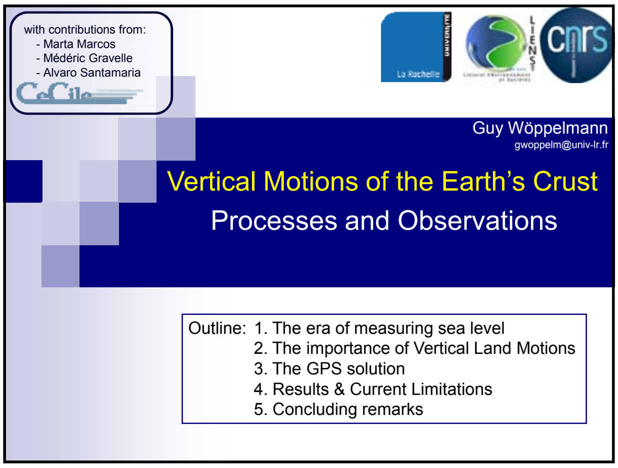
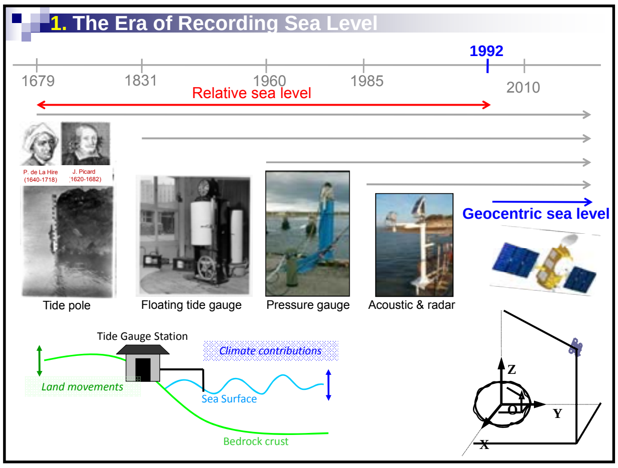
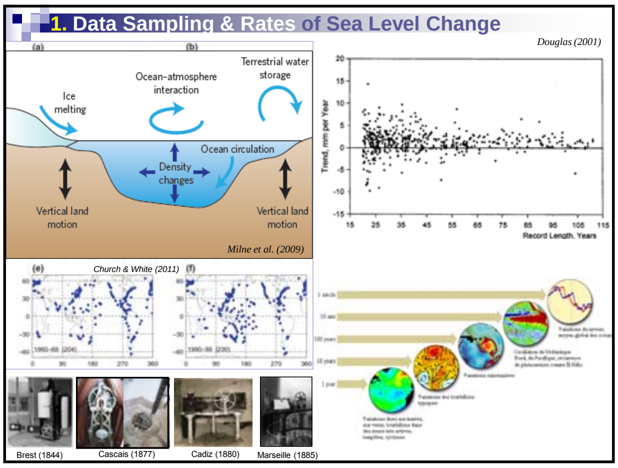
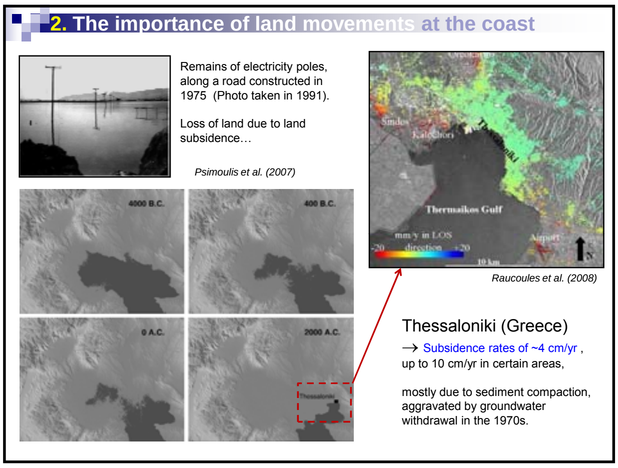
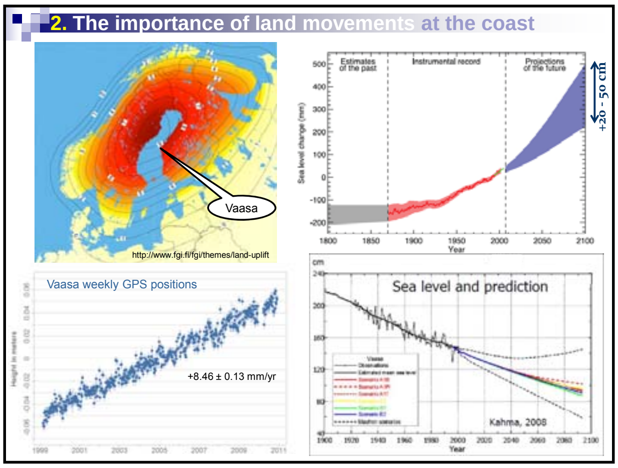
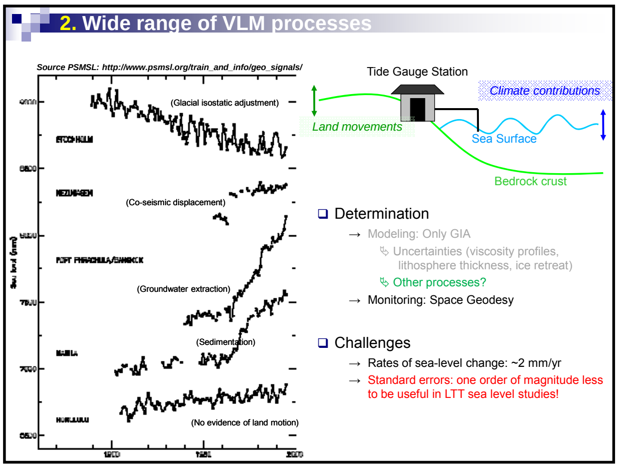

with contributions from:
- Marta Marcos
- Médéric Gravelle
- Alvaro Santamaria
Guy Wöppelmann
gwoppelm@univ-lr.fr
Vertical Motions of the Earth's Crust
Processes and Observations
Outline: 1. The era of measuring sea level
2. The importance of Vertical Land Motions
3. The GPS solution
4. Results & Current Limitations
5. Concluding remarks

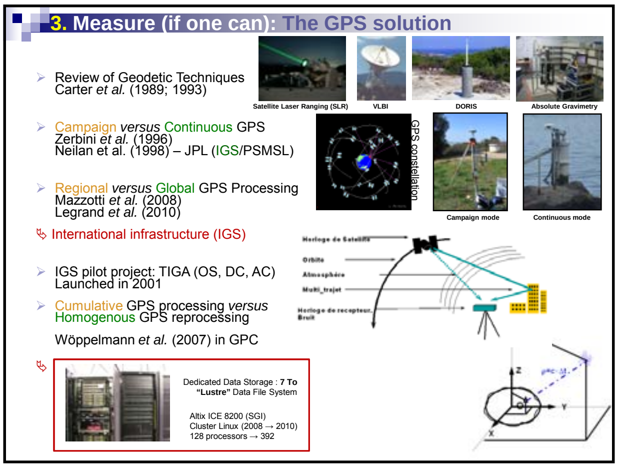

1. The Era of Recording Sea Level
1679
1831
1960
1985
1992
2010
Relative sea level
Geocentric sea level
Tide pole
Floating tide gauge
Pressure gauge
Acoustic & radar
Tide Gauge Station
Climate contributions
Land movements
Sea Surface
Bedrock crust
Z
Y
X

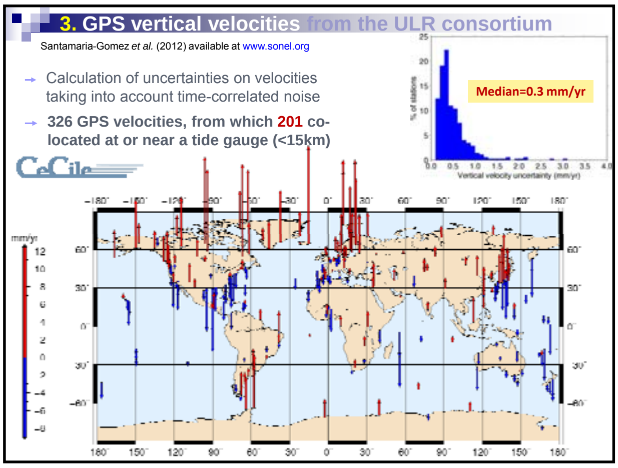

1. Data Sampling & Rates of Sea Level Change
Douglas (2001)
Ice melting
Ocean-atmosphere interaction
Terrestrial water storage
Ocean circulation
Density changes
Vertical land motion
Vertical land motion
Milne et al. (2009)
Record Length, Years
Church & White (2011)
Brest (1844)
Cascais (1877)
Cadiz (1880)
Marseille (1885)

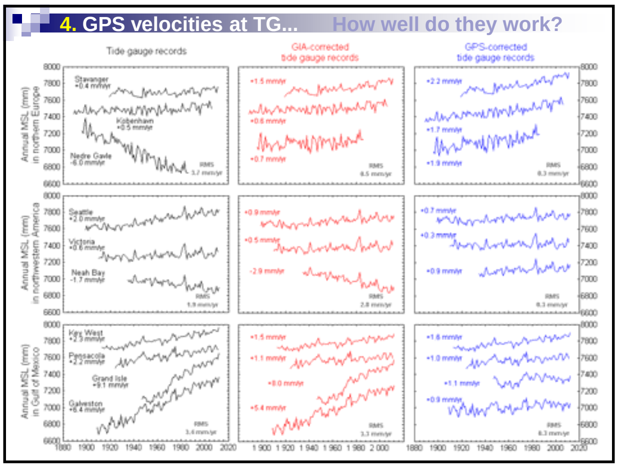

2. The importance of land movements at the coast
Remains of electricity poles, along a road constructed in 1975 (Photo taken in 1991).
Loss of land due to land subsidence…
Psimoulis et al. (2007)
4000 B.C.
400 B.C.
0 A.C.
2000 A.C.
Thermaikos Gulf
Raucoules et al. (2008)
Thessaloniki (Greece)
→ Subsidence rates of ~4 cm/yr, up to 10 cm/yr in certain areas,
mostly due to sediment compaction, aggravated by groundwater withdrawal in the 1970s.

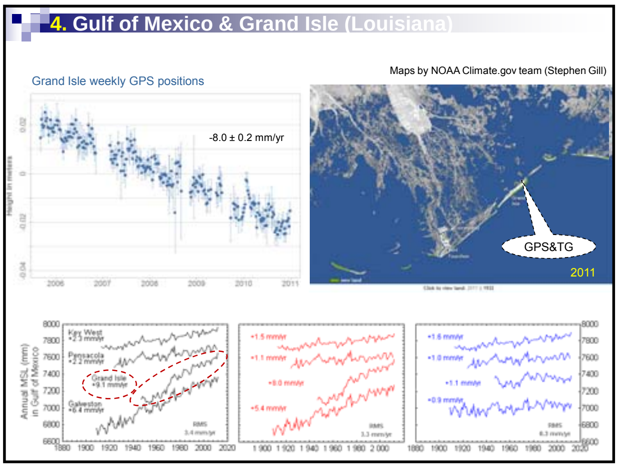

2. The importance of land movements at the coast
Vaasa
http://www.fgi.fi/fgi/themes/land-uplift
Estimates of the past
Instrumental record
Projections of the future
Sea level change (mm)
Year
+20 – 50 cm
Vaasa weekly GPS positions
+8.46 ± 0.13 mm/yr
Sea level and prediction
Kahma, 2008

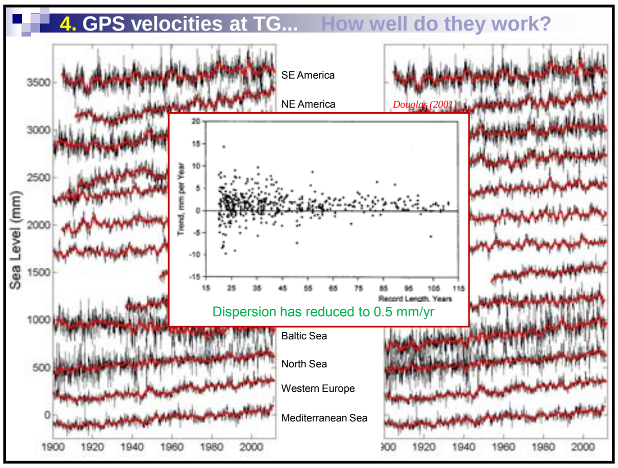

2. Wide range of VLM processes
Source PSMSL: http://www.psmsl.org/train_and_info/geo_signals/
STOCKHOLM
(Glacial isostatic adjustment)
(Co-seismic displacement)
(Groundwater extraction)
(Sedimentation)
(No evidence of land motion)
Tide Gauge Station
Climate contributions
Land movements
Sea Surface
Bedrock crust
Determination
→ Modeling: Only GIA
Uncertainties (viscosity profiles, lithosphere thickness, ice retreat)
Other processes?
→ Monitoring: Space Geodesy
Challenges
→ Rates of sea-level change: ~2 mm/yr
→ Standard errors: one order of magnitude less to be useful in LTT sea level studies!

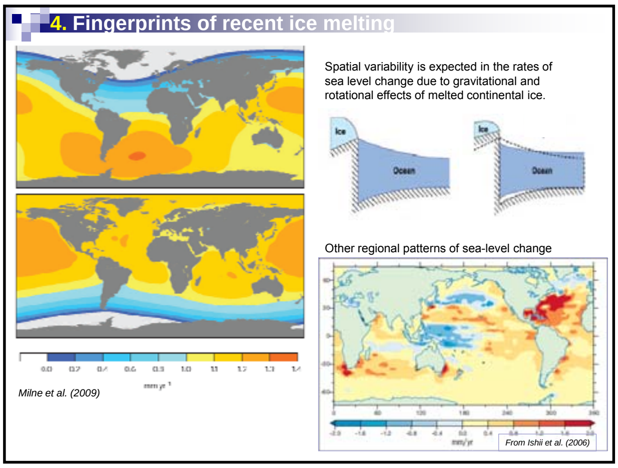

3. Measure (if one can): The GPS solution
Review of Geodetic Techniques
Carter et al. (1989; 1993)
Satellite Laser Ranging (SLR)
VLBI
DORIS
Absolute Gravimetry
Campaign versus Continuous GPS
Zerbini et al. (1996)
Neilan et al. (1998) – JPL (IGS/PSMSL)
GPS constellation
Campaign mode
Continuous mode
Regional versus Global GPS Processing
Mazzotti et al. (2008)
Legrand et al. (2010)
International infrastructure (IGS)
IGS pilot project: TIGA (OS, DC, AC)
Launched in 2001
Cumulative GPS processing versus
Homogenous GPS reprocessing
Wöppelmann et al. (2007) in GPC
Dedicated Data Storage : 7 To
"Lustre" Data File System
Altix ICE 8200 (SGI)
Cluster Linux (2008 → 2010)
128 processors → 392


3. GPS vertical velocities from the ULR consortium
Santamaria-Gomez et al. (2012) available at www.sonel.org
Calculation of uncertainties on velocities taking into account time-correlated noise
326 GPS velocities, from which 201 co-located at or near a tide gauge (<15km)
Median=0.3 mm/yr
% of stations
Vertical velocity uncertainty (mm/yr)
mm/yr

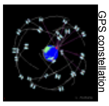

4. GPS velocities at TG… How well do they work?
Tide gauge records
GIA-corrected tide gauge records
GPS-corrected tide gauge records
Annual MSL (mm) in northern Europe
Annual MSL (mm) in northwestern America
Annual MSL (mm) in Gulf of Mexico

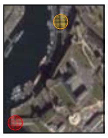

4. Gulf of Mexico & Grand Isle (Louisiana)
Grand Isle weekly GPS positions
-8.0 ± 0.2 mm/yr
Height in meters
Maps by NOAA Climate.gov team (Stephen Gill)
GPS&TG
2011
Annual MSL (mm) in Gulf of Mexico


4. GPS velocities at TG… How well do they work?
Sea Level (mm)
SE America
NE America
Douglas (2001)
Trend, mm per Year
Record Length, Years
Dispersion has reduced to 0.5 mm/yr
Baltic Sea
North Sea
Western Europe
Mediterranean Sea


4. Fingerprints of recent ice melting
Spatial variability is expected in the rates of sea level change due to gravitational and rotational effects of melted continental ice.
Ice
Ocean
Other regional patterns of sea-level change
Milne et al. (2009)
From Ishii et al. (2006)

4. GPS Limitations: Data access & Assumptions

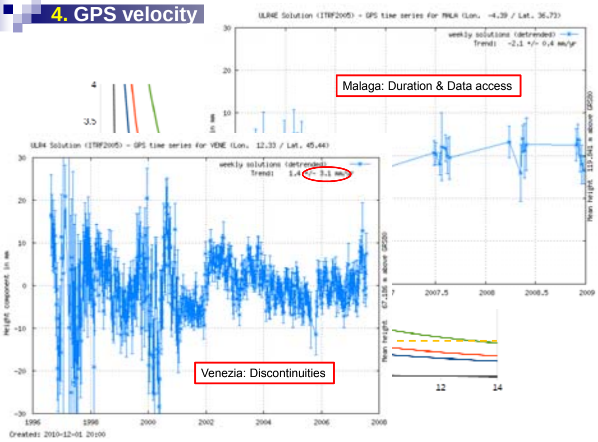




GLOSS dedicated GPS@TG Data Assembly Centre (www.sonel.org)

- Working hypotheses
  1. GPS antenna vertical movement ↔ Tide gauge land movement
  2. Land movements are linear over the tide gauge records length

4. GPS velocity



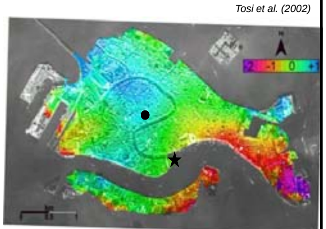
4. GPS Limitations: Data access & Assumptions

- GPS antenna link to the TGBM (mostly missing)
  - Hypothesis: GPS antenna & Tide gauge, same vertical land motion
  - Short distances (< 500m): GPS included in the TGBM leveling network
  - Longer distances: differential GPS campaigns (2-3 hours)
  - Alternative and complement: InSAR and PSI techniques

Wöppelmann & Marcos (2012)

Station Name (PSMSL)	Altimeter – TG[2] This study (all data)	GPS[3] (ULR Solution)
Santander I	0.91 ± 0.34	-0.09 ± 0.23
La Coruna I	0.73 ± 0.33	-2.19 ± 1.82
Vigo	0.57 ± 0.33	
Cascais	–	0.18 ± 0.16
Marseille	0.17 ± 0.20	-0.04 ± 0.25
Venezia (PDS)	-1.22 ± 0.19	1.40 ± 3.06
Trieste	0.30 ± 0.19	
Rovinj	0.75 ± 0.19	
Bakar	0.43 ± 0.18	
Split Marjana	0.61 ± 0.18	
Split Gradska Luka	0.70 ± 0.18	

Tosi et al. (2002)



★ TG VENEZIA (Punta della Salute) ● GPS station VENE

4. Case study of Alexandria (Egypt)

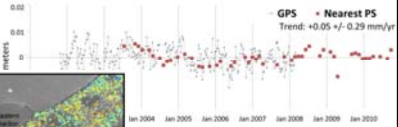
Station Name (PSMSL)	Altimeter – TG[2] This study (all data)	GPS[3] (ULR Solution)
Venezia (PDS)	-1.22 ± 0.19	1.40 ± 3.06
Thessaloniki	-1.96 ± 0.25	
Leros	1.28 ± 0.35	
Alexandria	-0.40 ± 0.23	-0.1 ± 0.5

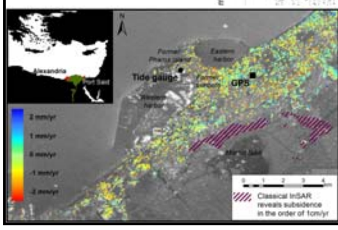
Wöppelmann & Marcos (2012)

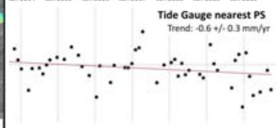
Ranked 11 in terms of population exposure to coastal flooding by 2070 (Hanson et al., 2011)

But our results reveal **moderate subsidence**, supported by 3 km distant GPS.

Previous studies indicate differential subsidence with lower rates to the east (e.g., *Stanley, 1990*).







Wöppelmann et al. (in press)

5. Concluding remarks

- GPS (GNSS) solution for monitoring Tide Gauges
  - Required accuracy is demanding for sea level applications
  - Demonstrative results have been obtained in the recent years
  - VLM are an important source of spatial variability
    - ↳ Detection of fingerprints & other patterns
- GPS antenna link to the TGBM (mostly missing)
  - Hypothesis: GPS antenna & Tide gauge, same vertical land motion
  - Short distances (< 500m): GPS included in the TGBM network
  - Longer distances: differential GPS campaigns (2-3 hours)
  - Alternative and complement: InSAR and PSI techniques
- Data availability (WMO/IPCC data policy…)
  - GLOSS dedicated GPS Data Assembly Center (SONEL)
  - Metadata, equipment changes: limit to the strict minimum
  - IGS (TIGA) infrastructure will ensure processing and results
- Need for a more robust and stable ITRF
  - Current accuracy: ~0.5 mm/yr origin, ~0.05 ppb/yr scale
  - Target accuracy: 0.2 mm/yr origin, 0.01 ppb/yr scale