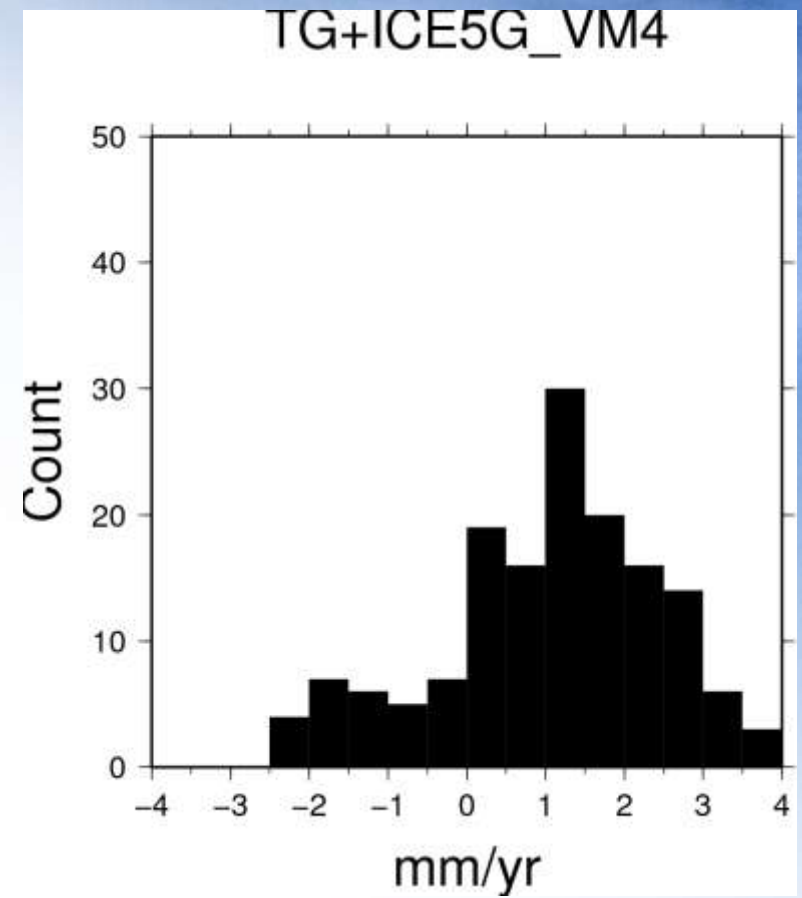
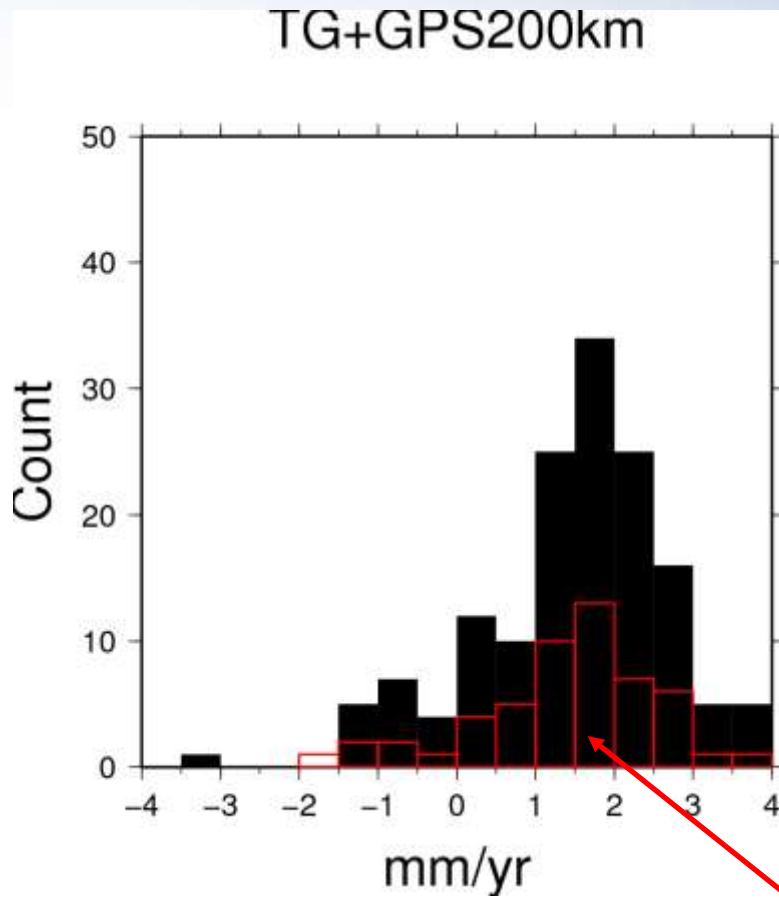


TG+ICE5G\_VM4



# GSL Consistency

Using sites in the GPS200km solution only, where available



**TG+15km**

# Comparison with Prior Work

**1.31 mm yr<sup>-1</sup> (26-28 gauges), Std. Dev. of all gauges 0.82 mm yr<sup>-1</sup>**

Peltier [2001]: **1.84** mm yr<sup>-1</sup> (27 gauges; GIA correction)

Church et al. [2005]: **1.7** ± 0.3 mm yr<sup>-1</sup> (and an acceleration of sea-level rise of 0.013 ± 0.006 mm yr<sup>-2</sup>); ~1000 gauges, GIA correction

Woppelmann et al. [2007]:

- **1.28** mm yr<sup>-1</sup> (28 gauges), Std. Dev. of all gauges 1.34 mm yr<sup>-1</sup>
- GPS in ITRF2000

Woppelmann et al. [2009] :

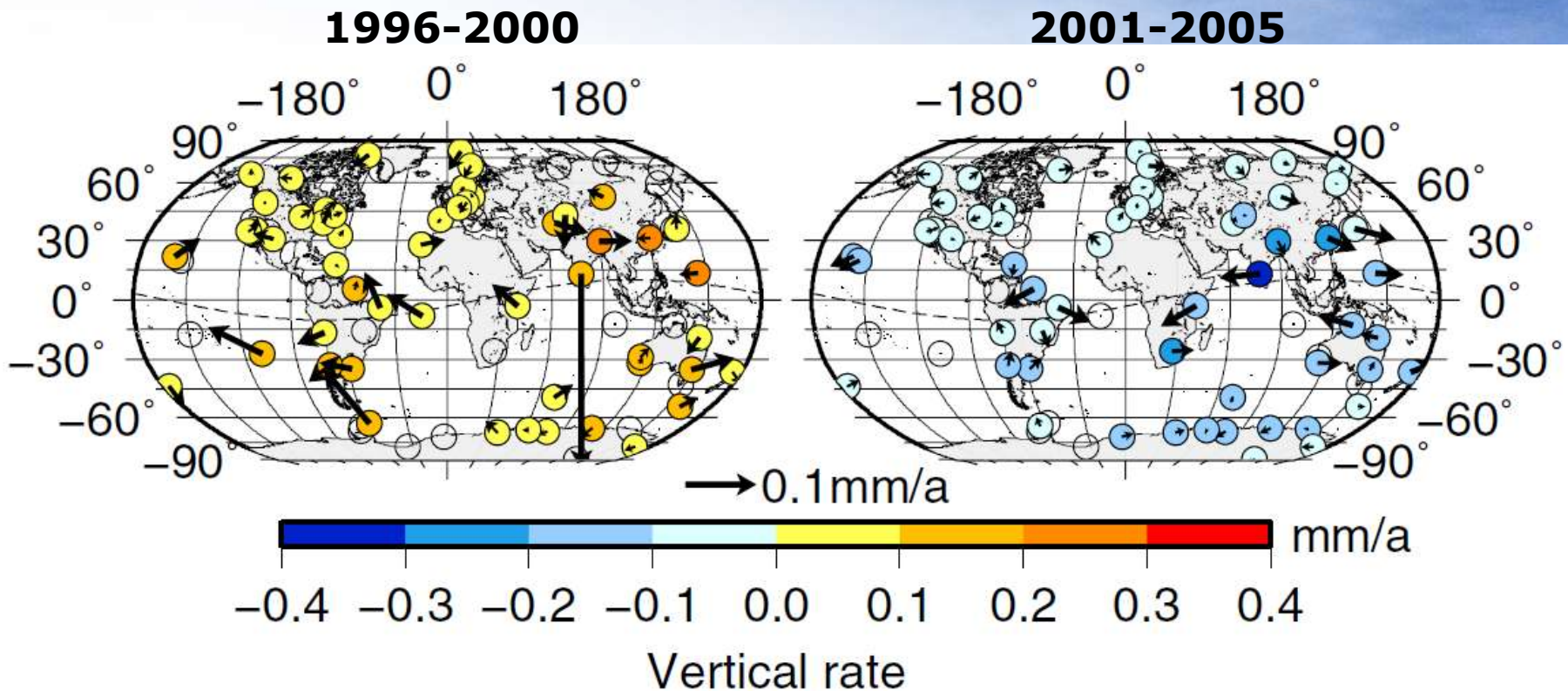
- **1.55** mm yr<sup>-1</sup> (28 gauges), Std. Dev. of all gauges 1.15 mm yr<sup>-1</sup>

Reason for differences with Wöppelmann et al [2009]

- We used slightly longer RLR records, but not exactly the same TGs
- Differences in site distribution, # sites (225 cf. 181), data spans, tropospheric models
- Higher order ionospheric models (not used by Wöppelmann) has an important effect [Petrie et al, accepted]

# Higher order ionospheric effects

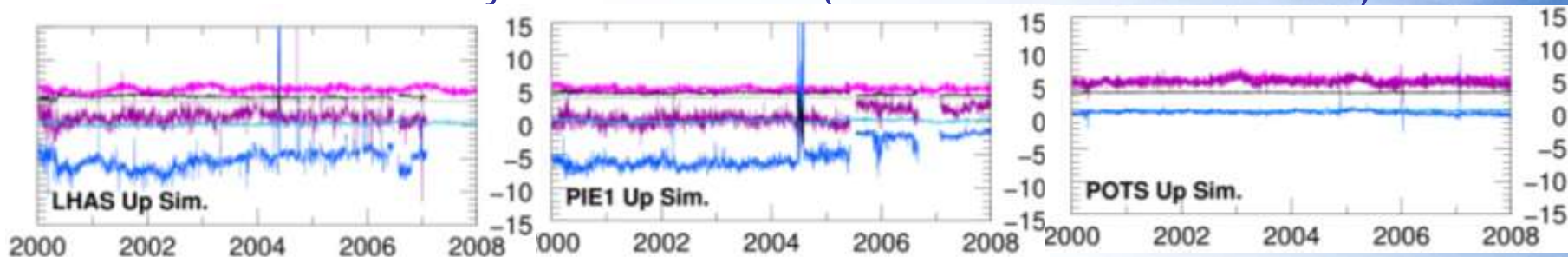
Most GPS@ TG started ~2000, so will report systematically too low  
GSL, by ~0.1-0.2mm/yr



# Ongoing challenges

Site stability: King and Williams, JGR, [2009] reported that of the 10 long running short baselines they studied, 4 showed vertical rates  $>\pm 0.25\text{mm/yr}$ .

Site multipath: King and Watson, JGR, [in press] reported that GPS signal reflections from nearby surfaces could result in site velocity biases of several mm/yr at some sites (and add substantial noise)



# Conclusions

Globally reprocessed GPS solutions using state-of-the-art models are now sufficiently accurate to correct for VLM at TGs

- Internally stable, reduced noise
- Reference frame accuracy appears improved in ITRF2005

Our [very] preliminary solution with 27 gauges shows

- ~1.3-1.4 mm/yr (using ITRF2005), ~0.3-0.5 mm/yr lower than previous estimates [expect these values to change with further analysis]
- Standard deviation of all gauges reduced by 50%
  - 0.82 mm/yr cf 1.15 mm/yr (Woppelmann)

Residual issues

- GPS still exhibit substantial site-specific variability [e.g., multipath]
- Some sites exhibit non-linearities that may be small enough to not be seen in the TG records [e.g., Perth]

Next at Newcastle:

- present-2012: further reanalysis using 500+ GPS sites