Monitoring the vertical motion of the UK using GPS and absolute gravity

Richard Bingley[1], Dionne Hansen[1],
Norman Teferle[1,2] and Simon Williams[3]

[1]IESSG, University of Nottingham; [2]FSTC, University of Luxembourg;
[3]National Oceanography Centre

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Symposium on Vertical Rates from GNSS
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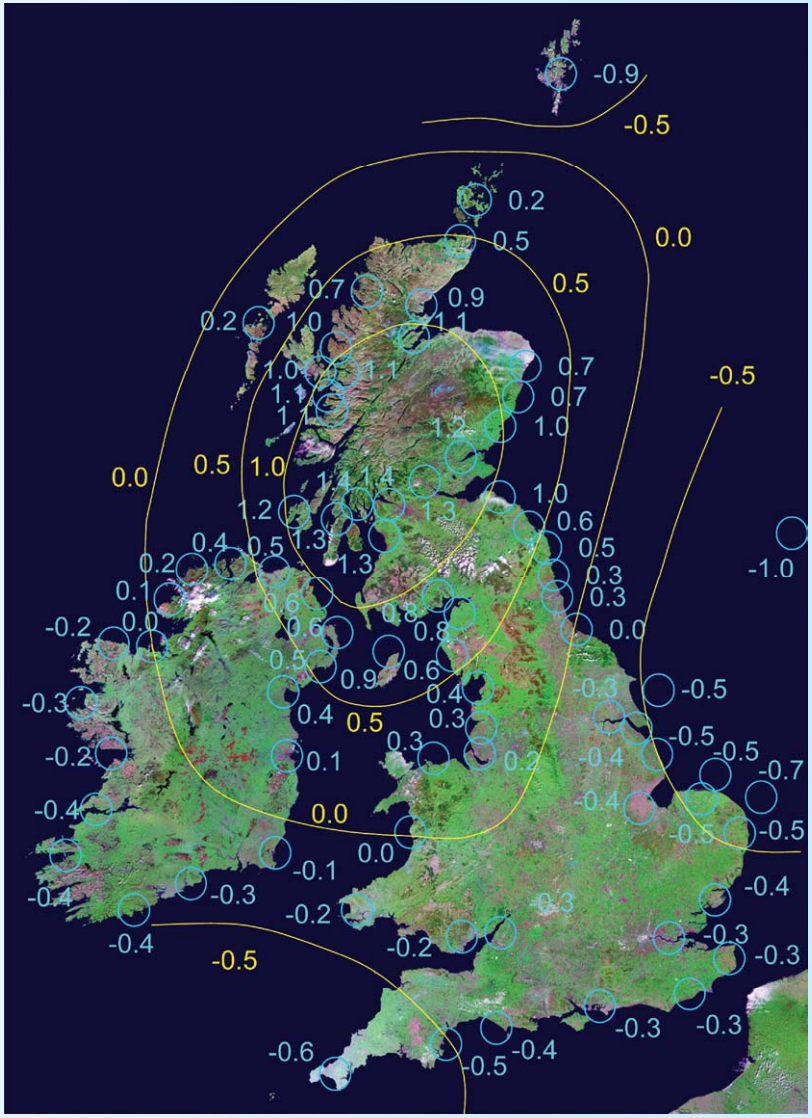
Overview

- Holocene land level changes in the British Isles
- Current vertical motions of the UK
  - Continuous GPS (CGPS)
  - Absolute gravity (AG)
- Comparison of AG-aligned CGPS and Holocene land level changes
- Changes in sea level (decoupled from changes in land level) around the coast of Great Britain
  - CGPS and AG at Tide Gauges (TGs)
- Conclusions

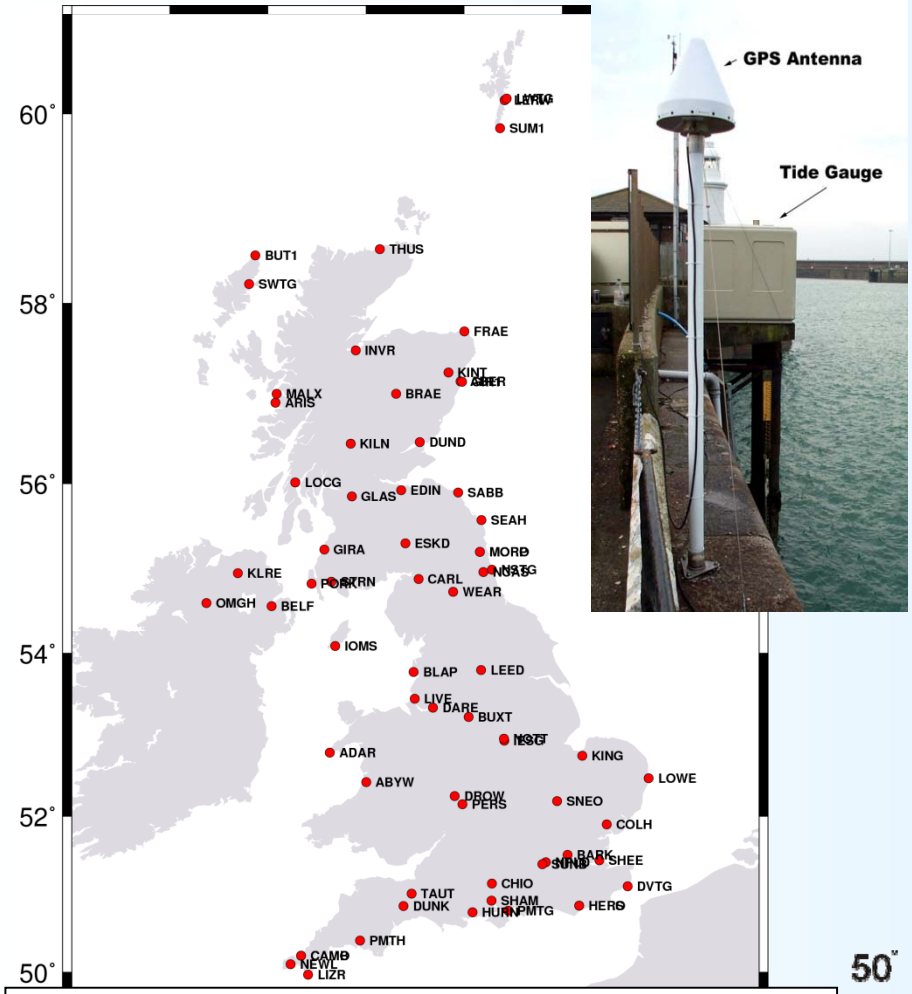
Relative land-level changes for British Isles from late Holocene relative sea-level data

- General pattern
  - Subsidence on Shetland
  - Uplift in Scotland, Northern Ireland, North of Ireland and North of England
  - Subsidence in Southern Ireland, Wales, Central England and South of England
- Based on geological evidence:
  - >1250 radiocarbon dated samples constrain relative sea levels over past 16,000 years with little information for last 4,000 years
  - Shennan and Horton (2002) then Shennan et al. (2006) then Shennan et al. (2009)
  - Dominant signal from glacial isostatic adjustment (GIA)



Shennan et al. (2009): Rates in mm/yr

UK CGPS and AG Stations



87 CGPS stations processed (mostly with >6 years of data within BIGF) including 10 CGPS@TG stations

Absolute Gravity (AG) measurement as a **complementary** (and **independent**) technique to CGPS for monitoring vertical motion

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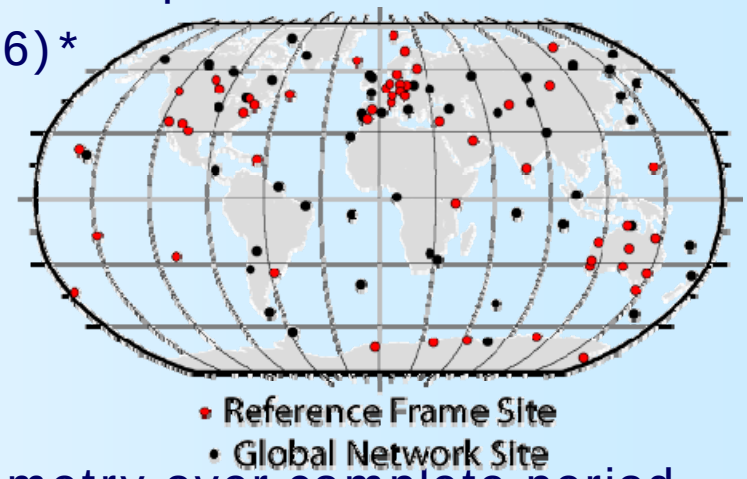
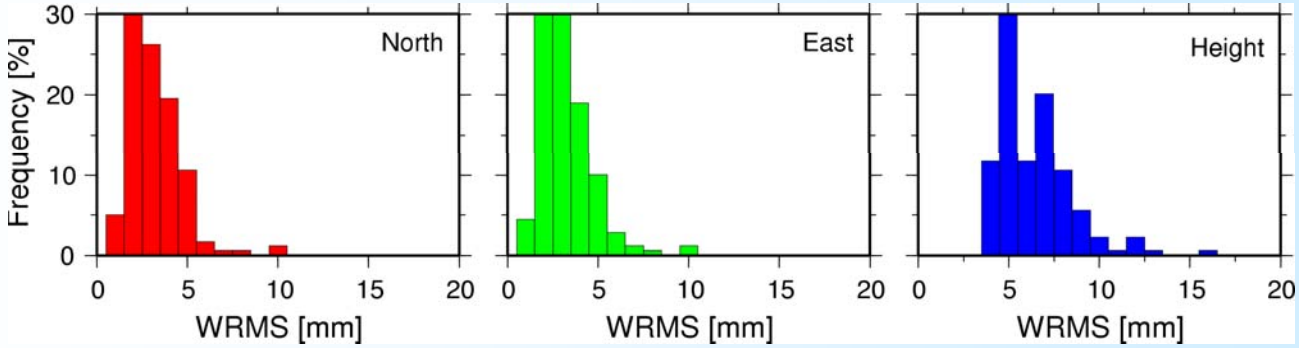
Re-processing of the UK CGPS Data Set

- In-house modified* Bernese GPS Software v5.0 (Dach et al., 2007) at the University of Nottingham
  - Models for absolute satellite and receiver antenna phase centres
  - Global Mapping Functions (Böhm et al., 2006)*
- Consistent GPS satellite orbit and Earth Orientation Parameter products used:
  - CO1: 1997:001 to 2007:365
  - COD: 2008:001 to 2010:010
- Reference frame implementation
  - 104 global IGS sites with homogeneous geometry over complete period
  - 67 global IGS sites to align daily position estimates to ITRF2005 (using a no-net translation and no-net scale minimum constraints approach)





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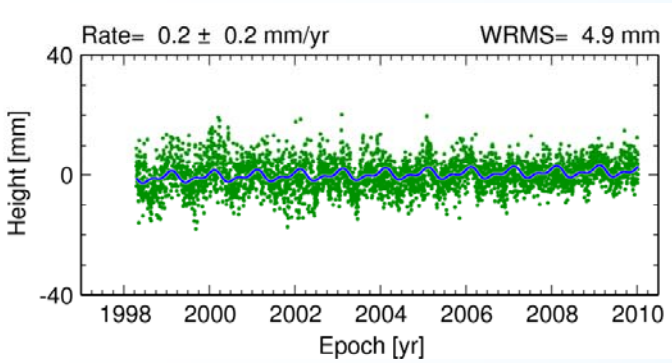
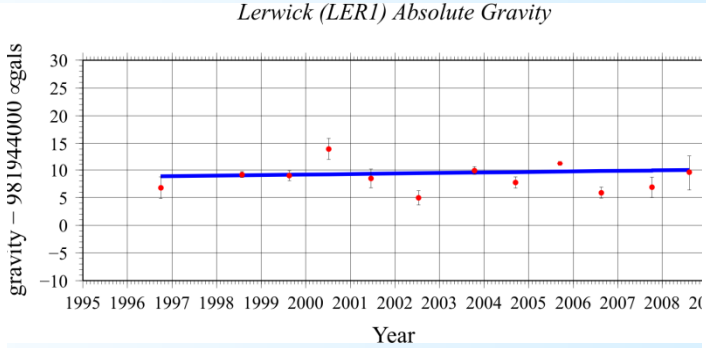
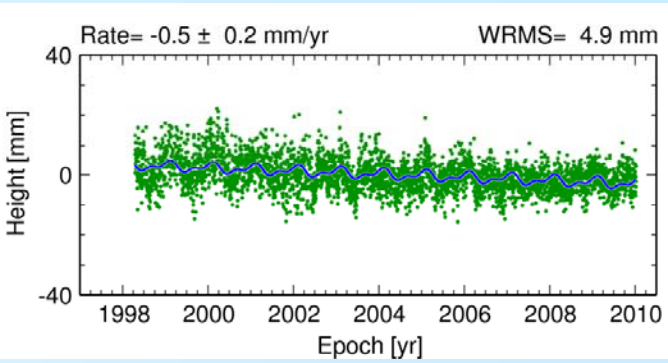
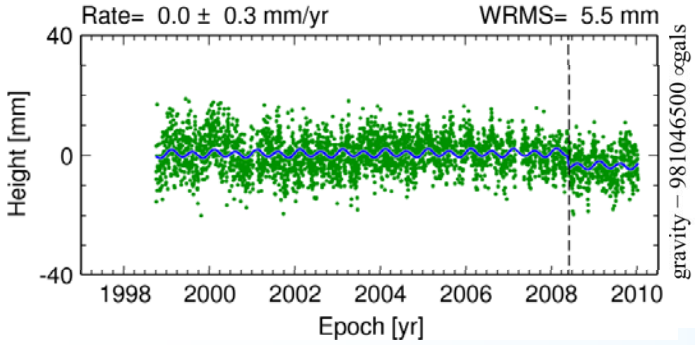
CGPS aligned to AG at LERW and NEWL

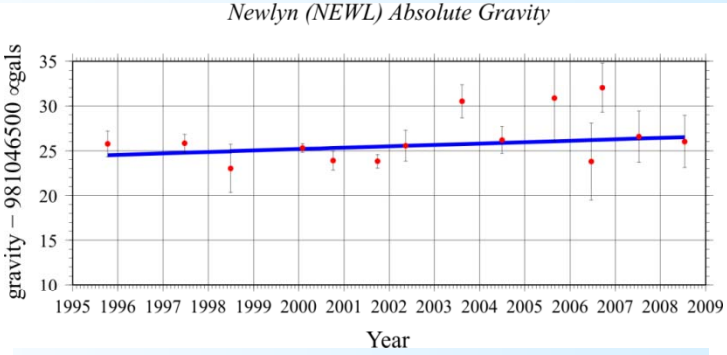


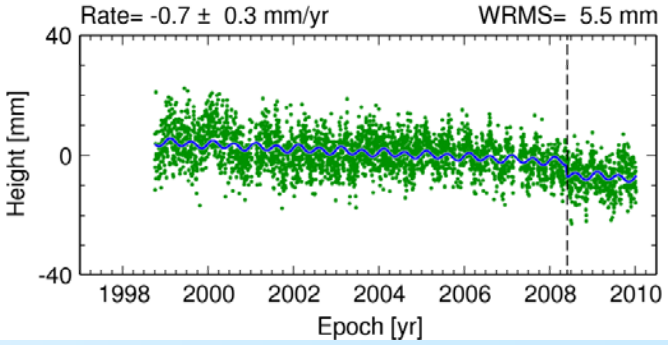




CGPS rate for LERW = +0.19 ± 0.25 mm/yr
AG rate for LERW = -0.48 ± 1.00 mm/yr
CGPS rate for NEWL = +0.04 ± 0.29 mm/yr
AG rate for NEWL = -0.78 ± 0.90 mm/yr
AG-alignment = -0.73 ± 0.08 mm/yr







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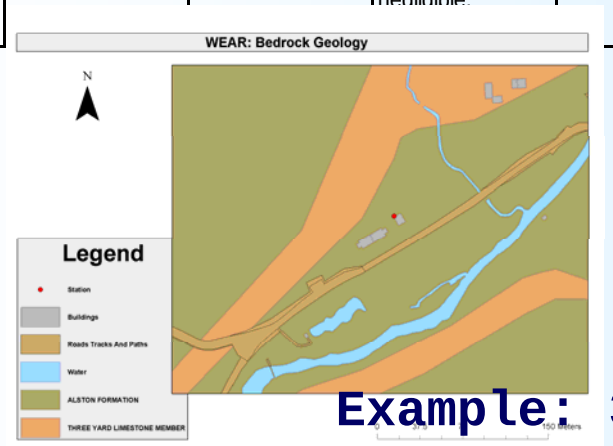
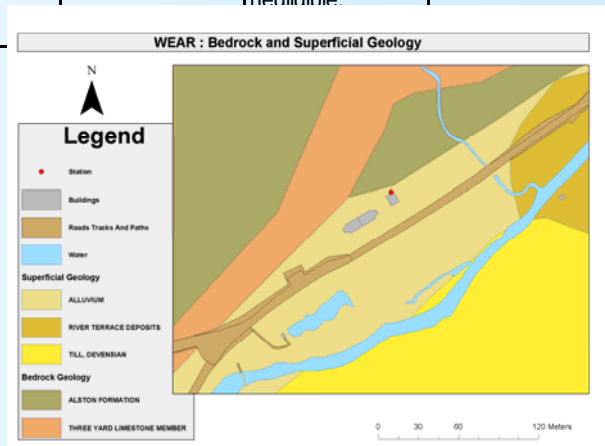
Station selection for Geodetic Map: Classification by Site Suitability Rating

Geological / engineering setting of CGPS station	Connected directly to solid rock.	Connected to solid rock via a monolith, concrete block or concrete plinth.	Connected to solid rock via a building or structure which has no structural deformation.	Connected to solid rock via a building or structure which may have structural deformation.	Not connected to solid rock, but on a monolith, concrete block or concrete plinth that is on top of consolidated sediments.	Not connected to solid rock, but on a building or structure: that is on top of, or piled into, consolidated sediments; and which has no structural deformation.	Not connected to solid rock, but on a building or structure: that is on top of, or piled into, consolidated sediments; and which may have structural deformation.	Not connected to solid rock, but on a monolith, concrete block or concrete plinth that is on top of unconsolidated sediments.	Not connected to solid rock, but on a building or structure: that is on top of, or piled into, unconsolidated sediments; and which has no structural deformation.	Not connected to solid rock, but on a building or structure: that is on top of, or piled into, unconsolidated sediments; and which may have structural deformation.
Current vertical motion contributors	Glacio-isostatic adjustment	Glacio-isostatic adjustment	Glacio-isostatic adjustment	Glacio-isostatic adjustment	Glacio-isostatic adjustment Natural compaction	Glacio-isostatic adjustment Natural compaction	Glacio-isostatic adjustment Natural compaction	Glacio-isostatic adjustment Natural compaction Man-made compaction	Glacio-isostatic adjustment Natural compaction Man-made compaction	Glacio-isostatic adjustment Natural compaction Man-made compaction Structural deformation
				Structural deformation			Structural deformation			
Site Suitability Rating (SSR)	**1A**	**1B**	**1C**	**2C**	**3B**	**3C**	**4C**	**5B**	**5C**	**6C**
What is being measured?	VCM	VCM	VCM	VCM, if structural deformation can be assumed to be negligible.	VLM	VLM	VLM, if structural deformation can be assumed to be negligible.	VSM	VSM	VSM



Example: 3C



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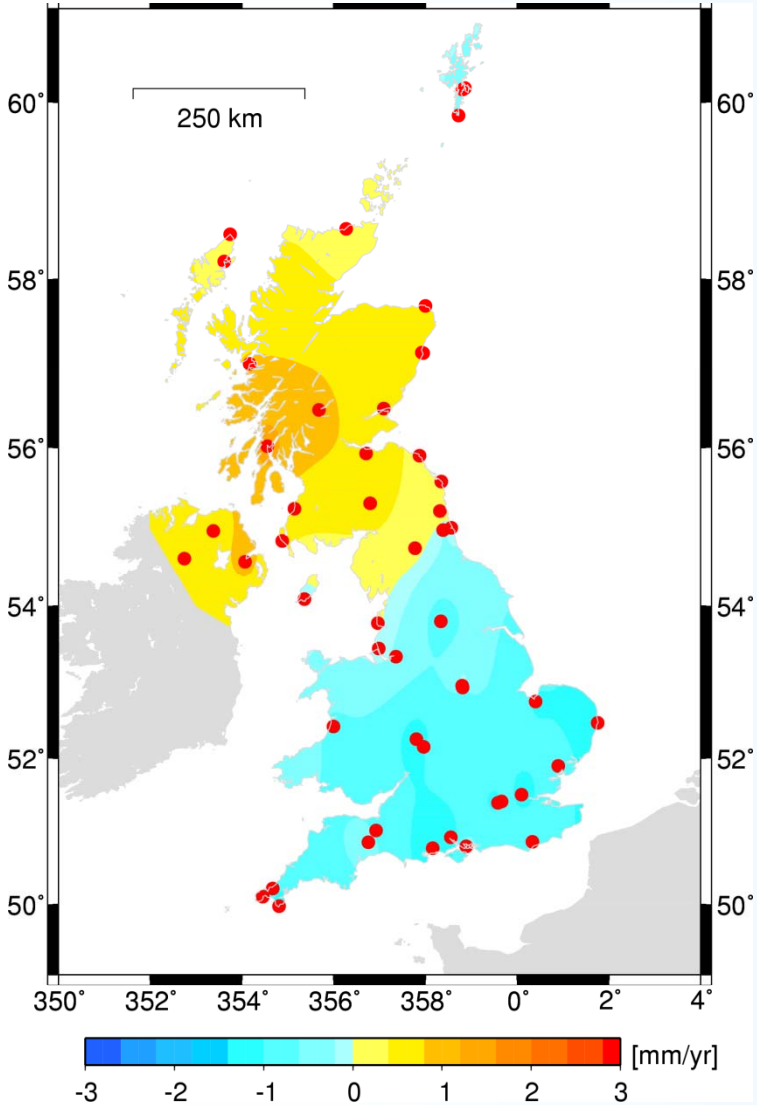
Comparison of current vertical motions and Holocene land level changes

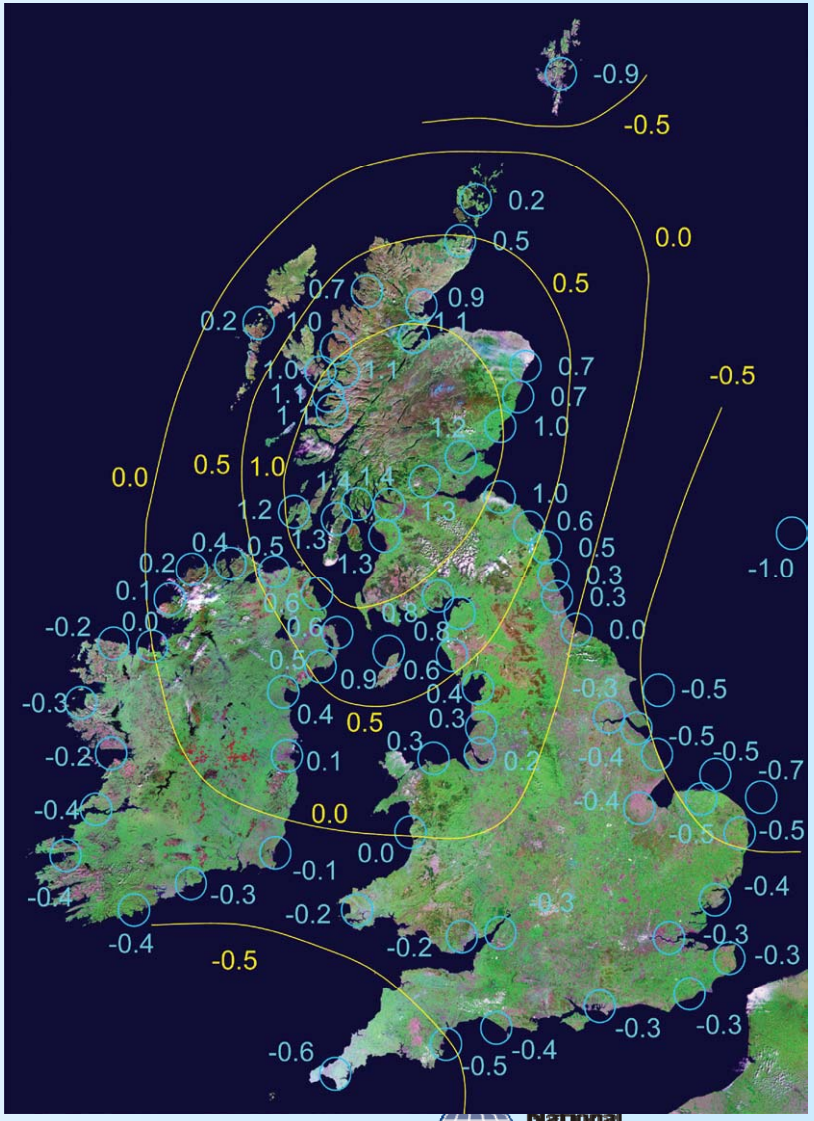


AG-aligned CGPS

Comparison at 34 'coastal' locations

Differences (geodetic minus geological) in mm/yr:

MEAN = -0.31
STDEV = 0.46
MAX = +0.59
MIN = -1.14



Shennan et al. (2009)

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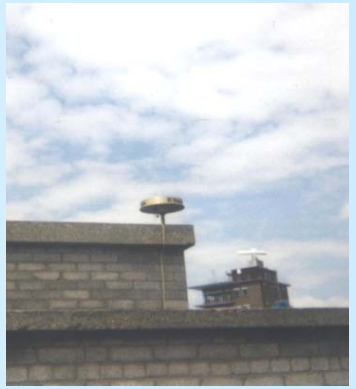
UK CGPS@TG Stations

Lerwick

Aberdeen

North Shields

Lowestoft



Sheerness

Dover

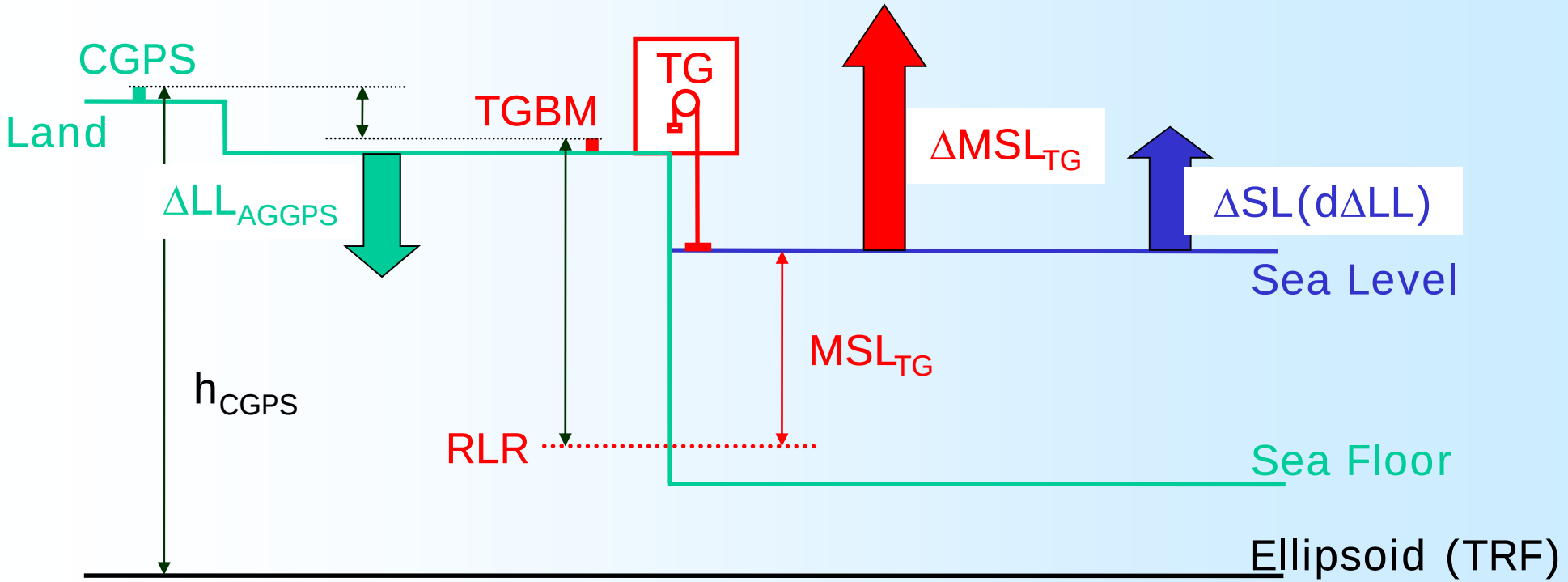
Portsmouth

Newlyn

Liverpool

Stornoway

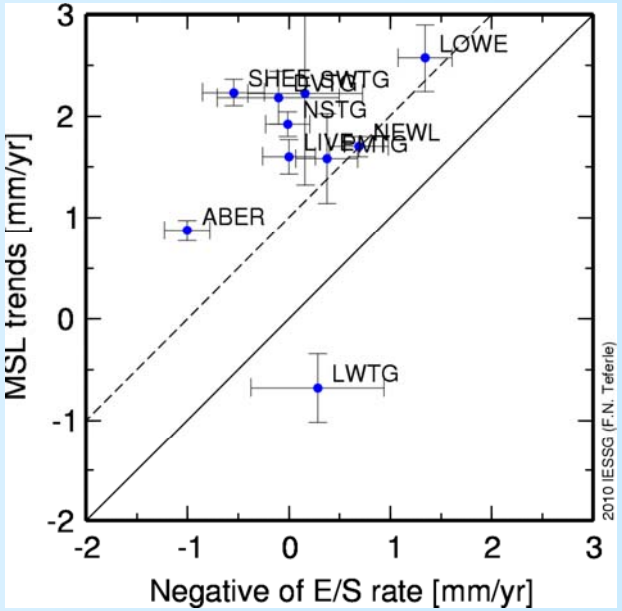
Changes in sea level (decoupled from changes in land level)



$$\Delta SL(d\Delta LL) = \underbrace{\Delta MSL_{TG}}_{\text{PSMSL}} + \underbrace{\Delta LL_{AGGPS}}_{\text{AG-aligned CGPS}}$$

Changes in sea level (decoupled from changes in land level) around the coast of Great Britain

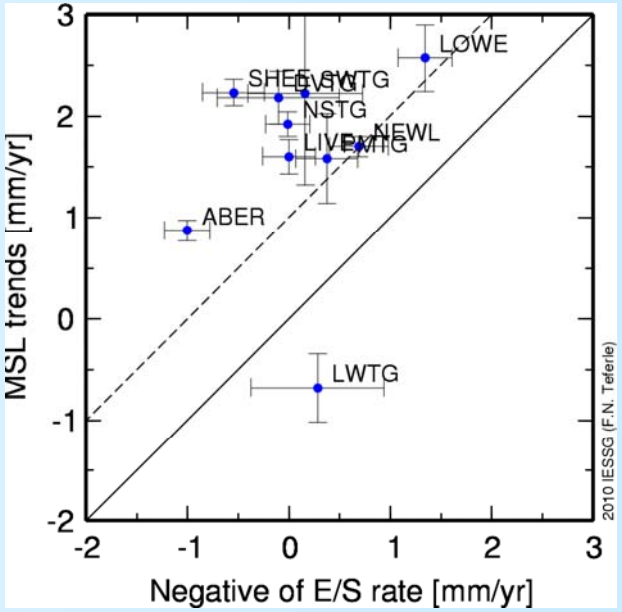
	Station name	ID	ΔMSL_{TG}	ΔLL_{AGGPS} (mm/yr)	$\Delta SL(d\Delta LL)$	
*	Lerwick	LWTG	-0.68	-0.28	-0.96	*
	Stornoway	SWTG	+2.22	-0.16	+2.06	
	Aberdeen	ABER	+0.87	+1.00	+1.87	
	N. Shields	NSTG	+1.92	+0.01	+1.93	
	Liverpool	LIVE	+1.60	0.00	+1.60	
	Lowestoft	LOWE	+2.57	-1.34	+1.23	
?	Sheerness	SHEE	+2.23	+0.55	+2.78	?
~	Dover	DVTG	+2.18	+0.10	+2.28	~
	Portsmouth	PMTG	+1.58	-0.37	+1.21	
	Newlyn	NEWL	+1.70	-0.69	+1.01	



- Notes:
  - MSL estimates taken from Woodworth et al. (2009)
  - * = latest estimates suggesting spurious tide gauge record, as LERW CGPS on solid rock has a similar (-0.54 mm/yr) change in land level to LWTG
  - ? = latest estimates suggesting recent local scale movements
  - ~ = latest estimates compromised by monument replacement

Changes in sea level (decoupled from changes in land level) around the coast of Great Britain

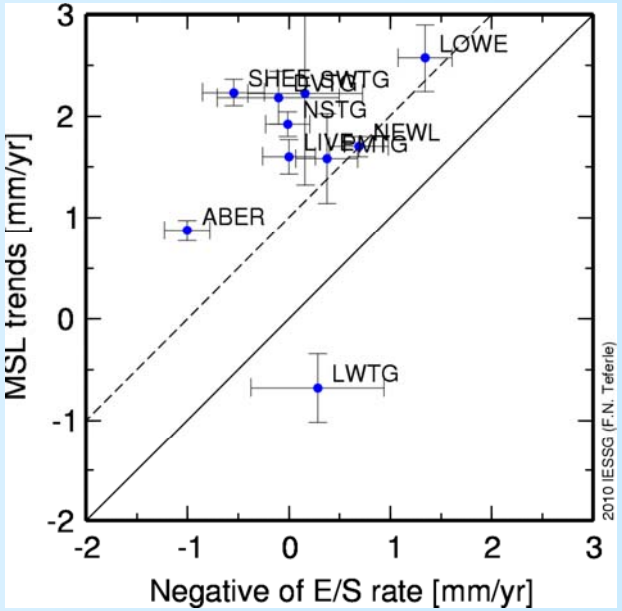
	Station name	ID	Latitude (degrees)	ΔSL(dΔLL) (mm/yr)
*	Lerwick	LWTG		
	Stornoway	SWTG	58.20 N	+2.06
	Aberdeen	ABER	57.15 N	+1.87
	N. Shields	NSTG	55.00 N	+1.93
	Liverpool	LIVE	53.45 N	+1.60
	Lowestoft	LOWE	52.47 N	+1.23
?	Sheerness	SHEE		
~	Dover	DVTG		
	Portsmouth	PMTG	50.80 N	+1.21
	Newlyn	NEWL	50.10 N	+1.01



- Notes:
  - Mean (excl. LWTG, SHEE and DVTG) of +1.56mm/yr
  - Possible increase with latitude?

Changes in sea level (decoupled from changes in land level) around the coast of Great Britain

	Station name	ID	MSL time series		ΔSL(dΔLL) (mm/yr)
*	Lerwick	LWTG			
	Stornoway	SWTG	18	1977-2006	+2.06
	Aberdeen	ABER	96	1901-2006	+1.87
	N. Shields	NSTG	84	1901-2006	+1.93
	Liverpool	LIVE	69	1901-2004	+1.60
	Lowestoft	LOWE	44	1956-2006	+1.23
?	Sheerness	SHEE			
~	Dover	DVTG			
	Portsmouth	PMTG	34	1962-2005	+1.21
	Newlyn	NEWL	89	1916-2006	+1.01



- Notes:
  - Mean (excl. LWTG, SHEE and DVTG) of +1.56mm/yr
  - Possible increase with latitude?
  - No apparent correlation with MSL time series length

Conclusions

- We have derived a geodetic map of current vertical motions in the UK:
  - based on 2 AG stations and 51 CGPS stations, and a recent reprocessing that included data for the period from 1997 to 2010;
  - which has similar (but not identical) characteristics to a ‘geological map’ of Holocene land level changes;
  - which is available for use in any assessments of future changes in relative sea level for flood and coastal risk management in the UK

Conclusions

- We have derived new estimates for the changes in sea level (decoupled from changes in land level):
  - based on 2 AG stations and 7/10 CGPS@TG stations, and a recent reprocessing that included data for the period from 1997 to 2010;
  - with an average for around the coast of Great Britain of +1.56mm/yr, when combining the current vertical motions from CGPS and AG, and changes in sea level for the past few decades/past century;
  - with an average for around the coast of Great Britain which is similar but slightly larger than the +1.4mm/yr obtained by Woodworth et al. (2009) using vertical motions based on geological evidence;
  - showing a possible correlation between changes in sea level and latitude over the 8 degrees extent in latitude of the British Isles

Additional Slides

ABER	13231M001	Aberdeen TG	3C
DVTG	13283M002	Dover TG	2C
LIVE	13233M001	Liverpool TG	3C
LOWE	13232M001	Lowestoft TG	3C
LWTG	19159M001	Lerwick TG	1C
NEWL	13273M001	Newlyn TG	1C
NSTG	13216M001	North Shields TG	3C
PMTG	13289M003	Portsmouth TG	3C
SHEE	13236M001	Sheerness TG	4C
SWTG	19158M001	Stornoway TG	1C

Averaged Sea Level Changes from Geodetic Techniques

Station	ID	TG*	GPS1	GPS2	GPS3	GPS4	TG + GPS1	TG + GPS2	TG + GPS3	TG + GPS4
Lerwick	LERW		-0.65 ± 0.54	-0.57 ± 0.28			-1.33	-1.25		
Lerwick	LWTG^	-0.68 ± 0.34		*-0.44 ± 0.76*				*-1.12*		
Aberdeen**	ABER	0.87 ± 0.10	0.00 ± 0.32	0.99 ± 0.27	0.67 ± 0.22	0.89	1.92	1.86	1.54	1.76
N. Shields	NSTG	1.92 ± 0.12	-0.26 ± 0.52	-0.03 ± 0.25			1.66	1.89		
Liverpool**	LIVE	1.60 ± 0.17	0.51 ± 0.43	-0.09 ± 0.26			2.11	1.51		
Lowestoft	LOWE	2.57 ± 0.33	-1.17 ± 0.40	-1.38 ± 0.31			1.40	1.19		
Sheerness	SHEE	2.23 ± 0.13	-0.77 ± 0.67	0.36 ± 0.32			1.46	2.59		
	SH03^^			-0.79 ± 0.66				1.44		
Portsmouth	PMTG	1.58 ± 0.44	-1.15 ± 0.46	-0.35 ± 0.34			0.43	1.23		
Newlyn	NEWL	1.70 ± 0.10	-0.43 ± 0.70	-0.66 ± 0.33	-0.21 ± 0.27	-0.25	1.27	1.04	1.49	1.45
Mean (long TG records):							1.68	1.62	1.52	1.61
S.D.:							0.34	0.35	0.04	0.22

*TG trend Woodworth et al. (2009)
**Composite record
^LWTG not used further as time series still short
^^SHEE but only with data up to 2003
GPS1: AG-aligned PPPGTF (Teferle et al, 2009)
GPS2: AG-aligned CGPS (this study)
GPS3: Wöppelmann et al. (2009)
GPS4: King et al. (2009)

Units in mm/yr
Uncertainties are 1-sigma

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Averaged Sea Level Changes from Geology and GIA Models

Station	Geology Site	TG*	GEO1	GEO2	GEO3	GIA1	GIA2	GIA3	GIA4	TG + GEO1	TG + GEO2	TG + GEO3	TG + GIA1	TG + GIA2	TG + GIA3	TG + GIA4
Lerwick	Shetland	-0.68 ± 0.34		-0.87		-0.47	-0.12	-0.27	-1.07		-1.55		-1.15	-0.80	-0.95	-1.75
Aberdeen**	Aberdeen	0.87 ± 0.10	0.69	0.73	0.54	0.60	0.54	0.01	0.32	1.56	1.60	1.41	1.47	1.41	0.88	1.19
N. Shields	NE Engl./Tees	1.92 ± 0.12	0.00	0.26	-0.16	0.00	-0.03	-0.13	-0.24	1.92	2.18	1.76	1.92	1.89	1.79	1.68
Liverpool**	Mersey	1.60 ± 0.17	-0.21	0.23	-0.38	0.37	-0.14	-0.14	-0.24	1.39	1.83	1.22	1.97	1.46	1.46	1.36
Lowestoft	East Anglia	2.57 ± 0.33	-0.61	-0.51	-0.79	-0.35	-0.50	-0.51	-0.86	1.96	2.06	1.78	2.22	2.07	2.06	1.71
Sheerness	Thames	2.23 ± 0.13	-0.85	-0.37	-1.04	-0.24	-0.35	-0.44	-0.73	1.38	1.86	1.19	1.99	1.88	1.79	1.50
Portsmouth	Hampshire	1.58 ± 0.44	-0.58	-0.30	-0.76	-0.14	-0.38	-0.39	-0.73	1.00	1.28	0.82	1.44	1.20	1.19	0.85
Newlyn	Cornwall	1.70 ± 0.10	-1.12	-0.63		-0.25	-0.88	-0.53	-1.16	0.58	1.07		1.45	0.82	1.17	0.54
									Mean (long TG records):	1.38	1.68	1.44	1.74	1.44	1.40	1.23
									S.D.:	0.49	0.39	0.24	0.28	0.44	0.40	0.44

*TG trend Woodworth et al. (2009)

**Composite record

GEO1: Shennan and Horton (2002); Shennan et al. (2006)

GEO2: Shennan et al. (2009)

GEO3: Gehrels (2009), in press

GIA1: ICE-4G (VM2) as per Peltier (2001)

GIA2: ICE-5G (VM2) (Peltier, 2004)

GIA3: Stocchi (2009), personal communication

GIA4: Bradley et al. (2009)

Units in mm/yr

Uncertainties are 1-sigma

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